TEXTILE YARNS

Technology, Structure, and Applications

B. C. GOSWAMI
Textile Research Institute
Princeton, New Jersey

J. G. MARTINDALE
Galashiels College of Textiles
Galashiels, Scotland

F. L. SCARDINO
Philadelphia College of Textiles and Science
Philadelphia, Pennsylvania

A Wiley-Interscience Publication
JOHN WILEY & SONS
New York · London · Sydney · Toronto

Kolon Industries, Inc.
Exhibit 2020
HS Hyosung v. Kolon
IPR2025-00664

Ex. 2020-001

Copyright © 1977 by John Wiley & Sons, Inc.

All rights reserved. Published simultaneously in Canada.

No part of this book may be reproduced by any means, nor transmitted, nor translated into a machine language without the written permission of the publisher.

Library of Congress Cataloging in Publication Data

Goswami, Bhuvenesh Chandra, 1937-
Textile yarns.

"A Wiley-Interscience publication."
Includes index.
1. Yarn. I. Martindale, J. G., joint author.
II. Scardino, F. L., joint author. III. Title.

TS1449.G66 677'.02862 77-398
ISBN 0-471-31900-7

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Ex. 2020-002

Contents

1. Classification of Yarns 1
2. Raw Materials 11
3. Yarn Structure 76
4. Yarn Specifications 88
5. Twist in Yarns 96
6. Mechanical Properties of Yarns 137
7. Uniformity Characteristics of Yarns 219
8. Yarn Structure in Relation to the Aesthetic and Tactile Qualities of Apparel Fabrics 262
9. Conversion of Staple Fibers into Yarn 273
10. Blending in Staple Yarn Systems 338
11. Continuous-Filament Yarns and Tows 363
12. Textured Yarns 382

Appendix A 417

Index 475

Ex. 2020-003

5

Twist in Yarns

INTRODUCTION

The subject of yarn structure is discussed in Chapter 3 of this book. It is pointed out that twist plays an important role in affecting the arrangement of fibers or filaments in the yarn cross section. The study of twist and how it effects some of the important properties of textile yarns is the subject of this chapter.

In staple yarns, twist is essential to hold the fibers together and to impart some degree of cohesiveness to the structure. On the other hand, the filaments in a multifilament yarn would fray away if there were no cohesive forces holding them together. Furthermore, the formation of plied or cabled yarns is also achieved by twisting single or plied yarns together to produce a coherent linear structure. In other words, twist is a means by which a bundle of fibers, filaments, or yarns in a plied yarn is held together so that the ultimate structure is made capable of withstanding the stresses and strains and the chafing action of the many processes involved in the manufacture and use of textile fabrics.

The role of twist is very profound in determining the properties of finished yarns vis-a-vis fabrics. The link between fiber properties and the end-use behavior of a textile fabric can be best explained by the following diagram (Figure 5.1).

When a number of components (fibers or filaments) in a continuous strand are twisted, radial forces develop which in turn affect the relative position of the components in the yarn structure, leading to a close packing of all components in a given cross section. Thus the insertion of twist in fiber assemblies (yarns) affects, in addition to the tensile properties (strength-extension), the diameter and the specific volume (in other words, softness or hardness) of yarns. The change in the fiber packing in turn determines the cover of a fabric and such other properties as warmth, crease recovery, permeability, and various other

Ex. 2020-004

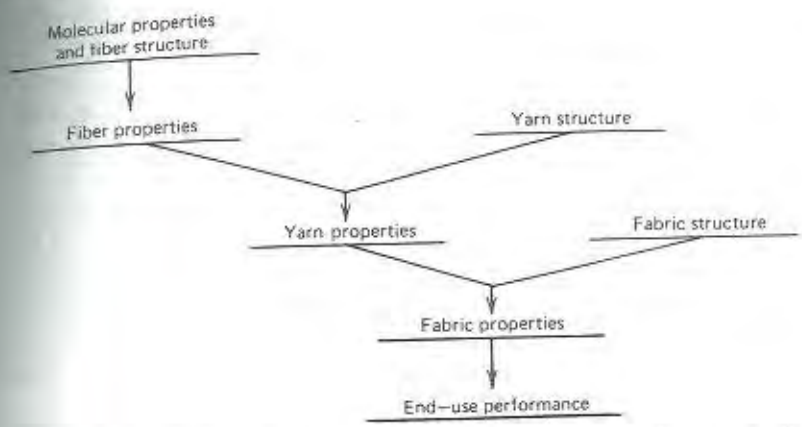


Figure 5.1. Relationships among fiber, yarn, and fabric structure and properties [From Hearle (1)].

related characteristics. Twist also affects the hairiness of yarns, which is a very important property in determining the pilling behavior and the economics of the singeing process.

In his Mather lecture, titled "Twisted Structures," Treloar (2) adequately recognizes the role of twist in yarns and the part it plays in the design of textile structures. He discusses the obvious necessity of twist in the natural and staple fibers and points out:

"Twist is essential to provide a certain minimum coherence between fibers, without a yarn having a significant tensile strength cannot be made. This coherence is dependent on the frictional forces brought into play by the lateral pressures between fibers arising from the application of a tensile stress along the yarn axis. With the introduction of continuous filament yarns, however, the role of twist must be reconsidered. In continuous-filament yarns, twist is not necessary for the attainment of tensile strength (in fact, it reduces it) but it is necessary for the achievement of satisfactory resistance to abrasion, fatigue, or other types of damage associated with stresses other than a simple tensile stress, and typified by the breakage of individual filaments, leading ultimately to total breakdown of the structure. High twist produces a "hard" yarn, which is highly resistant to damage of this kind. The role of twist in continuous-filament yarn is thus to produce a coherent structure that cannot readily be disintegrated by lateral stresses.

From the engineering standpoint, the interesting thing about this structural function of twist is that, in contrast to most structure-building techniques, it produces its effect without significantly increasing the flexural rigidity or resistance to bending of the system. A yarn of 100 filaments has only 100 times

Ex. 2020-005

the flexural rigidity of a single filament; if the filaments were all cemented together to form a solid rod, it would have 10,000 (100^2) times the flexural rigidity of a single filament.

Extending this line of thought to woven fabrics, we find again that the stiffness of the fabric is of the same order as the total stiffness of all the filaments in a given cross section as shown by Livesey and Owen, and similar considerations apply, no doubt, to knitted or other types of fabric structure. We see, therefore, that the major processes of textile fabrication are concerned with the production of coherent structures having maximum flexibility or minimum resistance to bending stresses, and hence also to compressive or buckling stresses, while retaining, of course, the inherent strength of the original filament material under the action of tensile stresses. This objective is in curious contrast to that normally encountered in engineering structures, where the general problem is to produce maximum resistance to bending and compressive stresses, combined with maximum tensile strength. The engineer achieves his objective of maximizing the rigidity by the introduction of suitably disposed fixed linkages between the various components of the structure. In textile structures, on the other hand, the objective of maximum flexibility is ingeniously achieved by the introduction of geometrical restraints, which, while strongly resisting forces of disruption, do not interfere appreciably with the small relative movements of individual elements associated with bending or other types of lateral deformation. However, a difference of objective does not necessarily imply a difference in method of approach, and there is no reason why the design of a textile structure should not be treated by the same rigorous analytical techniques as the design of any other engineering structure, such as a bridge or an aeroplane. The materials with which the textile engineer works have an inherent strength and other mechanical properties comparable with those of typical structural-engineering materials, and research is continually being concentrated on the improvement of these inherent properties. If these valuable characteristics are to be utilized to the fullest extent, it is equally important to see that the problem of design from the engineering standpoint receives something like the same kind of attention."

The study of twist, therefore, is very important to understanding the structure and behavior of yarns and their ultimate influence on the end-use properties of fabrics.

DEFINITION OF TWIST

When two ends of a straight strand (yarn) are rotated relative to one another, the fibers on the surface of the yarn lie in helices about the yarn axis. In other words, a yarn is twisted when fibers on the surface, which were originally parallel to the axis of the yarn, are now deformed (rotated) so that they make an angle θ with the axis, and the amount of twist is a function of this angle (Figure

Ex. 2020-006

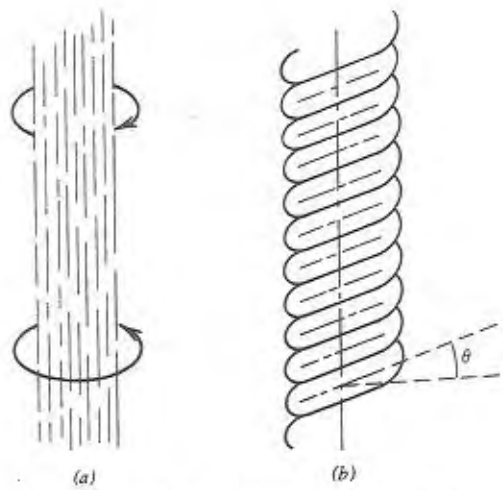


Figure 5.2. (*a*) Parallel bundle of fibers, (*b*) twisted bundle of fibers.

5.2). This definition of twist only applies to the ideal case of an originally straight fiber assembly. However, in actual yarns, variability of yarn diameter, contraction because of twist, migration of fibers from one zone to the other, radial compression of the yarn, and fiber slippage are some of the factors that tend to make the yarn geometry depart from the ideal.

The implications of some of these factors have been taken into account by Woods (3), who studied the kinematics of twist. He introduced the concept of "tortuosity" and stated that when a yarn is distorted its axis lies in a helix rather than in a single plane. On this basis, he has proposed a definition of twist, which is considered valid for all states of a yarn. According to his definition: "The twist is defined as the rotation of the transverse to any chosen generator about the axis, per unit length of the axis; that is to say that as we pass along the axis, the transverses rotate about the axis at a rate which is proportional to the twist in the string at the point considered." The "generator" is defined as any line on the surface that is parallel to the axis when the string is straight and untwisted; the radius of any cross section is the transverse in that section.

DIRECTION OF TWIST

In the designation of yarns, it is essential to specify the direction of twist. Besides its importance in simplifying the trade, it is of great technical significance in designing fabrics. For example, in a twill fabric, the direction of twist in the yarn is of particular importance in determining the predominance of twill

Ex. 2020-007

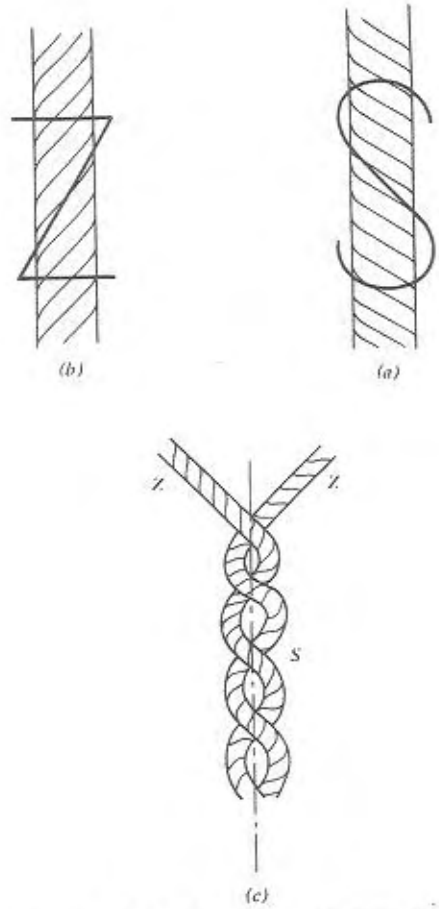


Figure 5.3. Direction of twist. (*a*) Right-handed twist, S, (*b*) left-handed twist, Z, (*c*) twist in folded yarns.

effect. For a right-handed twill, the best contrasting effect will be obtained when a yarn with Z twist is used; on the other hand, a left-handed twist will produce a fabric having a flat appearance.

The direction of twist in a yarn is designated in two ways:

1. Right-handed twist. S twist or clockwise (Figure 5.3*a*).
2. Left-handed twist. Z twist or anticlockwise (Figure 5.3*b*).

Single yarns are generally twisted in anticlockwise directions, whereas the S or right-handed twist is very common in ply yarns.

Ex. 2020-008

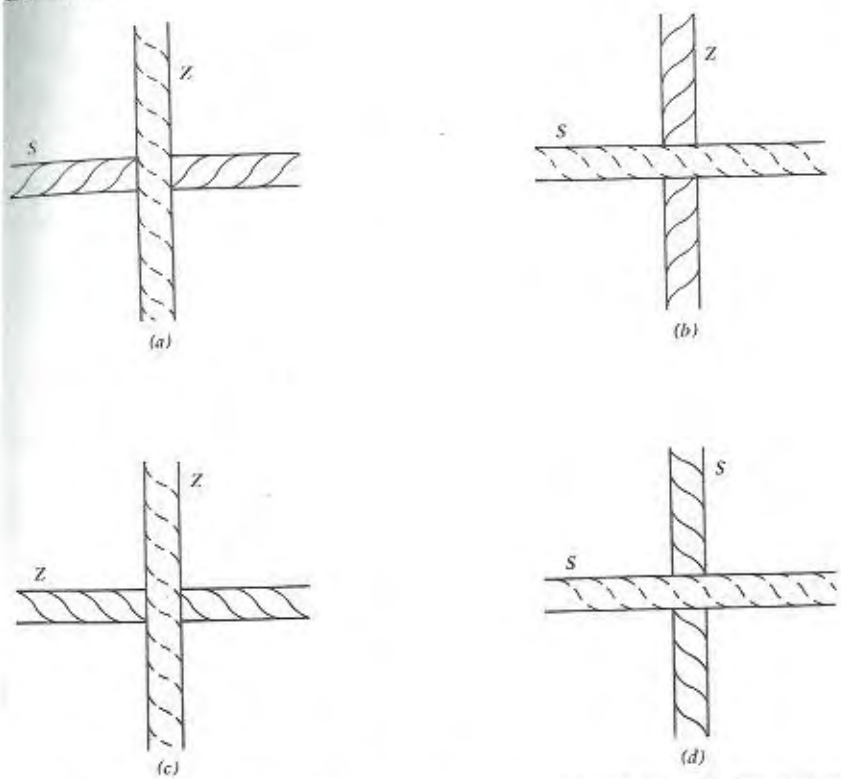


Figure 5.4. (*a*) and (*b*) Conditions that preclude nesting, (*c*) and (*d*) conditions that promote nesting.

Fabric Appearance and Twist Direction

Single warp yarns are generally given Z twist, and the weft or filling yarns, S twist (Figures 5.3*a* and *b*). When the warp and weft yarns are interwoven, they generally lie at an angle approximately 90° at the intersection, as shown in Figure 5.4. It is clear from Figure 5.4*a* and *b* that there is no possibility of the warp and weft yarns bedding or nesting into each other. However, if the two sets (warp and weft) of yarn have similar twist, that is, both Z or both S (Figures 5.4*c* and *d*), the fibers at the point of yarn contact will be more or less parallel. It is likely that this situation may induce nesting of yarns into each other. Consequently, the fabric produced will be thinner and firmer in hand than when nesting is prevented.

However, there is one important condition that must be satisfied before the kind of bedding effect described above occurs. This condition, according to Brunnschweiler (4), is that the sum of the angles of twist in warp and filling

Ex. 2020-009

yarns must approach 90°. But the angle of twist in normal staple yarns varies between 20 and 30°. It follows that if the angle of twist in a yarn is 20°, the fibers will cross at 90–(2 × 20) = 50°, which is far from the condition required for bedding. On the other hand, with a 45° twist angle (a twist factor far in excess of 77 $tex^{1/2}$ turns/cm used for crepe yarns), the yarn produced would be so compact that it would inherently resist nesting. Nevertheless, the relative direction of twist in the warp and filling yarns with normal twist does affect the fabric structure and the bedding behavior, as has been pointed out by Backer (5, 6). He gives the following reasons: (1) Yarns tend to flatten at the crossover points, and this causes an increase in twist angle. (2) Yarn crimping also increases the angle of twist on the inside of the bend.

Sometimes yarns with opposite twist directions are used to produce special surface texture effects in crepe fabrics. For example, the use of 1S:1Z crepe yarn twist arrangement in both warp and filling produces the finest figure effect in a crepe fabric.

The relative direction of twist has very important implications in determining the distinctness of the diagonal lines in a twill fabric. There are three major considerations that must be taken into account when designing twill constructions. These are:

1. The twist direction in relation to the twill hand. The diagonal twill effect will be predominant if the yarn twist (warp or filling) opposes the twill direction.
2. The relative direction of twist in the warp and filling. The use of warp and filling yarns with the direction of fibers opposing each other will result in a distinct twill effect. In other words, both sets of yarn should have the same twist direction.
3. Nesting or bedding of yarns. This factor is of minor consequence. However, if nesting is prevented by using warp and filling yarns twisted in opposite directions, the yarn floats become prominant, thus emphasizing the twill line.

Similar twist-twill relationships are valid in the designing of satin and sateen weaves for which either the suppression or prominance of the incipient twill lines is a requirement.

Determination of Twist

Accurate determination of twist, particularly in spun yarns, is important, since it is related to strength and other physical characteristics of yarns and fabrics. There are essentially two methods that are used in the industry for determination of twist in single yarns. These are 1. direct counting method, and 2. indirect untwist-twist method.

Ex. 2020-010

In the direct counting method, twist can be determined either by directly counting the number of turns in a unit length under a magnifying glass or by the parallel-fiber method in which the specimen is untwisted to zero twist until all the fibers are parallel. Because of the large variation of twist between short segments along the length of the yarn, it is necessary to take a very large number of observations to obtain a representative test average. In the parallel fiber method, the length of the specimen also plays an important role. If the specimen is longer than the staple length of the fiber, there is a possibility of the entanglement of fibers, which makes observation of when the twist is removed more difficult. On the other hand, specimen lengths shorter than or equal to the staple length of the fiber are easier to handle.

The untwist-twist method is much simpler and easier to perform. It is based on the assumption that when the twist in one direction is removed and retwisted by an equal number of turns in the opposite direction, the initial conditions of length and tension will be achieved. Thus the average turns per unit length is obtained. Worner (7) points out some of the limitations of the direct counting and the indirect untwist-twist methods for determination of twist in carded cotton yarns. He reports that there is a good correlation between the nominal (machine) twist and that obtained by the direct counting method. However, the correlation between the machine twist and the values obtained by the untwist-twist method is governed by the degree of tension applied to the test specimens; the best agreement is obtained at the highest tension used in the experiment. He has also shown that the number of turns per unit length obtained by this method is somewhat lower than that observed by the direct method.

GEOMETRY OF TWISTED YARNS

The translation of the physical properties of textile fibers into textile structures such as yarns and fabrics is a function of both the fiber properties and the geometric configuration they assume in the ultimate end product. Earlier studies of the relationships between yarn structure and properties have been along empirical or semi-empirical lines. However, many technologists who are concerned with the evaluation of the physical properties of textile structures have since realized that these relationships are governed by the same physical and engineering concepts as those used so successfully in the characterization of the more classic structural materials such as steel and concrete, etc. Hearle and Backer (1) have given an excellent account of the progressive development of the ideas in this field of study. Nevertheless, it is considered appropriate to introduce the reader to some basic concepts that are revelant to the study of yarn structure and properties. One such aspect is the understanding of the geometry of twisted yarns that is so vital in analyzing the stress-strain behavior of yarns in addition to

Ex. 2020-011

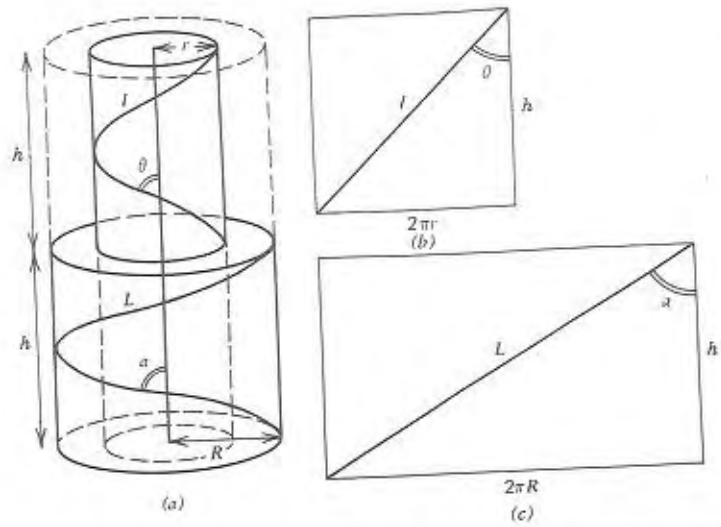


Figure 5.5. Idealized helical yarn geometry. (*a*) Idealized geometry, (*b*) "opened-out" diagram of cylinder at radius *r*, (*c*) "opened-out" yarn surface. [From Hearle (1)].

various other physical properties. A partial list of the pertinent physical characteristics that are influenced by twist will demonstrate its extreme importance:

bending behavior
resistance to creasing
resistance to abrasion
drapability
elastic performance
impact strength
stress distribution and analysis.

Idealized Helical Geometry

In defining the geometry of a single yarn, the model usually adopted is that of an ideal physical form. This is the coaxial-helix model illustrated in Figure 5.5 (1). The assumptions underlying the model are characterized by the following postulates:

1. The yarn is circular in cross section and is uniform along its length.
2. It is built up of a series of superimposed concentric layers of different radii in each of which the fibers follow a uniform helical path so that its distance from the center remains constant.

Ex. 2020-012

3. A filament at the center will follow the straight line of the yarn axis, but going out from the center the helix angle gradually increases, since the twist per unit length in all the layers remains constant.
4. The axis of the circular cylinders coincides with the yarn axis.
5. The number of filaments of fibers crossing the unit area is constant, that is, the density of packing of fibers in the yarn remains constant throughout the model.
6. The structure is assumed to be made up of a large number of filaments; this will avoid any complications arising because of any descrepancies in packing of fibers.

This idealized model can be used to derive some very useful geometrical relations. Let us first define the parameters involved in characterizing the idealized geometry:

R = yarn radius (cm)
r = radius of cylinder containing the helical path of a particular fiber (cm)
T = yarn twist, turns per unit length (cm^{-1})
h = length of one turn of twist (cm)
α = surface angle of twist (the angle between the axis of a fiber on the surface and a line parallel to the yarn axis (degrees)
θ = helical angle at radius r (degrees)
l = length of fiber in one turn of twist, at radius r (cm)
L = length of fiber in one turn of twist, at radius R (cm)

It is clear from the model that

$$h = \frac{1}{T} \tag{5.1}$$

If the concentric cylinders in Figure 5.5*a* are cut along a line parallel to the yarn axis and opened out flat, they will appear as shown in Figure 5.5*b* and *c*. From the geometry of the opened-out diagrams one can obtain the following relations:

$$l^2 = h^2 + 4\pi^2 r^2 \tag{5.2}$$

$$L^2 = h^2 + 4\pi^2 R^2 \tag{5.3}$$

$$\tan\theta = 2\pi\ r/h \tag{5.4}$$

$$\tan\alpha = 2\pi\ R/h \tag{5.5}$$

Ex. 2020-013

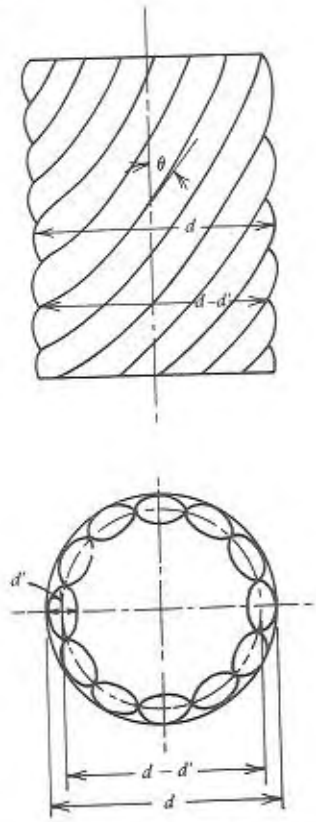


Figure 5.6. Multifilament yarn, showing difference between outer diameter and the diameter (d-d') effective in measuring twist angle.

In practice the relation in equation 5.5 does not apply exactly in actual yarns with a finite number of fibers. This complexity of twist geometry has been discussed by Schwarz (8) and later by Woods (3) and Treloar (9). Schwarz (8) argued that, in the measurement of yarn diameter, the value obtained corresponds to the diameter of the circle (d), which circumscribes the outer layer of fibers, as shown in Figure 5.6. But in the measurement of twist angle (by a microscopic technique), it is the edges of the fibers in the outer layer that are observed. Therefore, the effective twist angle measurement is made at a diameter represented by the cylinder containing the centers of fibers in the outer layers. The modified form of equation 5.5 then becomes:

$$\tan \alpha = \pi(d\text{-}d')/h \tag{5.6}$$

$$= \pi dkT \tag{5.7}$$

where d = yarn diameter
d' = fiber diameter

Ex. 2020-014

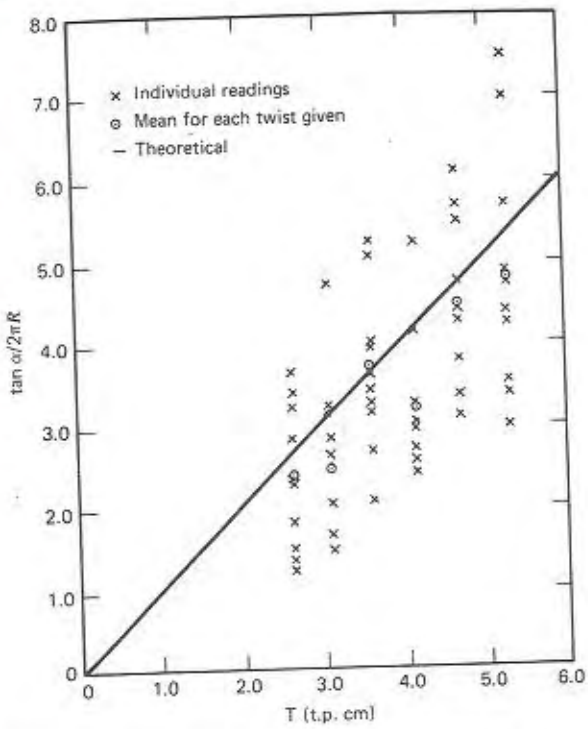


Figure 5.7. External filament angle as function of twist 1650-den. Tenasco. tension = 100 g wt. (Model uptwister) From Riding (11)

and $k = (d\text{-}d')/d$ = Schwarz's constant.

The value of k approaches unity for large numbers of fibers. Schwarz has reported the values of k for single, plied, and cabled yarns and has pointed out its usefulness in twist analysis.

In real yarns, assumptions (2) and (3) made above are incompatible in view of the observations made by Morton (10) on "fiber imigration" in staple yarns. His observations suggest that the path of a fiber in a yarn (continuous filament as well as staple yarn) is in fact not a cylindrical helix, but one whose radius changes along the length of the yarn.

Riding (11) has reported an experimental study in which he examined the validity of equation 5.5 in determining the relationship between twist and yarn structure. He points out that the agreement between experiment and theory is very good for continuous-filament yarns twisted by the continuous method. Figure 5.7 shows the values of tan $\alpha/2\pi R$ plotted against T, turns of twist per unit length for a 1650-den Tenasco yarn. The external filament angle and the yarn radius were measured with the aid of a microscope. The value of α and R

Ex. 2020-015

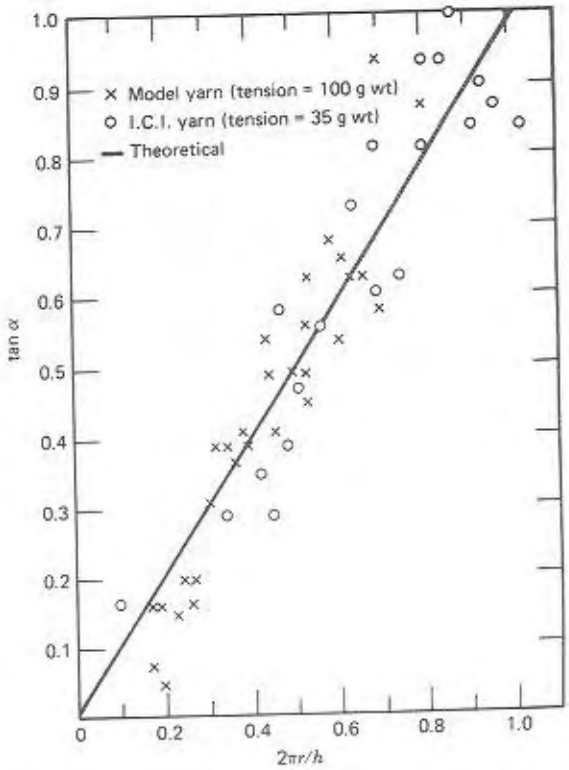


Figure 5.8. Internal filament angle as function of twist factor. (Model uptwister) From Riding (11)

were measured at ten points along the yarn. The theoretically calculated line is also plotted. It is clear from this figure that the experimentally measured values of twist angle are in good agreement with the predictions of the theory (equation 5.5). In the same study, Riding has also examined the dependence of filament angle on pitch and its radial position in the yarn cross section. To measure the filament angle at various radial positions along the length of the yarn, the tracer fiber technique developed by Morton and Yen (12) was used. (This is discussed briefly in Chapter 3.) Figure 5.8 shows the values of tan α plotted against $2\pi\ r/h$. It can be seen that "except for small values of r/h (i.e., small amplitudes), where the experimental errors are relatively large, there is no systematic deviation from the theoretical formula."

Ex. 2020-016

YARN SIZE AND TWIST MULTIPLIER

It was pointed out in Chapter 4 that textile yarns are generally specified by their count or size, namely, mass per unit length or linear density. The reason for this is that the diameter (or radius) of a yarn is very difficult to define because of its hairy nature and an indefinite packing density; on the other hand, linear density is easier to measure and control during spinning. The various traditional yarn count systems (direct and indirect) are discussed thoroughly in Chapter 4.

Twist multiplier or twist factor is a measure of the "twist-hardness" of a yarn; it is given by the product of yarn twist and square root of yarn size in the direct system, or the division of the turns per unit length by the square root of the count in an indirect system. Expressed in mathematical terms:

1. Direct system (tex system)—turns per centimeter multiplied by

$$\sqrt{\text{count of yarn, tex}} = \text{turns/cm} \times \text{tex}^{1/2}$$

2. Indirect system (cotton or worsted, etc., count system)—turns per inch divided by

$$\sqrt{\text{count, (cotton or worsted) of yarn}} = \text{tpi/count}^{1/2}$$

Some examples of the major yarn count systems and the twist multipliers and their relationships (conversion of one system to the other) are given in Table 5.1.

Table 5.1. Some Major Yarn Count Systems

Name of System	Unit of Count	Conversion to tex	Unit of Twist Multiplier	Conversion to $\text{tex}^{1/2}$ turns/cm
Direct Systems:		Multiply by:		Multiply by:
Tex	g/km	1	$\text{tex}^{1/2}$ turns/cm	1
Denier	g/9000 m	1/9 = 0.111	–	–
Indirect Systems:		Divide into:		Multiply by:
Cotton count	840 yd hanks/lb	590.5	$\text{tpi/count}^{1/2}$	9.57
Worsted count	560 yd hanks/lb	885.8	$\text{tpi/count}^{1/2}$	11.72
Metric number	km/kg	1000	–	–

The idealized yarn geometry can be used to express the relation between yarn count and twist multiplier as derived in the following manner:

Ex. 2020-017

Volume of unit length of idealized yarn = πR^2 and if v_y is the specific volume of the yarn expressed in cm^3/g, then its mass is $\pi R^2/v_y$.

From this it follows that:

$$\text{Yarn count} = C = \text{mass of 1 km (in tex system)}$$
$$= (\pi R^2/v_y) \times 10^5 \text{ tex} \tag{5.8}$$

Rearranging equation 5.8:

$$R = (v_y C/10^5 \pi)^{1/2} \tag{5.9}$$

and combining this with equations 5.1 and 5.5, we get:

$$\tan \alpha = 10^{-3} (40\pi v_y)^{1/2} C^{1/2} \tau \tag{5.10}$$
$$= 0.0112 v_y^{1/2} \tau \tag{5.11}$$

where $\tau = C^{1/2} T \text{ tex}^{1/2}$ turns/cm (twist multiplier).

The amount of twist needed in a yarn depends on the yarn size, the staple length of the fibers used, and the desired end-use application. A yarn may be soft-twisted (such as knit yarns) or it may be hard-twist (crepe yarns); the factor used to achieve these desired characteristics is the "twist multiplier." It is used in the industry in such a way that it is independent of the yarn size. This is made clear by equation 5.11, which shows the relation between twist multiplier and twist angle. "(These) two quantities are directly related in yarns of different counts but of the same twist factor will be geometrically similar differing only by a dimensionless scale factor" as stated by Hearle (1), Hearle has given values for twist factors and twist angles for some typical yarn specific volumes (Table 5.2).

Table 5.2. Twist Factor and Twist Angle

Specific Volume (cm^3/g)	Twist Factor, $Tex^{1/2}$ Turns/cm						
	0	20	40	60	80	100	120
	Twist Angles (degrees)						
0.5	0	9	18	25	32	38	44
1.0	0	13	24	34	42	48	53
1.5	0	15	29	39	48	54	59

Ex. 2020-018

Some typical values of twist multiplier used in the textile industry are given in Table 5.3. Generally, long staple fibers have a tendency to bind themselves together better than short staple fibers. It is therefore usual to use a slightly

Table 5.3. Twist Factors of Typical Textile Yarns

	Twist Factor ($tex^{1/2}$ turns/cm)	Twist Factor (traditional units tpi/$count^{1/2}$)
Cotton yarns		
Doubling weft	29-32	3.0-3.3[a]
Ring weft	32-35	3.3-3.6
Ring twist	38-43	4.0-4.5
Voile	49-53	5.5-5.5
Crepe	57-77	6.0-8.0
Worsted yarns		
Hosiery	17	1.4[b]
Soft worsted	20	1.7
Medium worsted	23	1.9
Hard worsted	26	2.2
Extra hard worsted	29	2.5

[a]Using cotton count.
[b]Using worsted count, from Stanbury and Byerley (27).

lower twist multiplier for the former case than that used for the corresponding yarn made from shorter staple fibers. Because of the helical arrangement of the fibers, a yarn suffers some contraction, which may range from 2 to 3% in a soft-twist yarn and up to 10 to 12% for hard-twist yarns. Consequently, there will be a considerable difference between the nominally calculated twist factor and twist based on the zero-twist yarn length and the actual values in the twisted yarns. The effect of contraction is of importance in adjusting draft during spinning of staple yarns. The subject of contraction because of twist is discussed in section 5.6.

Optimum Twist Factor

There is a certain minimum value of twist factor below which it is impossible to spin a staple yarn. Above this minimum twist factor, which is strongly influenced by staple length, fineness, and fiber surface (frictional) characteristics, the cohesiveness (yarn strength) between fibers increases at a fairly rapid rate initially. At low twist factors, the initial increase in yarn strength is determined by the resistance of fibers to slippage.

Ex. 2020-019

At high twist factors, the contribution because of resistance to slippage reaches a steady maximum. However, as the twist factor becomes high, the effect of fiber obliquity comes into play, and this has a tendency to cause a decrease in yarn strength. The twist-strength relationship is therefore the result of the simultaneous operation of the two effects discussed above. The twist factor at which maximum strength is achieved in any given staple yarn is sometimes called the "optimum twist factor." The optimum twist factor and the lowest practicable twist will both depend on such fiber characteristics as fiber length, fineness, bending and flexural rigidity, and frictional properties. The optimum twist factor will also vary with the count of yarn being spun, and it is entirely possible for the maximum value of breaking load and breaking extension to occur at different levels of twist. A more detailed discussion of the twist strength relationship in staple yarn is found in Chapter 6.

CONTRACTION BECAUSE OF TWIST

One effect of twist in a yarn is to cause contraction as a result of the longer path (because of helical geometry) followed by the fibers. The theoretical calculation of contraction has been dealt with by Treloar (9), Morton and Hearle (13), and Gracie (14). The theoretical treatment is based on the consideration of an idealized twist geometry and the occurrence of fiber migration in the yarn. The existence of fiber migration accounts for the effective averaging within the yarn of the different fiber lengths at different positions; the deficiency in length for filaments near the surface is made up by the excess occurring when they are near the center.

The yarn contraction can be defined in two ways:

$$\text{contraction factor} = C_y = \frac{\text{length of zero twist yarn}}{\text{length of twisted yarn}}$$

and

$$\text{retraction} = R_y = \frac{\text{length of zero twist yarn} - \text{length of twisted yarn}}{\text{length of zero twist yarn}}$$

In other words,

$$C_y = 1/(1 - R_y) \tag{5.12}$$

The contraction factor is very useful when dealing with staple yarns. Its value ranges from 1 for no contraction to infinity for contraction to zero length. The

Ex. 2020-020

contraction affects the size or count of the spun staple yarn; therefore, contraction factor indicates the factor by which the draft must be adjusted to prevent the twist contraction from decreasing the yarn size. For example, if a 1.0 hank roving is spun to 18 single yarn 5% contraction is allowed, the draft adjusted at the drafting rollers must be greater than 18; that is, it should be 18.90 instead of 18. The parameter "retraction" is commonly used for continuous-filament yarns, and its value ranges from 0 to 1. The retraction represents the fractional decrease in length or increase in the linear density (denier) on twisting continuous-filament yarns.

The theoretical relationship that expresses retraction in terms of surface twist angle has the following form (9, 13):

$$R_y = (\bar{\ell}-h)/\bar{\ell}$$
$$= \frac{\sec\alpha - 1}{\sec\alpha + 1} = \frac{1-\cos\alpha}{1+\cos\alpha} = \tan^2(\alpha/2) \qquad (5.13)$$

Where ℓ = mean length of filaments in the length h of twisted yarn, and
α = surface twist angle.

The contraction factor is given by:

$$\text{contraction factor} = C_y = \frac{\ell}{h} = \frac{1}{2}(1+\sec\alpha) \qquad (5.14)$$

(For derivation of these expressions, the reader is referred to reference 9 or 13).

The theoretical values of contraction factor and retraction for various surface twist angles are shown in Table 5.4.

Table 5.4. Yarn Contraction[a]

Twist Angle (α)	Contraction Factor (C_y)	Retraction (R_y)
0°	1.0	0
10°	1.008	0.008
20°	1.032	0.031
30°	1.078	0.072
40°	1.153	0.132
50°	1.278	0.217

[a]from Hearle (1).

Tattersal (15) and Riding (11) have carried out experimental studies of the effect of twist on the retraction of continuous-filament yarns. They have compared their experimentally obtained results with the predictions of Treloar's

Ex. 2020-021

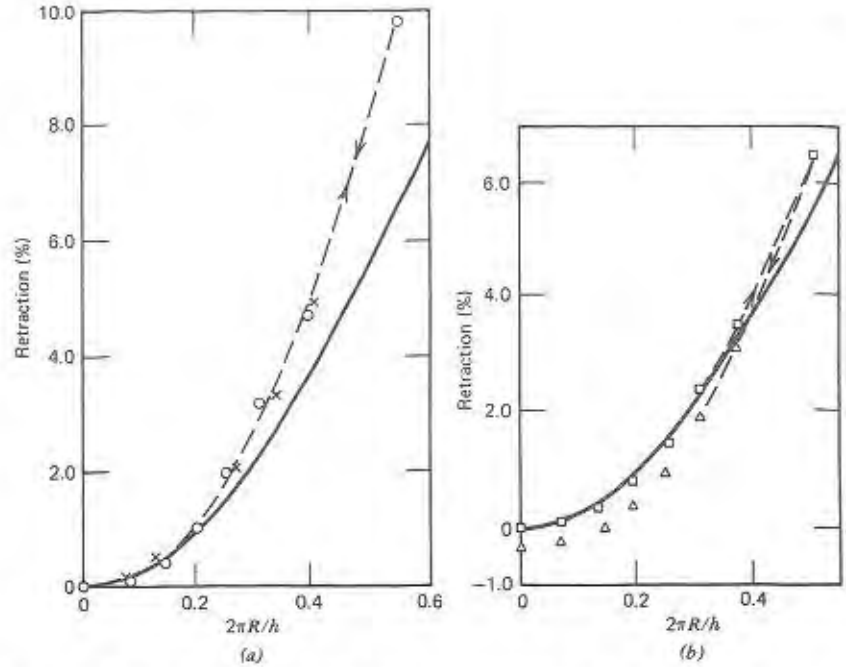


Figure 5.9. Retraction on "static twisting" of 1650 denier Tenasco; Riding (11). (*a*) Twisted under tension of 100 g wt, (x) Twisting, (○) Untwisting, (–) Theroretical; (*b*) Twisted under tension of 500 g wt.

theory (9). The measured retraction values obtained during "static twisting" (a length of yarn mounted between a twist head and a traversing trolley) plotted against $2\pi R/h$, that is, tan α, did not show a good agreement with the theoretical curve. The retraction was found to be dependent on twisting tension, as shown in Figure 5.9. Twisting at low tension gave retraction values considerably higher than predicted but showed perfect reversibility, on the other hand, at higher twisting tension, the retraction was lower than the predicted value and gave negative values on untwisting to zero twist. This latter behavior has been attributed to the irreversible straining of the filaments and kink formation, which was confirmed by visual observation. These kinks are formed during static twisting when the filaments are locked in place and are relatively restrained from migrating freely. The free migration of filaments in a twisted yarn is essential for averaging of path length. However, when retraction values were obtained by untwisting yarns made on either commercial machines or on special laboratory machines (continuously twisted yarns) as described by Riding, the agreement with the theory was found to be excellent. This is shown in Figure 5.10. Twist-

Ex. 2020-022

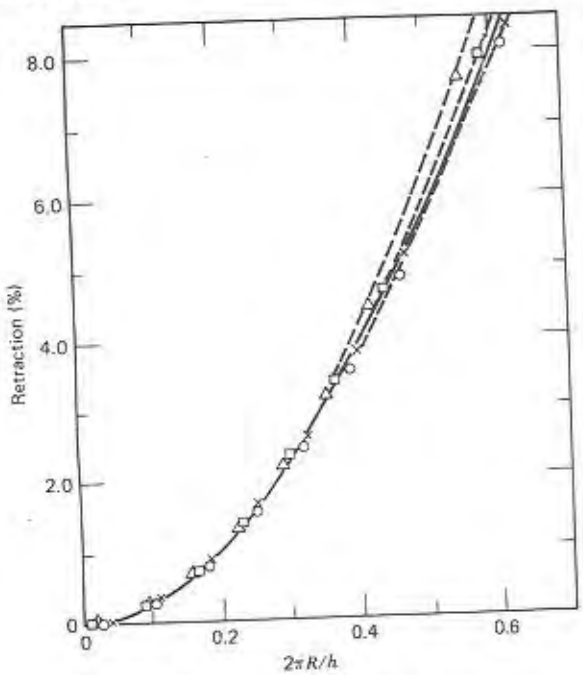


Figure 5.10. Retraction on continuous twisting of 1650 denier Tenasco on a model uptwister, at various twisting tensions. (Riding, 11) (x) 50 g wt tension, (○) 200 g wt tension, (□) 400 g wt tension, (△) 700 g wt tension, (——) theoretical.

ing tension was found to have a negligible effect on retraction values. The retraction values were also found to be independent of the maximum twist inserted and the yarn linear density.

Hearle et al. (16) have suggested the rearrangement of equation 5.14 to the following form.

$$C_y\ (C_y - 1) = 1/4\ \tan^2\ \alpha \tag{5.15}$$

This equation suggests that a plot of $C_y\ (C_y - 1)$ against $\tan^2 \alpha$ should yield a slope of 1/4 and can be conveniently used to check the correspondence of experimental results with the theory. Figure 5.11 shows the results for polyester (Terylene) and viscose yarns. The polyester yarn showed good agreement with the theory. On the other hand, viscose rayon yarn was highly influenced by twisting tension. It showed lower contraction than the predicted value when twisted at high tension. The authors attributed this difference to some permanent straining of the twisted filaments. Figure 5.12 shows the comparison of

Ex. 2020-023

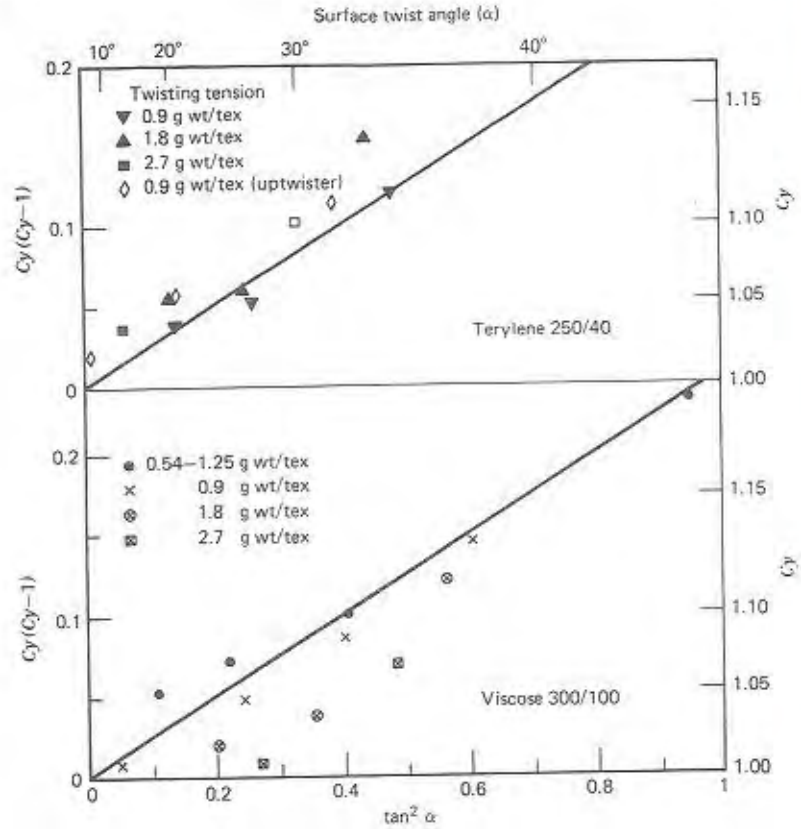


Figure 5.11. Contraction factor results. After Hearle, El-Behery, and Thakur (16). The line is drawn according to equation 5.15.

contraction values for various materials. Viscose rayon and acetate yarns showed good agreement with theory, whereas Tenasco gave anomalously high values.

It is clear from the above discussion that, with minor exceptions, equations 5.14 and 5.15 give good predictions of the contraction and retraction behavior of continuous-filament yarns. The disturbing features that can cause deviations are:

1. irregular twisting of yarn
2. permanent extension of filaments
3. kinking or buckling of the central filaments

Ex. 2020-024

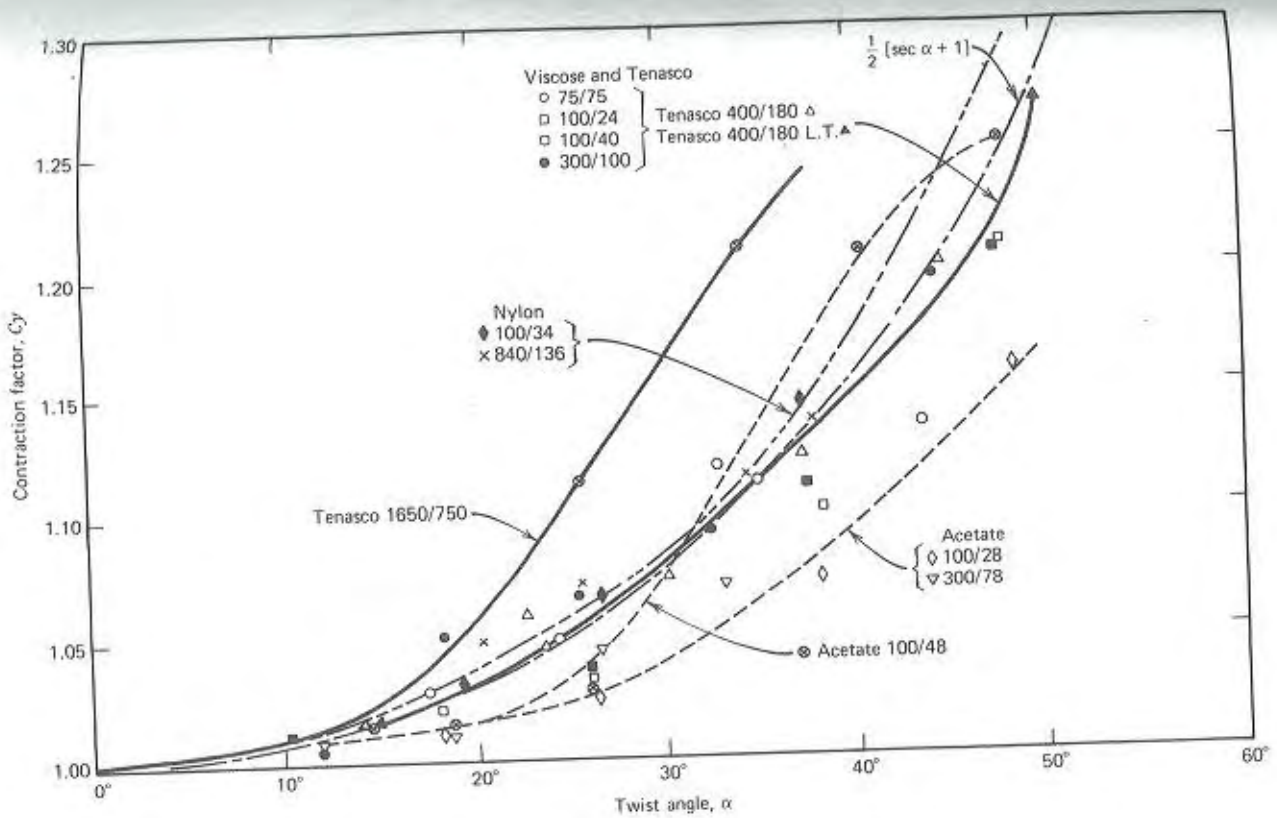


Figure 5.12. Comparison of contraction factors. Hearle, El-Behery, and Thakur (16).

Ex. 2020-025

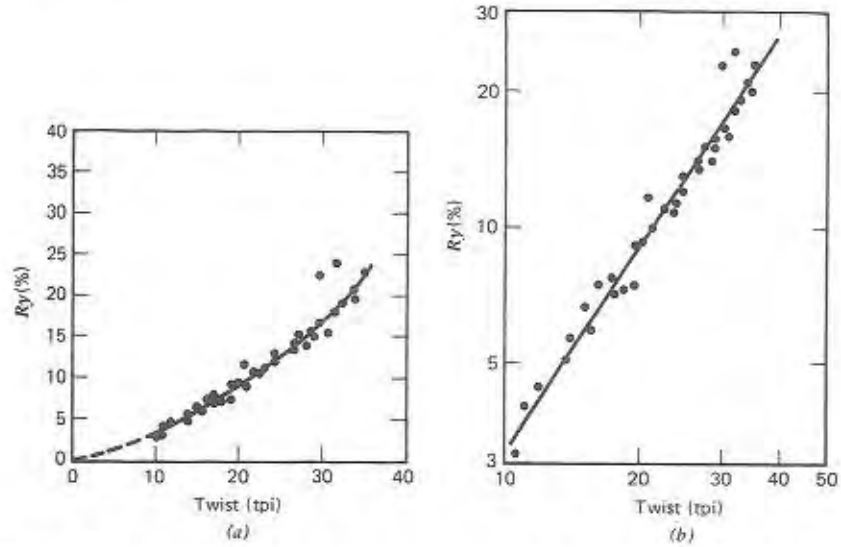


Figure 5.13. Contraction due to twisting of cotton yarn. Landstreet, Ewald, and Simpson (17) (*a*) Plot of retraction against twist, (*b*) log-log plot.

The contraction behavior of spun cotton yarns has been discussed by Landstreet et al. (17). Contraction is plotted against turns per unit length supplied at zero twist for one set of yarns in Figure 5.13. When the data shown in Figure 5.13*a* are presented in the form of a log vs. log plot, as shown in Figure 5.13*b*, there is a good fit with an empirical equation of the form:

$$R_y = k(T)^n \tag{5.16}$$

In practice, the exponent n is found to be of the order of 1.5, which represents the average condition in cotton spun yarns.

TWIST AND FIBER PACKING IN YARNS

Another feature of yarn structure that can be described in a simple idealized form is the packing of fibers in yarns. Schwarz (18, 19) has theorized that the packing of circular fibers can be described by two basic forms: (1) open packing and (2) hexagonal close packing.

Ex. 2020-026

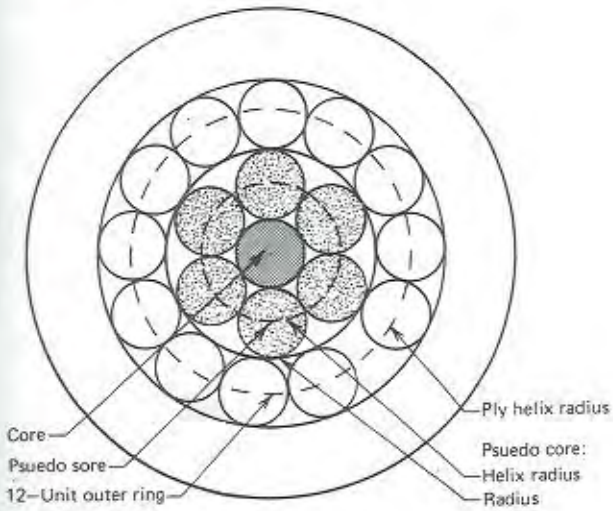


Figure 5.14. Concepts of open-packed structure. From Schwartz (19)

Open Packing

In this form, the fibers lie in layers between successive concentric circles, as shown in Figure 5.14. In this assembly, the first layer is a single core fiber around which six fibers are arranged so that all are touching. The third layer, which has twelve fibers, is arranged so that the fibers first touch the circle that circumscribes the second layer. Additional layers are added between the successive circumscribing circles.

The number of fibers in each layer and the total number of fibers in an ideally packed open structure are given in Table 5.4 (for a theoretical explanation reader is referred to reference 1).

Table 5.4. Open Packed Yarn Structure

Layer No.	Maximum No. of Fibers in Layer	Total No. of Fibers
1	1	1
2	6	7
3	12	19
4	18	37
5	25	62
6	31	93

Ex. 2020-027

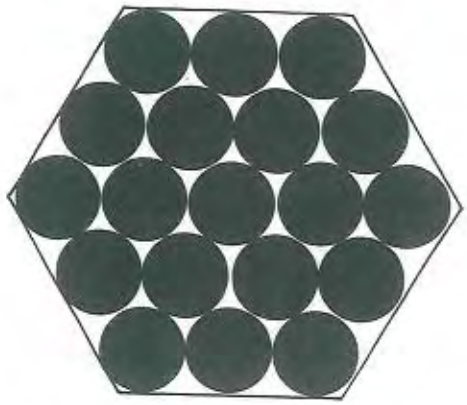


Figure 5.15. Hexagonally close-packed yarn, with three layers.

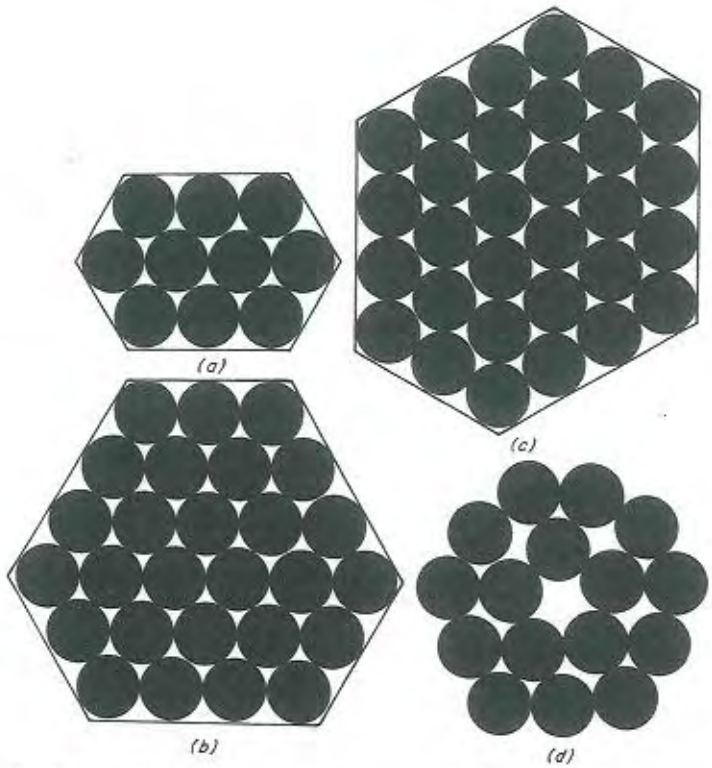


Figure 5.16. Hexagonal close packing on other cores. (*a*) Core of two, (*b*) core of three, (*c*) core of four, (*d*) core of five. From Hearle (1)

Ex. 2020-028

Hexagonal Close Packing

The packing of fibers of circular cross section around a single core fiber in a hexagonal configuration leads to what is called "close packing." In this form, all fibers touch each other, as shown in Figure 5.15. Other close hexagonal configurations obtained with cores of two, three, four, and five fibers are shown in Figure 5.16. As the number of fibers in the cross section increases (number of layers), the yarn outline tends to become complicated and deviates from the preferred hexagonal shape. For an ideal close-packed structure, the number of fibers in each layer and the total number of fibers in the cross section are given in Table 5.5.

Table 5.5. Close Packing of Fibers in Yarn

Layer No.	Number of Fibers in Layer	Total No. of Fibers
1	1	1
2	6	7
3	12	19
4	18	37
5	24	61
6	30	91
7	36	127
8	42	169
9	48	217

Real Yarns

The two ideal forms described above are very rarely achieved in real yarns. There are numerous factors, such as fiber geometry and twist, among others, that influence the yarn configuration obtained in real yarns. Hearle (1) suggests that the factors that operate in determining real yarn structures can be described into two groups, namely, (1) concentrating factors and (2) disturbing factors.

Concentrating factors

(1) One of the concentrating features is the general tendency of fibers to follow the path of minimum energy. In addition, they tend to settle down and cohere like any other materials.

(2) The other factor is twist, which has a stronger effect. Twist causes the development of tangential and radial forces in fibers that tend to bind the fibers together. Any imposed tension in a yarn will generate inward pressure from the outer layers on those inside, leading to a close packing of filaments.

Ex. 2020-029

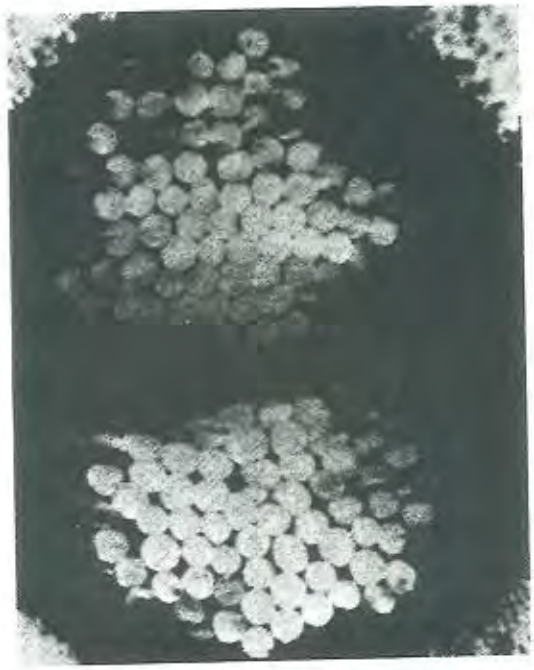


Figure 5.17. Cross section of a hot stretched nylon tire cord, showing filament distortion under pressure. From Wood, Goy, and Daruwalla (26)

High tension and twist can cause deformation in the fiber shape, especially in thermoplastic yarns, as shown in Figure 5.17. This shows a cross section of a hot stretched two-ply nylon tire cord in which the filaments near the center seem to have deformed into polygonal shapes under pressure.

Disturbing factors

(1) Ideal packing is not achieved if the total number of fibers in the yarn cross section differ from the figures given in Tables 5.4 and 5.5. Any deviation from the appropriate number would make the fibers pack unevenly, resulting in an irregularly shaped cross section.

(2) The simple ideal forms discussed earlier are true for a circular fiber shape. Other fiber shapes will modify the ideal packing arrangement.

(3) Twist has a profound effect on the arrangement of fibers in the yarn cross section. Because of twist, the fibers in the outer layers of the yarn follow a helical path; this introduces ellipticity in the cross section of the fibers. The elliptical cross section further affects the packing, thus modifying the ideal arrangement of fibers in the yarn cross section.

Ex. 2020-030

Figure 5.18. Close packed Cotton Yarn. From Schwartz (19)

(4) The other disturbing effect of twist is the variation in the path length between fibers at different radial positions in the yarn cross section. These differences in the path length must be nullified either by buckling of fibers in the center or by an interchange of radial position of fibers (migration), which results in the effective averaging of path lengths.

(5) Sometimes irregularities in the arrangement of fibers prior to yarn formation (such as in roving) may persist in the final yarn structure. Irregularities in the arrangement of fibers can also result from the variations in fiber length supplied to the twisting zone in staple yarn spinning.

(6) Other processing factors, such as the passing of yarns over guides or between feed rolls during winding, may cause changes in yarn shape. In addition, the form of twisting, that is, whether the fibers are presented in a ribbon form or in a cylindrical shape, may introduce asymmetry and irregularity in the shape of the yarn.

Observed Packing of Fibers in Real Yarns

Schwarz (19) has reported a few examples of the kind of fiber packing achieved in actual yarns. Figure 5.18 shows the cross section of a cotton yarn in which

Ex. 2020-031

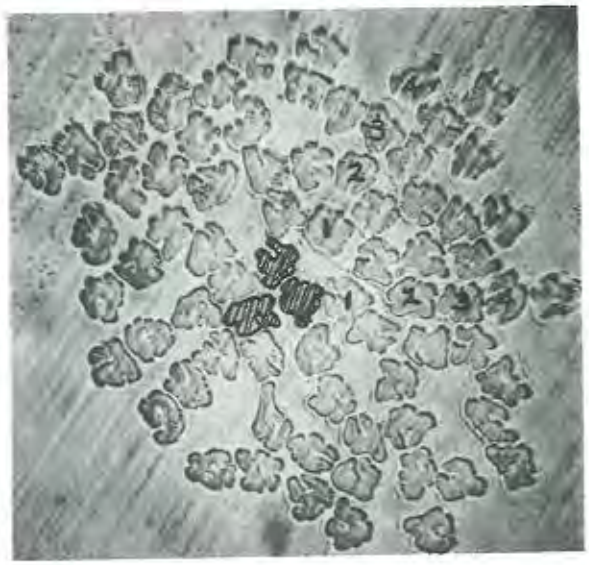


Figure 5.19. 75-filament viscose yarn showing 3 unit core with four outer layers. From Schwatrz (19)

fibers appear to be close packed in a polygonal shape (almost in a square shape). On the other hand, Figure 5.19 shows an example of an open-packed structure for a 75-filament low-twist viscose rayon yarn. This structure has a three-unit core with four outer layers, as identified in the illustration.

Some further examples of the packing of filaments in the cross sections of continuous-filament yarns have been reported by Hearle and Bose (20). These cross sections (Figure 5.20), prepared by embedding yarns in resin and then cutting sections, show that in almost all cases the fibers tend to pack in a close-packed form. There is some evidence of the irregularity and asymmetry in the packing, as pointed out by the authors. The presence of asymmetry has been attributed to the ribbon-twisting effect.

EFFECT OF TWIST ON YARN DIAMETER AND SPECIFIC VOLUME

In woven fabrics, especially in tightly woven structures, the interthread pressures set up during weaving can cause considerable thread flattening. This effect demands considerable attention in understanding the geometry of fabric structures. The changed cross-sectional shape of yarns in fabrics has a significant

Ex. 2020-032

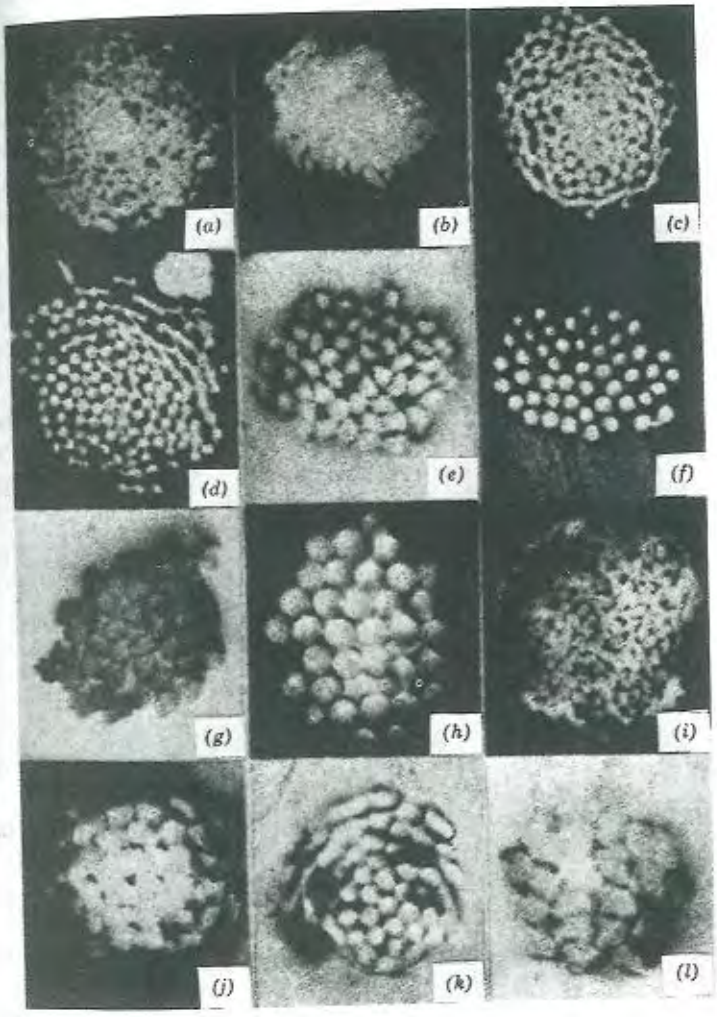


Figure 5.20. Yarn cross sections obtained by Hearle and Bose (20). (*a*) Tenasco 400/180, 10 tpi, uptwisted, (*b*) Tenasco 400/180, 10 tpi, uptwisted, (*c*) nylon 840/136, 10 tpi, uptwisted, (*d*) nylon 840/136, 10 tpi, ring twisted, (*e*) viscose 300/50, 10 tpi, uptwisted, (*f*) terylene 100/48, 10 tpi, uptwisted, (*g*) viscose 100/40, 10 tpi, uptwisted, (*h*) nylon 100/34, 10 tpi, ring twisted, (*i*) Tenasco 400/180, 30 tpi, uptwisted, (*j*) viscose 300/50, 30 tpi, uptwisted, (*k*) Terylene 100/48, 30 tpi, uptwisted, (*l*) viscose 100/24, 30 tpi, uptwisted.

Ex. 2020-033

effect on the aesthetic as well as some physical characteristics of fabrics. Some of these effects are discussed in a later chapter.

The bulk density or the specific volume of a yarn is a direct manifestation of the way the fibers pack in the yarn cross section. The factors that are likely to affect the yarn density are the fiber type, the density of the fiber material itself, yarn twist, and some external factors such as thread tension and compression encountered during winding, warping, weaving, or twisting. The yarn specific volume is given by the following relationship, which is obtained by rearranging equation 5.9:

$$v_y = \pi R^2/C \times 10^5$$

$$v_y = \tan^2 \alpha/4\pi\ CT^2 \times 10^5 \tag{5.17}$$

With the exception of monofilament yarns, which have a specific volume equal to that of the fiber material, the specific volume of all other textile yarns is determined by the volume occupied by the fibers and the air spaces incorporated into the body of the yarn. Consequently, the yarn specific volume is always more than that of the fibers themselves. This relationship can be analytically expressed in terms of a parameter, packing fraction, ϕ, as follows:

$$\phi = v_f/v_y = \text{fiber volume/yarn volume}$$

or

$$v_y = v_f/\phi \tag{5.18}$$

The specific volumes of textile fibers range from as low as 0.4 for glass fiber to as high as 1.1 for polypropylene.

It must be pointed out that, in addition to the influence of yarn twist, the yarn specific volume is also affected by such factors as the staple length, fiber fineness, the system on which a staple yarn has been spun, and the conditions of tension and compression in different processes.

From equation 5.17 it can be realized that the measurement of the specific volume of a yarn requires the determination of yarn linear density (C, count of yarn) and either yarn diameter of yarn twist and twist angle. Experimentally, the yarn linear density is easily obtained. However, twist and yarn diameter present some difficulty, particularly in the case of staple yarns. Experimental errors in the measurement of twist and diameter of staple yarns result from the diffused nature of their surface outline. Twist measurement is especially a problem with open-end spun staple yarns. Hearle et al. (21) and Hearle and Merchant (22) have used a simple microscopic technique to evaluate the yarn diameter and

Ex. 2020-034

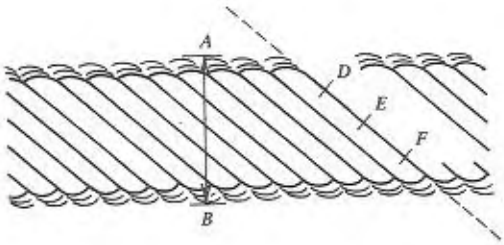


Figure 5.21. Diameter overestimated as AB due to loose fiber on surface. Twist angle underestimated from mean slope of DF instead of true tangent at E. From Hearle (1)

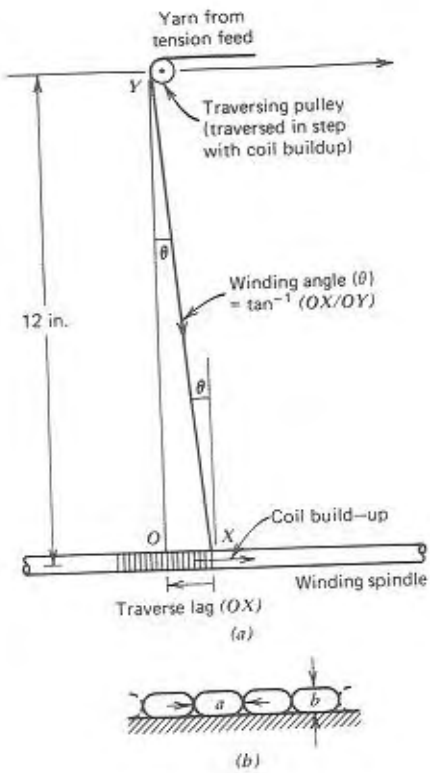


Figure 5.22. Coil winding method of measuring yarn dimensions. From Hamilton, (22) (*a*) Principles of apparatus, (*b*) arrangement of coils on spindle under normal winding conditions.

Ex. 2020-035

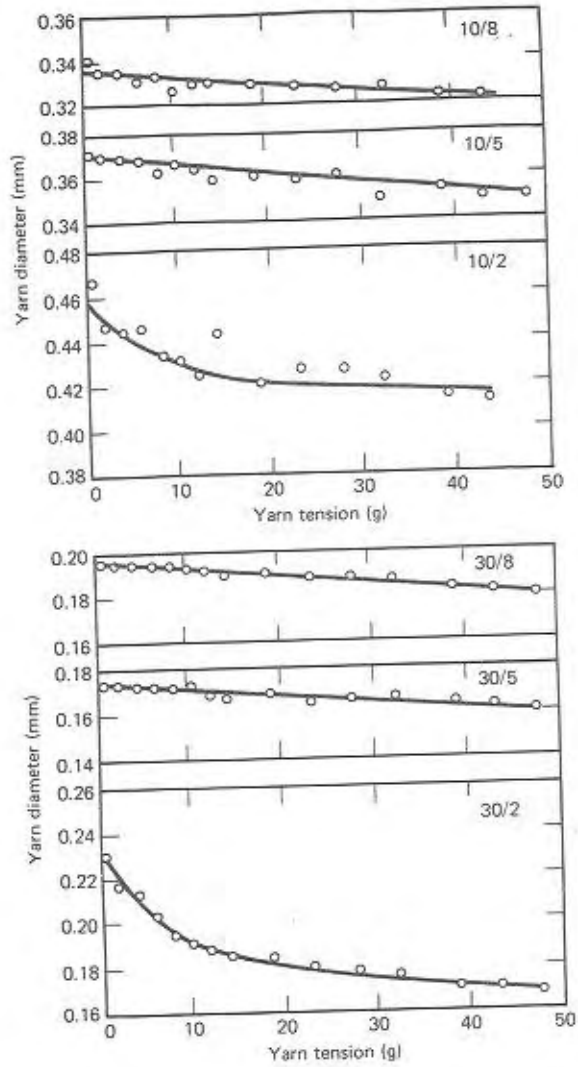
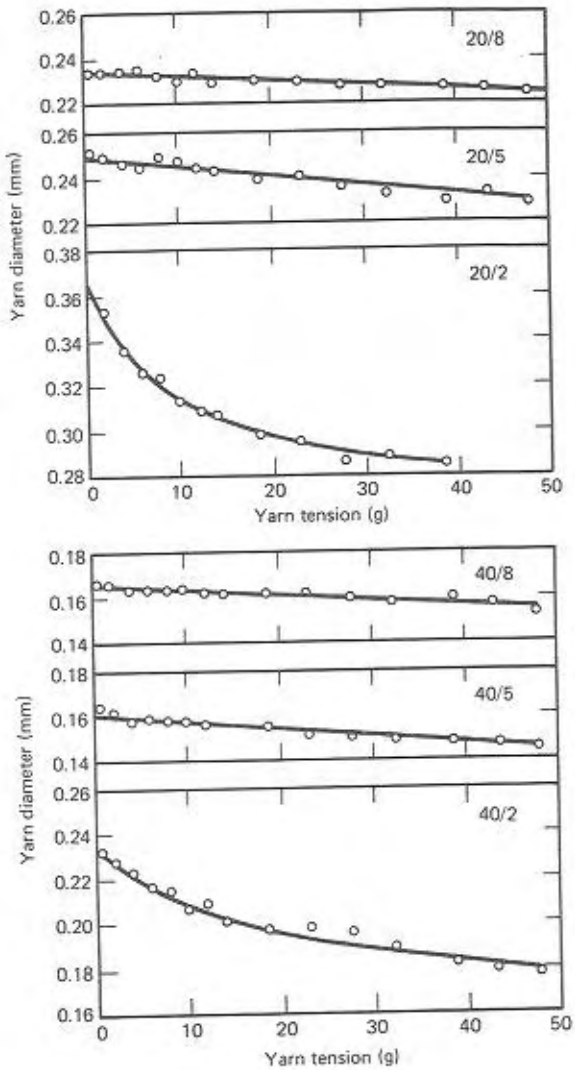


Figure 5.23. Effect of tension on diameter of spun nylon yarns. The figures identifying each diagram refer to cotton count and twist factor, that is, 10/8 is 10s cottons count and twist factor of 8. Hearle and Merchant (22) See overleaf for additional diagrams.

Ex. 2020-036



Ex. 2020-037

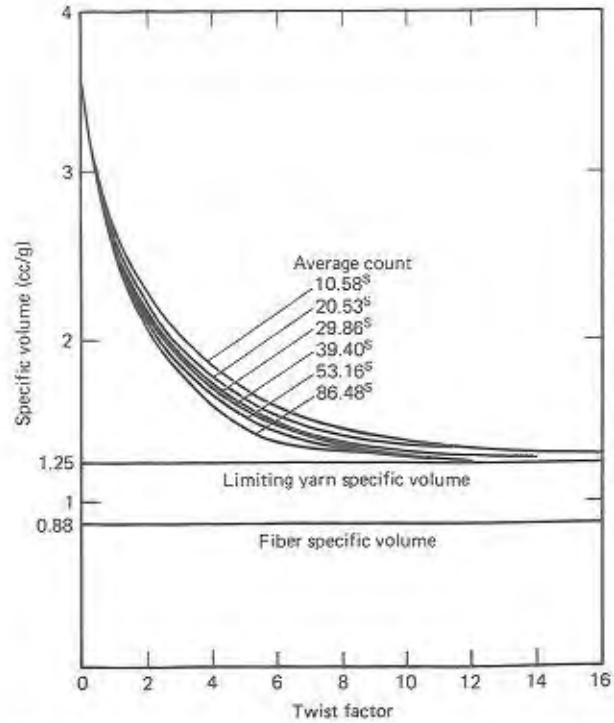


Figure 5.24. Collected curves of specific volume against twist. Hearle and Merchant (22)

twist angle. They observed that the microscopic technique tended to give a rather high value of specific volume, whereas the twist angle appeared to be low. Hearle (1) has suggested reasons for this, as illustrated in Figure 5.21.

Van Issum and Chamberlain (23) have described a photographic technique in which a blurred image of a running yarn is obtained. This tends to average the effect of protruding fibers at the surface. The photograph is then photometrically scanned for diameter values.

However, to understand the structural geometry of fabrics it is essential to consider the thread flattening caused by the interyarn pressure in the fabric. Hamilton (24) has described a method for measuring both the major and the minor diameters of a yarn under conditions of thread tension and compression similar to those which occur during weaving, package winding, warping and knitting. The method consists of winding the yarn in adjacent coils onto a spindle of suitable diameter, as illustrated in Figure 5.22. This method is applicable to both filament and staple yarns over a wide range of yarn sizes. The major diameter a is calculated from the number of turns of coils per unit length,

Ex. 2020-038

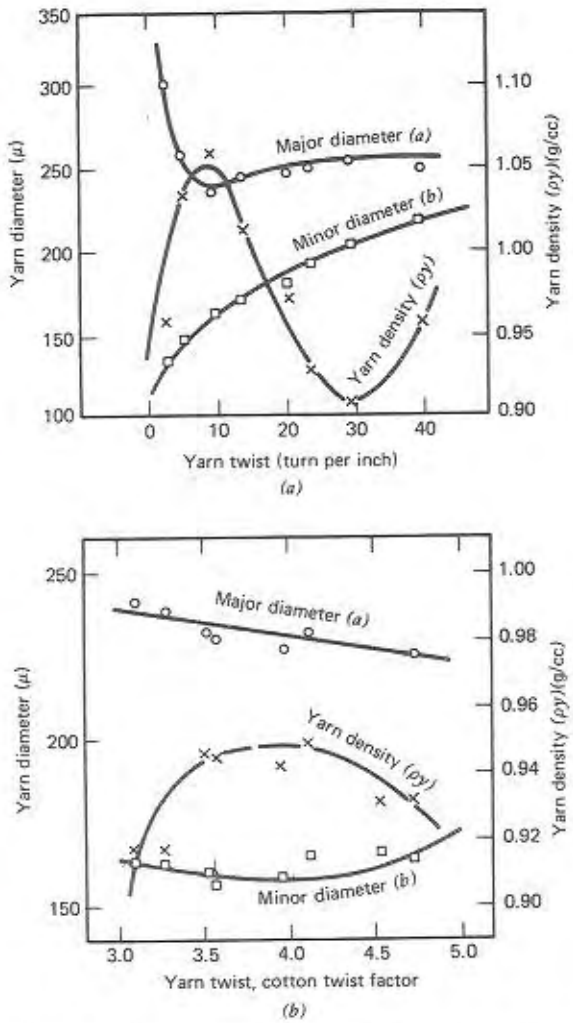


Figure 5.25. Effect of twist on yarn dimensions using coil-winding method. From Hamilton (*a*) 300-Denier continuous-filament rayon yarn, (*b*) 20s staple rayon yarn.

and the minor diameter b is measured by pressing a special wheel against the yarn: The feeler wheel is driven by surface contact with the yarn on the winding spindle. There is a provision to change the load on the pressure wheel to achieve desired thread compression. This direct measurement of major and minor yarn diameters, together with the yarn count, allow the determination of the cross-sectional shape and the specific volume. The effect of yarn tension on yarn

Ex. 2020-039

diameter is shown in Figure 5.23; the dependence of specific volume of nylon yarn on twist is illustrated in Figure 5.24 (22). On the other hand, results of the effect of winding tension and twist measured by the coil win method are shown in Figure 5.25*a* and 5.25*b*.

The values of specific volume reported by various workers are summarize Table 5.6, 5.7, and 5.8. It is clear that the yarn specific volume, as well as

Table 5.6. Yarn Specific Volumes (Ignoring Effect of Twist) (van Issum and Chamberlain, 23)

Yarn Type	Specific Vol. (cm^3/g)	Packing Fraction (ϕ)
Spun rayon	1.54	0.427
Cotton	1.84	0.358
Worsted	1.70	0.452
Woolen	2.40	0.321

Table 5.7. Dimensions of Staple Fiber Yarns (Cotton-spun; Twist Factor = 33 $tex^{1/2}$ turns/cm) (Hamilton, 24)

Yarn	Diameter (μ)		Linear Density (tex)	Yarn Sp Vol (cm^3/g)	Fiber Sp Vol (cm^3/g)	Pack Fact (ϕ)
	Major	Minor				
Rayon, 1½ den, 1 7/16 in.	230	162	29.5	1.08	0.66	0.61
Rayon, 3 den, 2½ in.	241	171	31.3	1.11	0.66	0.59
Rayon, 3 den 1 7/16 in.	243	166	30.3	1.14	0.66	0.58
Acetate 3 den, 1 7/16 in.	265	183	31.9	1.30	0.76	0.59
Triacetate, 3 den, 1 7/16 in.	262	179	28.8	1.39	0.77	0.55
Courtelle (acrylic), 3 den, 1 7/16 in.	287	173	27.0	1.61	0.87	0.54
Nylon, 3 den, 1½ in.	276	166	27.4	1.45	0.88	0.60
Terylene (polyester) 3 den, 1½ in.	284	176	33.6	1.30	0.72	0.56
Cotton, Tanguis	273	165	32.0	1.22	0.65	0.53

packing fractions, vary widely for both spun and filament yarns. The packing fractions range from about 0.30 for some spun yarns up to approximately 0.9 for highly twisted filament yarns. The theoretical value for hexagonal close packing is 0.91. In addition to yarn tension and compression, the yarn packing fraction is also affected by fiber variables and blending. These include fiber length, fineness, crimp, and the blending of fibers with different bulking characteristics.

Ex. 2020-040

Table 5.8. Specific Volume of Continuous Filament Yarns (Hearle, El-Behery, and Thakur, 21)

Yarn	Twist Factor ($tex^{1/2}$ turns/cm)	Specific Vol (cm^3/g)	Packing Fraction (ϕ)
100 den/ 40 filament/ viscose rayon	3.9	1.67	0.40
	14.5	1.21	0.54
	29.5	1.11	0.59
	42.7	1.01	0.65
	69.9	0.94	0.70
	102.1	0.90	0.73
100 den/ 28 filament/ acetate	1.8	2.10	0.36
	15.6	1.20	0.63
	27.6	1.12	0.68
	41.3	1.12	0.68
	69.6	1.01	0.76
	101.9	0.96	0.89
100 den/ 34 filament/ nylon	1.0	3.12	0.25
	16.8	1.35	0.65
	26.1	1.20	0.73
	37.0	1.23	0.72
	62.7	1.15	0.76
	97.5	0.99	0.89
100 den/ 48 filament/ Terylene polyester	0.5	2.65	0.27
	13.6	1.16	0.63
	27.6	1.05	0.69
	42.5	1.03	0.70
	57.9	0.98	0.74
	82.9	0.97	0.75
	113.9	0.97	0.75

TWIST IN RELATION TO YARN BENDING

Textile yarns are rarely used in a straight form. They are generally bent into helical forms when twisted to make plied structures and held into torus shapes during the weaving process and into a looped shape when converted into a knitted structure. Yarn bending attains an added dimension during the wear life of a textile structure. Yarns are subjected to bending during draping, creasing (in the bending of a collar or a cuff) or wrinkling of an apparel fabric, in the fluttering of a tent, or the flexing of a rope over a pulley, to name a few.

The mechanical properties of a textile structure during its operational life will be greatly influenced by the kind and the amount of strain deformation that individual components of the structure suffer. The level of deformation in

Ex. 2020-041

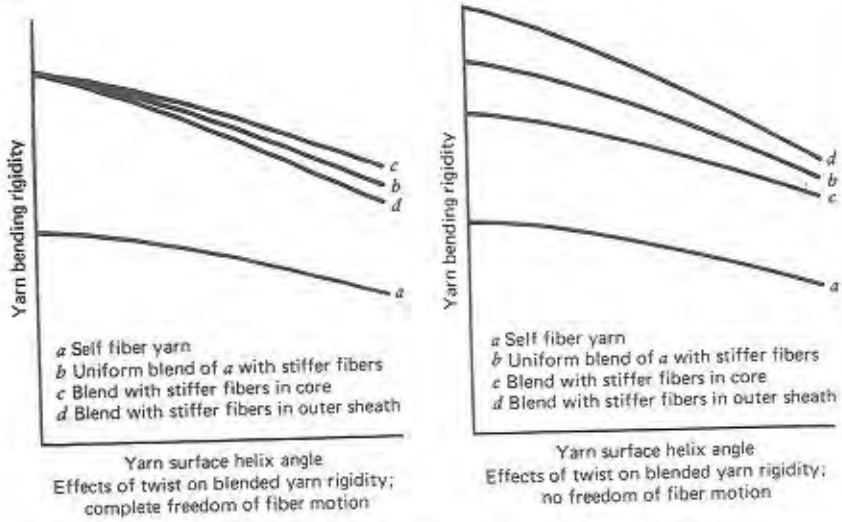


Figure 5.26. Yarn surface helix angle. From Platt et al. (28)

individual fibers will in turn be affected by the geometric form in which the fiber is made to lie in a yarn and subsequently in a fabric. In a staple yarn, the component fibers do not lie straight but assume a helical configuration imposed by twist. It is therefore essential that a knowledge of the effect of twist on the bent yarn geometry be obtained to help in analyzing the strain and consequently the stress distribution in a textile structure. Backer (25) has reported a geometric analysis of the idealized structure of a bent yarn. The analysis deals particularly with the prediction of local and average fiber strains that occur in highly twisted structures—that are deformed in bending. Specific cases of the relative motion between fibers in both the loosely and tightly twisted structures have been considered. Relationships predicting local fiber curvature because of bending have been derived. This analysis reveals that the level of yarn strain becomes less as the radius of bent yarn (torus) is increased relative to the radius of the yarn. On the other hand, the local strain level decreases as the level of twist in the yarn increases. Furthermore, it is shown that fibers occupying the position at the neutral axis of the yarn experience no strain; the fibers lying at the uppermost and the lowermost positions suffer maximum strain both in the tension and compression modes. Backer has also considered the case of no friction between the fibers in a yarn. This assumption helped in calculating the change in the local helix angle of the fiber at the inside and outside of the bend. This type of prediction can help in the understanding of internal wear in a fabric as well as the crease and wrinkle recovery of textile structures. Platt et al. (28) have reported a theoretical analysis of the effect of fiber properties and yarn structure on singles

Ex. 2020-042

yarn bending rigidity. The parameters considered are the fiber dimensions, fiber stiffness, torsional to bending rigidity ratio, yarn density, size, twist, fiber clustering and prior relaxation treatments of yarns. The two extreme cases of complete freedom and no freedom of relative fiber movement are analyzed. The theoretically predicted effect of twist on the bending rigidity of the yarn for the two extreme cases is shown in Figure 5.26. This figure also shows how the blend distribution and the stiffness of the fibers being blended affect the bending rigidity of the blended structure. It is obvious that increase in yarn twist has the effect of lowering the bending rigidity. The position (blend distribution) of the stiffer fibers in the yarn cross section influences the yarn bending rigidity differently for the two cases of complete freedom of fiber motion and no freedom of fiber movement. Recently Hunter et al. (29) have shown experimentally that the flexural rigidity of worsted yarns decreased when yarn twist was increased, thus confirming the hypothesis put forward by Platt.

REFERENCES

1. Hearle, J. W. S., P. Grosberg, and S. Backer, *The Structural Mechanics of Fibers, Yarns, and Fabrics.* Wiley-Interscience, New York, 1969.
2. Treloar, L. R. G., *J. Text. Inst.*, 1964, **55**, p. 13.
3. Woods, H. J., *J. Text. Inst.*, 1933, **24**, T317.
4. Brunnschweiler, D., *J. Text. Inst.*, 1953, **44**, p. 114.
5. Backer, S., *J. Text. Inst.*, 1953, **44**, T477.
6. Backer, S., *Text Res. J.*, 1956, **26**, 87.
7. Worner, R. K., *Text. Res. J.*, 1956, **26**, 455.
8. Schwartz, E. R., *J. Text. Inst.*, 1933, **24**, T105.
9. Treloar, L. R. G., *J. Text. Inst.*, 1956, **47**, T348.
10. Morton, W. E., *Text. Res. J.*, 1956, **26**, 325.
11. Riding, G., *J. Text. Inst.*, 1959, **50**, T425.
12. Morton, W. E. and K. C. Yen, *J. Text. Inst.*, 1952, **43**, T60.
13. Morton, W. E. and J. W. S. Hearle, *J. Text. Inst.*, 1957, **48**, T159.
14. Tattersall, G. H., *J. Text Inst.*, 1958, **49**, T295.
16. Hearle, J. W. S., H. M. A. E. El-Behery, and V. M. Thakur, *J. Text. Inst.*, 1960, **51**, T299.
17. Landstreet, C. B., R. R. Ewald, and J. Simpson, *Text. Res. J.*, 1957, **27**, 486.
18. Schwartz, E. R., *Text. Res. J.*, 1950, **20**, 175.
19. Schwartz, E. R., *Text. Res. J.*, 1951, **21**, 125.
20. Hearle, J. W. S., and O. Bose, *J. Text. Inst.*, 1966, **57**, T308.
21. Hearle, J. W. S., H. M. A. E. El-Behery, and V. M. Thakur, *J. Text. Inst.*, 1959, **50**, T83.
22. Hearle, J. W. S. and V. B. Merchant, *Text. Res. J.*, 1963, **33**, 417.
23. van Issum, B. E., and N. H. Chamberlain, *J. Text. Inst.*, 1959, **50**, T599.

Ex. 2020-043

24. Hamilton, J. B., *J. Text. Inst.*, 1959, 50, T655.
25. Backer, S., *Text. Res. J.*, 1952, 22, 668.
26. Wood, J. O., R. S. Goy, and F. S. Daruwala, *Text. Res. J.*, 1959,29
27. Stanbury, G. R. and W. G. Byerley, in *Wool Research 1918-1948*, WIRA, 1949, Leeds, England.
28. Platt, M. M., W. G. Klein, and W. J. Hamburger, *Text. Res. J.*, 1959, 29, 611.
29. Hunter, I. M., R. I. Slinger, and P. J. Kruger, *Text. Res. J.*, 1971, 41, 361.

Ex. 2020-044

6

Mechanical Properties of Yarns

INTRODUCTION

In addition to the contribution of fiber structure and fiber properties, the behavior of textile materials is significantly influenced by the role played by the yarn structure and yarn properties. This can easily be visualized when one considers the textile material properties that have important technological significance and that determine end-use performance. The textile material properties may be classified into three main groups, as suggested by Backer (1). These are (1) bulk properties, (2) surface properties, and (3) transfer properties. Backer has given a list of material properties that fall under each classification. They are summarized as follows:

1. *Bulk Properties,* which include uniaxial tension and compression; biaxial tension, compression, and shear; bending behavior (including creasing and crease resistance); torsional characteristics; behavior under stress concentration (such as tear resistance or cutting resistance); dimensional stability (shrinkage resistance, puckering resistance, pilling and shedding resistance); and fatigue resistance in tension, compression, and bending.
2. *Surface Properties,* such as hand, roughness, wear resistance, friction, and resistance to stress concentration (snag and pill resistance).
3. *Transfer Properties,* namely, air and water permeability, filtration efficiency, penetration resistance, and heat transfer.

A close look at the above list of properties would clearly indicate that the yarn structure and the mechanical properties of yarns are of great importance in modifying the ultimate behavior of a textile structure. Consequently, to predict

Ex. 2020-045

and evaluate the behavior of the ultimate textile structure, an understanding of the structure and the mechanical behavior of yarns is essential. Some features of the geometry of yarn structure are discussed in Chapter 3. The intention here is to report and discuss some of the studies dealing with the theoretical prediction of the mechanical properties of yarns, arrived at by the application of simple mechanics, and the actual behavior of these structures.

YARN STRENGTH

There are essentially two ways in which the yarns are characterized as to their strength behavior. These are:

1. Lea or skein test–including the ballistic test.
2. Single thread tests

Lea Strength Test

The first method is commonly used in the older sections of the cotton, wool, and flax textile industries. In this test, a hank or a skein of 120 yards (made into 80 loops with the starting and finishing ends knotted) is broken on a pendulum lever tester from which the lea strength of the hank is obtained. This test does not give a measure of the absolute value of the yarn strength, but yields a relative value that is quite useful for quality control purposes. The strength of the yarn in a lea test is determined largely by the thinnest places in the yarn and the frictional forces between the threads and the hooks on the tester. The strength of the yarn is expressed in terms of the product of lea strength and count, which is called the "count-strength product" or "break factor."

The count-strength product is used for comparing yarns of slightly different counts. This quantity is also used in determining the "spinning efficiency" of a cotton by comparing the break factor of a yarn with a standard value. The count that has a break factor equal to the standard value is called the "highest standard count" and is taken as the measure of the spinning quality of that cotton.

The count strength product is merely the tensile strength divided by the weight per unit length of yarn. This quantity has the dimensions of length and is termed the "breaking length" of a yarn. This is the length of yarn having a weight equal to the breaking load that is observed to cause the yarn to break under free suspension.

The hank of yarn can also be tested under impact loading on a ballistic tester. This test combines the three characteristics of the yarn, namely, breaking load, breaking extension, and work factor. The value obtained from the ballistic test is the amount of energy or work required to rupture a hank of yarn. This test is

Ex. 2020-046

sometimes used to detect the changes in quality of cotton, machinery performance, and yarn quality.

Single Thread Tests

Single thread tests provide better information regarding the strength characteristics of yarns. They eliminate the disadvantages of the lea test where no measure of the extension of yarns is available. These tests yield load-elongation diagrams that provide a wealth of information regarding yarn properties. There is apparently no simple relation between the lea strength and the single-end strength. However, Gregory (2) reports that the ratio of lea breaking length to single-end breaking length, obtained for a number of experimental yarns, varies from 0.56 to 0.90.

The load-elongation characteristics of yarns are easy to measure by using standard instruments such as the Scott or Uster automatic constant-rate-of-loading inclined plane testers, the Instron constant-rate-of-elongation tester, and the Goodbrand and/or the Cambridge Textile Extensiometer. The experimental conditions such as the rate of extension, rate of loading, the specimen length, temperature, humidity, and the initial tension used to mount the specimen should be controlled and specified when quoting results.

The behavior of a yarn under a gradually increasing applied load is fully expressed by the load-elongation curve including the breakage point (Figure 6.1). The load may be measured in gram weight or dynes and the elongation in centimeters. However, for the purpose of comparing the properties of different types of yarns, quantities that are independent of the dimensions of the specimen must be used. In most physical and engineering applications, load is replaced by stress, which is defined as

$$\text{Stress} = \frac{\text{load}}{\text{area of cross section}}$$

The units of stress are dyne/cm^2 or kg wt/mm^2. In the case of textile materials, it is difficult to measure the cross-sectional area. Moreover, it is the weight and not the bulk of the material that is important. Consequently, the stress is expressed in terms of the mass of the specimen and is called specific stress, defined as:

$$\text{Specific stress} = \frac{\text{load}}{\text{mass/unit length}}$$

The units used for specific stress are g wt/denier and g wt/tex.

Ex. 2020-047

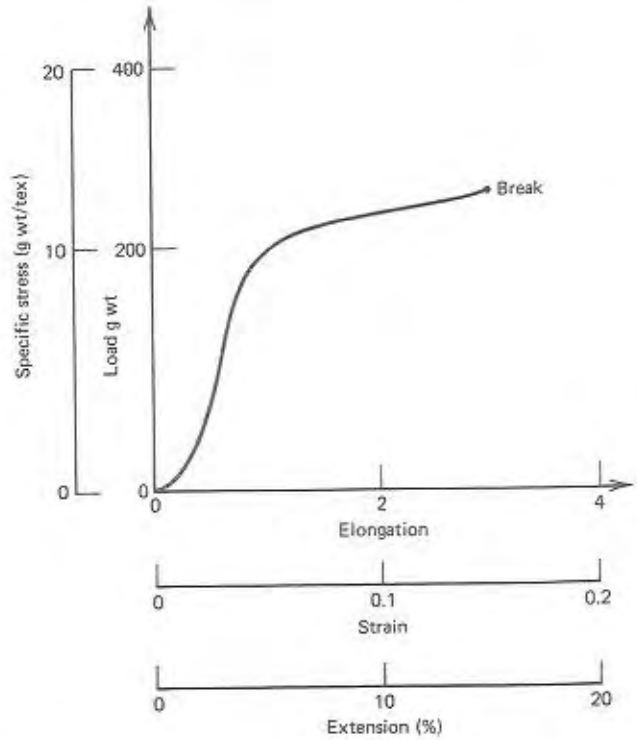


Figure 6.1. Load-elongation diagram for 20cm specimen of 20 tex yarn.

The elongation of the specimen is expressed as tensile strain or percent extension, which takes into account the original length of the specimen:

$$\text{Tensile strain} = \frac{\text{elongation}}{\text{initial length}}$$

The load-elongation curve can thus be converted to a stress-strain curve by changing the units only; the shape of the curve remains the same, as shown in Figure 6.2.

In addition to the abovementioned quantities, there are some other useful parameters that are obtained from the shape of load-elongation curves and the position of the end point where breakage occurs. These are defined as follows:

1. *Strength.* Strength is a measure of the steady force required to break a yarn; for an individual yarn, it is given by the breaking load in g wt or oz wt. To compare different yarns, specific stress at break is used and is called tenacity or

Ex. 2020-048

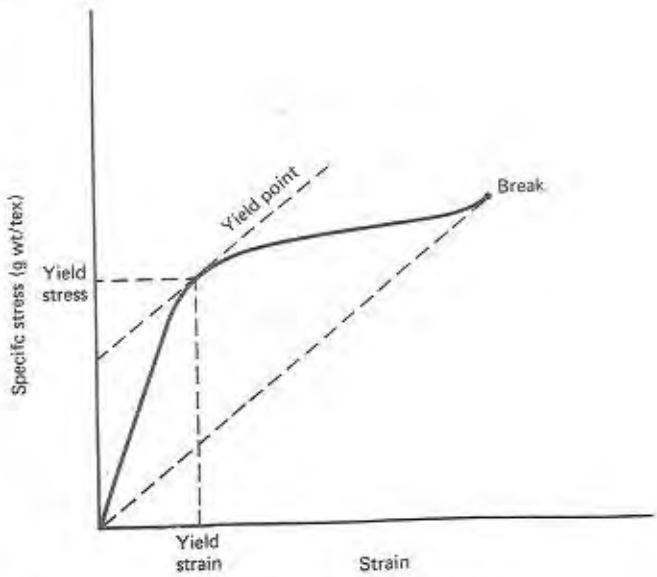


Figure 6.2. Yield point–Meredith's construction.

specific stress; the units for tenacity are g wt/tex or g wt/denier. Alternatively, breaking length may also be used to express the tenacity. When strength is compared on the basis of the area of the cross section, the stress at break is called the ultimate tensile stress, the units for which are kg wt/mm^2 or dyn/cm^2.

2. *Elongation-at-Break.* The elongation-at-break may be expressed by the actual fractional or percentage increase in length and is called the breaking extension.

3. *Work of Rupture.* This is defined as the energy required to break the yarn and is sometimes called "toughness." The work of rupture is given by the area under the load-elongation curve, and its units are dyne cm or g wt × cm.

4. *Initial (Young's) Modulus.* The initial modulus is the slope of the tensile stress-strain curve at the origin. The initial part of the curve is fairly straight, and its slope (ratio of stress to strain) usually remains constant. The modulus is measured in units of stress or specific stress (g wt/tex). Modulus gives a measure of the force required to produce a small extension. A highly inextensible yarn will have a large modulus; an easily extensible material will have a low modulus. The reciprocal of the modulus is called compliance.

5. *Yield Point.* After the initial strength part, the curve tends to bend, and in this region large extensions are produced with relatively small increases in the applied stress, as indicated by the shape of the curve in Figure 6.2 (this is the

Ex. 2020-049

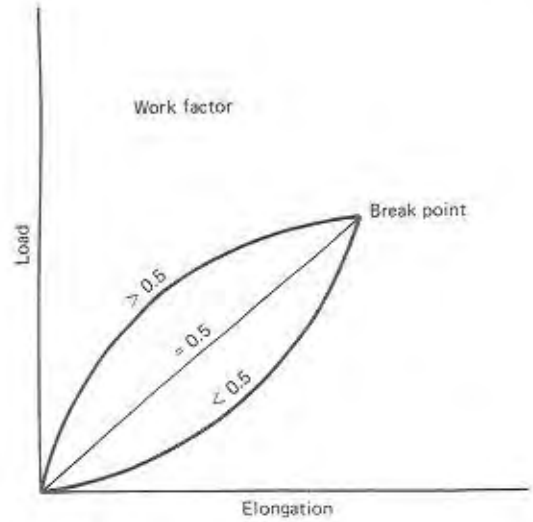


Figure 6.3. Work factor.

usual trend followed by most stress-strain curves). The yield point is located in the bent part of the curve and is determined geometrically. According to Meredith (3), the yield point is defined by the point at which the tangent to the curve is parallel to the line joining the origin and the breaking point. Yield point is also sometimes termed the "limit of proportionality," that is, where the extension ceases to be proportional to stress and "elastic limit." The yield point is characterized by particular values of stress and strain—the yield stress and yield strain.

6. *Work Factor.* For a material obeying Hooke's law, the load-elongation curve would be a straight line from start to the breaking load, and the work of rupture will be given by:

$$\text{Work of rupture} = 1/2\ (\text{breaking load} \times \text{breaking elongation})$$

Any deviation from the ideal state is defined by a quantity termed the "work factor":

$$\text{Work factor} = \frac{\text{Work of rupture}}{\text{breaking load} \times \text{breaking elongation}}$$

The work factor for an ideal state will be 0.5. If the curve stays above the straight line, the work factor will be more than 0.5, and if below it, less than 0.5 (Figure 6.3).

Ex. 2020-050

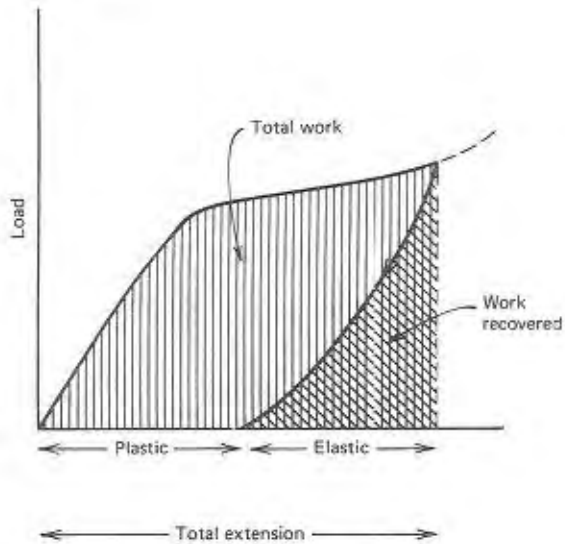


Figure 6.4. Elastic and plastic extension.

7. *Elastic Recovery.* Elasticity, as defined by the American Society for Testing Materials (4), is "that property of a body by virtue of which it tends to recover its original size and shape after deformation." Its opposite is plasticity. The recoverable (elastic) and the nonrecoverable (plastic) part of the deformation observed after stress removal is shown in Figure 6.4. Quantitatively, the elastic recovery may be defined as:

$$\text{elastic recovery} = \frac{\text{elastic extension}}{\text{total extension}}$$

Similarly, work recovery is defined as:

$$\text{Work recovery} = \frac{\text{work returned during recovery}}{\text{total work done in extension}}$$

MECHANICS OF YARN STRUCTURES

In recent years the subject of the mechanics of yarn structure has attracted the attention of many scientists. Backer (1) has given an excellent account of the development of various approaches adopted in analyzing yarn mechanics. Hearle (5) has dealt with the theoretical analysis of the extension behavior of twisted

Ex. 2020-051

Table 6.1. Papers on Theory of Tensile Properties of Twisted Continuous Filament Yarns[a]

Name and Reference	Nature of Theoretical Treatment
Gegauff (6)	Theory of spun yarns, but includes basic equations of simplest treatment of filament yarns
Platt (7, 8)	Tensile forces only; includes effects of lateral contraction, large extensions, and deviations from Hooke's law
Hearle (9)	Tensile and transverse forces: Small strains, Hooke's law, no lateral contraction
Hearle, El-Behery, and Thakur (12)	(i) Tensile and trnasverse forces, small strains Hooke's law, with lateral contraction; (ii) Tensile forces only: large strains, lateral contraction, deviations from Hooke's law
Treloar and Hearle (13)	Corrects an error in previous two papers
Treloar (14)	Continuum rubber filament model
Wilson and Treloar (15)	Two-filament rubber model
Wilson (16)	7 and 19 filament rubber models
Treloar and Riding (17)	Energy method–includes effects of transverse forces, constant volume deformation, large strains, deviations from Hooke's law
Symes (18)	Cord properties, with approximations
Kilby (19)	Develops theory to consider effect of equalization or nonequilization of tension in migrating filaments; and effect of bending strains
Treloar (20)	Applies energy method to yarn with migrating filaments
Treloar (21)	Applies energy method to multiply cords
Wilson (22)	Model yarns with five filaments in regular pattern around a core filament
Hearle (84)	Reexamines the energy method and simplifies the treatment of the theory. Suggests four general equations to predict the mechanical properties.
Konopasek and Hearle (85)	Analysis of the mechanics of bending curves
Cheng, White, and Duckett (86)	Apply continuum mechanics and tension matrix analysis

[a]Partially reproduced from Hearle (5).

Ex. 2020-052

continuous-filament and staple yarn structures. He has discussed this subject thoroughly, and any attempt to deal with it here would be repetitious. However, to understand the mechanical behavior of actual yarns, a basic knowledge of theories of the mechanics of such structures is considered desirable. A brief discussion of the theories of the load-extension characteristics of continuous-filament and later of staple yarns is presented, this is followed by a discussion of experimental studies reported in the literature.

Most theoretical work on the mechanics of yarn structure found in the literature pertains to continuous-filament yarns. This is because such yarns are easy to manipulate to form twisted yarn structures for theoretical studies and experimental investigation. A summary of published papers on the subject of the theory of the extension of continuous-filament yarns is given in Table 6.1. To work out the analysis of the mechanics, the procedure adopted involves first the calculation of the strains due to an imposed deformation; the next step is to calculate either the stress distribution and equilibrium of forces or the energy due to deformation. Table 6.1 includes the method adopted and the assumptions made by each author in working out the analysis.

Analysis of Tensile Behavior of Continuous-Filament Single Yarns

Hearle (5) has carried out a simple analysis of the mechanics of yarn structure for calculating the modulus of a continuous-filament yarn. He assumed that the yarn has an ideal geometry, as shown in Figure 6.5; the component filaments in

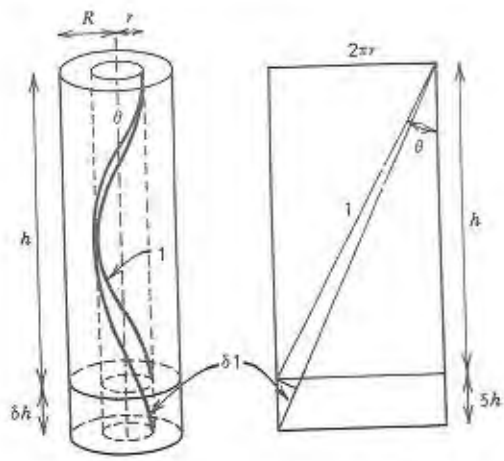


Figure 6.5. Geometry of a yarn subject to extension $E_y = \frac{\delta h}{h}$. From Hearle (5)

Ex. 2020-053

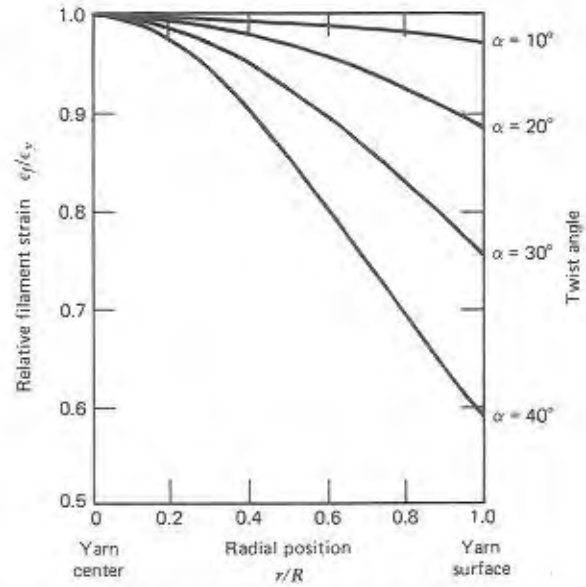


Figure 6.6. Variation of filament strain through yarn. From Hearle (5)

the yarn cross section have uniform properties, and each filament maintains a fixed helical path within the yarn, with no change in radial position. Further, there is no change in yarn diameter during extension, and the packing density is constant.

From the consideration of the yarn geometry and the relationship between the applied yarn strain and axial fiber strain, Hearle reports a relationship worked out by Platt (7):

$$\epsilon_f = \epsilon_y \cos^2 \theta \tag{6.1}$$

where

ϵ_f = filament extension
ϵ_y = yarn extension
θ = helix or twist angle.

This relationship indicates that the extension of the straight filament at the center ($\theta = 0$) of the yarn is equal to the value of yarn extension, and that it decreases to a value $\epsilon_y \cos^2 \theta$ at the yarn surface. This relationship is shown in Figure 6.6, in which the ratio of filament strain to yarn strain (ϵ_f/ϵ_y) is plotted against the radial position of the filament in the yarn (r/R) where r is the radius of a cylinder containing the helical path of a particular fiber, and R is the yarn radius.

Ex. 2020-054

Now, considering the forces acting along the filament axis, the expression derived by Hearle for the yarn tension turns out to be of the form:

$$\text{Total yarn tension} = (\pi R^2 \ E_f e_y / v_y) \cos^2 \alpha \qquad (6.2)$$

where

R = yarn radius
E_f = filament modulus
v_y = yarn specific volume

and

α = surface angle of twist.

This expression can now be used to calculate yarn specific stress and modulus. These quantities are expressed in units of g wt/(g/cm) which is equal to 10^{-5} g wt/tex.

$$\text{Yarn specific stress} = \text{yarn tension} \times (v_y / \pi R^2)$$
$$= E_f e_y \ \cos^2 \alpha$$

and by definition yarn tensile modulus =

$$E_y = \frac{\text{yarn specific stress}}{\text{yarn extension}}$$
$$= E_f \cos^2 \alpha \qquad (6.3)$$

This expression predicts that yarn modulus will decrease with an increase in the value of α (twist angle). This simple relationship has been shown to agree reasonably well with experimental results.

Platt (7) points out that, since the fiber strain at the yarn axis equals the axial strain of the yarn, the rupture will first take place in the central filament, followed by successive rupturing of the remaining filaments terminating in the ultimate yarn break. This kind of phenomenon, in which catastrophic failure occurs because of instantaneous rupture propagation, has been observed; however, this does not apply universally in all cases of yarn breaks. The propagation of failure will depend on factors such as twist, fiber surface properties, blend ratio, etc.

The above treatment of yarn mechanics ignores one very important aspect: the role played by lateral forces (forces acting at right angles to the filament axes) in affecting the load-extension characteristics of yarns, especially spun yarns. The lateral forces are very important in affecting the load transfer from fiber to fiber during the extension of the yarn. The other important parameter is the effect of the reduction in yarn diameter because of contraction. The influence of lateral forces on fiber and yarn in the treatment of the mechanics

Ex. 2020-055

of twisted yarn structures has been recognized by many research workers. Hearle (9) has worked out the most extensive analysis of the prediction of yarn strength, taking the lateral forces into account.

His procedure was to establish first a relationship between fiber strain and yarn strain, taking into account the yarn contraction ratio σy (Poisson's ratio):

$$\text{Fiber strain} = \epsilon_f = \epsilon_y \ (\cos^2 \theta - \sigma_y \sin^2 \theta) \tag{6.4}$$

and yarn contraction ratio

$$\sigma_y = \frac{\text{yarn radial contraction}}{\text{yarn axial tension}}$$

He then calculated the fiber strain by assuming that the fiber extension follows Hooke's law (linearly elastic fiber), and reported the following expressions on the basis of elasticity theory:

$$\text{Fiber strain} = \epsilon_f = \frac{X}{E_f} - \frac{2\,\sigma_2}{E_{f'}}\,(-G)$$

where

X = fiber tensile stress
E_f = fiber tensile modulus
$E_{f'}$ = fiber transverse modulus
G = compressive transverse stress
σ_2 = transverse Poisson's ratio, that is, (axial strain/transverse strain) for a transverse stress.

He further assumed that the fiber has an axis of symmetry that coincides with its geometric axis; this gives

$$\sigma_2/E_{f'} = \sigma_1/E_f$$

therefore,

$$\epsilon_f = \frac{X}{E_f} - \frac{2\sigma_1}{E_f}\,(-G) \tag{6.5}$$

where

σ_1 = axial Poisson's ratio, that is, (transverse strain/axial strain) for a tensile stress

and by combining equations 6.4 and 6.5 we can get the expression for tensile stress X.

Ex. 2020-056

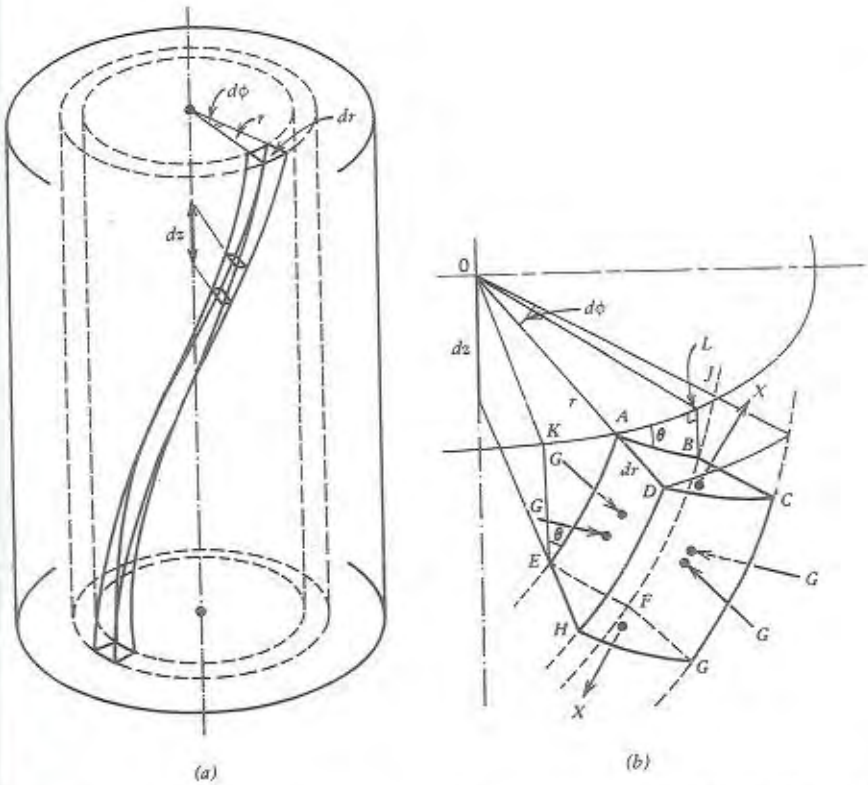


Figure 6.7. (*a*) Helically twisted yarn model showing element defined by dr, $d\phi$, dz, (*b*) Enlarged view of element. From Hearle (5)

$$X = E_f \, \epsilon_y \, [\cos^2 \theta - \sigma_y \sin^2 \theta)] - 2\sigma_1 G. \tag{6.6}$$

Hearle normalized the fiber tensile stress X and fiber compressive stress G by dividing each by a factor X_f ($X_f = E_f \epsilon_y$—which would be present in a filament subjected to yarn axial strain ϵ_y):

$$X = X/X_f$$

$$g = G/X_f$$

Next he established the force acting on the yarn element, shown in Figure 6.7, and derived a differential governing the radial equilibrium in the yarn, after which he solved the differential equation by assuming that the fibers and yarn

Ex. 2020-057

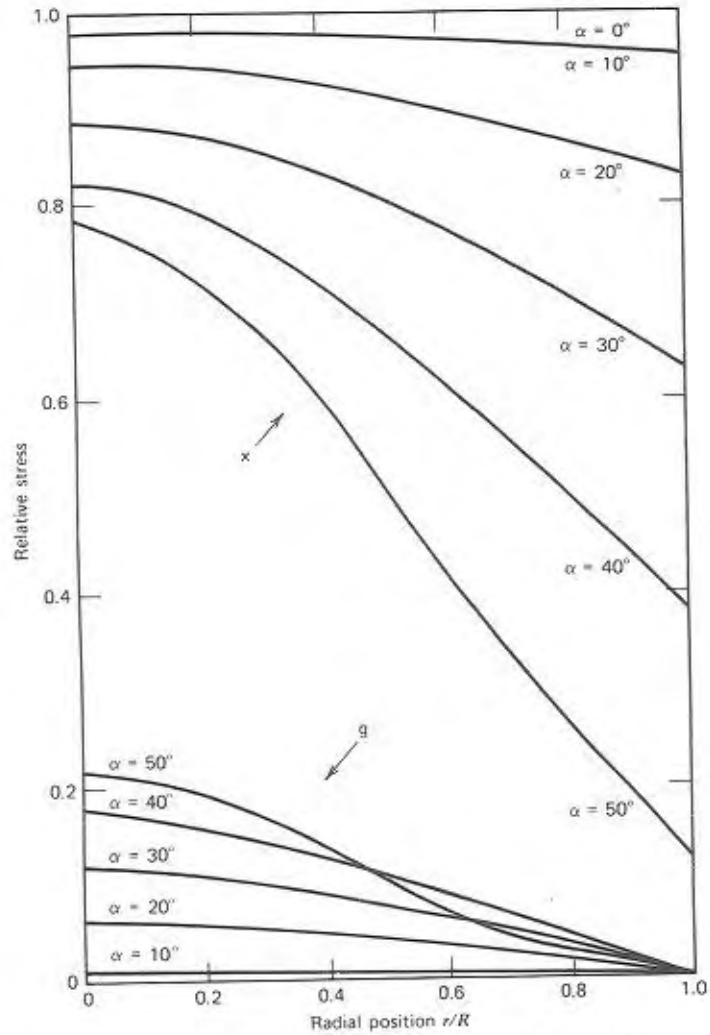


Figure 6.8. Variation of stress with radial position in yarn. From Hearle (5)

deform at constant volume. For the case $\sigma_1 = 0.5$, the expressions for the stresses in a yarn become:

$$x = \tfrac{3}{4}\cos^2\alpha[1 + (\ell/L)^2] - \tfrac{1}{2}[1 + \ln(\ell/L)] \tag{6.7}$$

$$g = \tfrac{3}{4}\cos^2\alpha[1 - (\ell/L)^2] + \tfrac{1}{2}\ln(\ell/L) \tag{6.8}$$

where

ℓ = length of fiber at radius r

Ex. 2020-058

and

L = length of fiber at the surface of the yarn (radius R)

These relations are plotted in Figure 6.8 for various values of twist angle (the relative stresses are plotted against radial position of filament, r/R). Hearle (9) further derived an expression for mean normalized yarn stress for a yarn subjected to small axial yarn strain. The normalized yarn stress is the specific stress in the yarn divided by the specific stress in the individual filaments under small axial yarn strain. This is a useful quantity, since it also leads to the prediction of yarn modulus.

$$\frac{\text{yarn modulus}}{\text{fiber modulus}} = \frac{\text{yarn specific stress at } \epsilon_y}{\text{fiber specific stress at } \epsilon_y}$$

$$= F_y\ (\alpha,\ \sigma_1,\ \sigma_y)$$

Table 6.2 shows the values of yarn parameters reported by Hearle (5) for various values of α, σ_1, σ_y [for $\sigma_y = 0$ (no contraction), and $\sigma_y = 0.5$, constant yarn volume].

Table 6.2. Values of Yarn Parameters

α	$\cos^2 \alpha$	σ_1	G_c/X_f	X_c/X_f	$F_y(\alpha, \sigma_1, \sigma_y)$ with $\sigma_y = 0$	$F_y(\alpha, \sigma_1, \sigma_y)$ with $\sigma_y = 0.5$
0°	1	any value	0	1	1	1
10°	0.970	−0.25	0.0153	1.0076	0.973	0.966
		0	0.0152	1	0.970	0.962
		0.25	0.0151	0.9924	0.966	0.959
		0.5	0.0151	0.9849	0.962	0.955
20°	0.883	−0.25	0.0612	1.0306	0.896	0.867
		0	0.0603	1	0.882	0.854
		0.25	0.0594	0.9703	0.868	0.841
		0.5	0.0585	0.9415	0.855	0.828
30°	0.750	−0.25	0.139	1.0694	0.772	0.713
		0	0.134	1	0.745	0.689
		0.25	0.129	0.9353	0.718	0.665
		0.5	0.125	0.8750	0.693	0.643
40°	0.587	−0.25	0.250	1.1248	0.612	0.522
		0	0.234	1	0.572	0.491
		0.25	0.220	0.8902	0.535	0.462
		0.5	0.207	0.7934	0.502	0.435
50°	0.413	−0.25	0.397	1.1983	0.430	0.321
		0	0.357	1	0.384	0.293
		0.25	0.323	0.8384	0.343	0.268
		0.5	0.293	0.7066	0.309	0.246

Ex. 2020-059

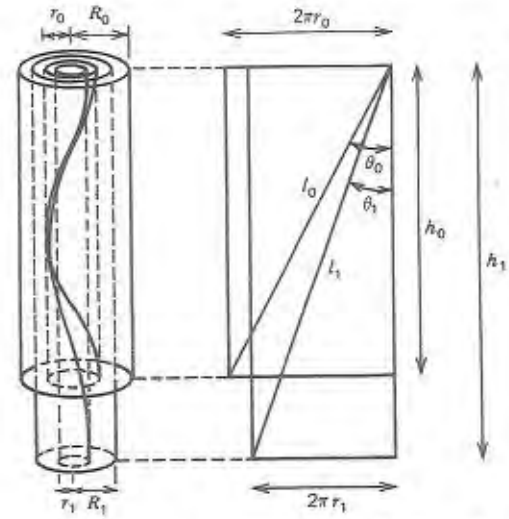


Figure 6.9. Geometry of yarn subject to large extension. From Hearle (9)

It is worth noting that the simple analysis taking the parameter $\cos^2 \alpha$ seems to give reasonably good agreement when compared to the values obtained by the more complex and sophisticated analysis at surface angles below 30°. The agreement above 30° for the $\cos^2 \alpha$ case deviates considerably from the more complex analysis, with differences as high as 25-30% at 40° and over 45% at 50°.

Analyses accounting for lateral pressures have also been reported by Sullivan (10) and Grosberg (11). Grosberg has reported an analysis for predicting resistance to fiber slippage in a low-twist sliver.

Large-Strain Analysis

The analysis discussed in the previous section applies to the case of small strains (such as encountered during draping, wrinkling, etc.) in the filament and yarn. However, if one considers the rupture behavior of yarns in industrial applications, the rupture strains encountered in the filaments are of the order of 15-30%. It would therefore seem desirable that an analysis that takes the yarn strength at break into account should also be carried out. Hearle (5) reports a rigorous analysis and derived the following expression for filament strain from the yarn geometry (Figure 6.9) and large yarn extension:

$$\epsilon_f = \epsilon_y(\cos^2 \theta_1 - \sigma_y \sin^2 \theta_1) - 3/2\ \epsilon_y^2 (1 + \sigma_y)^2 \sin^2 \theta_1 \cos^2 \theta_1 \quad (6.9)$$

Ex. 2020-060

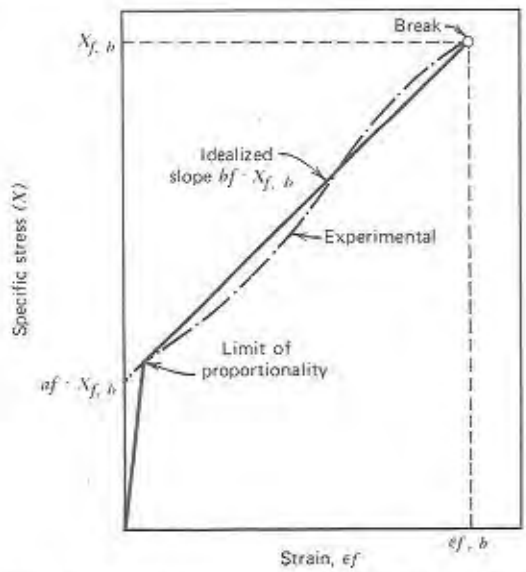


Figure 6.10. Idealized stress-strain curve of filament, compared with a typical viscose rayon curve. From Hearle (5)

Hearle (5) has reported the values of ϵ_f calculated by using various equations. He stated that equation 6.1 gives reasonable agreement for yarn extensions up to 10%, and equation 6.9 (also the one for constant volume deformation not considered here) at 30% yarn extension. He also pointed out that the difference between the use of $\sigma_y = 0.5$ and the correct constant volume equations is small except at high strains (30%) and high twist angles (25°).

For further analysis, Hearle assumed that the stress-strain curve of a filament beyond the yield region up to the breaking point is linear, this idealized stress-strain curve is compared to the actual curve for viscose rayon in Figure 6.10. He then derived the following expression for predicting yarn stress by generalizing the treatment given earlier for large extensions, neglecting the transverse forces but taking the lateral contraction into account and normalizing the non-Hookean region of the stress-strain curve:

$$\frac{\text{Specific stress in filament}}{\text{Filament tenacity}} = \frac{X}{X_{f,b}} \; a_f + b_f \; \epsilon_f --- \qquad (6.10)$$

where $X_{f,b}$ is the filament tenacity which is related to fiber breakage and a_f and b_f are coefficients. This equation is then combined with the expressions in 6.1 and 6.2 to obtain a detailed expression for the prediction of the stress-strain curve of idealized twisted continuous-filament yarns near the breaking point. Con-

Ex. 2020-061

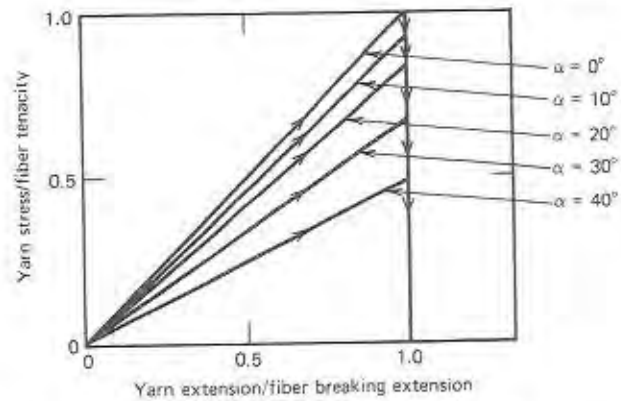


Figure 6.11. Expected behavior of yarns with catastrophic rupture.

sideration of the transverse forces makes the analysis more complex, but Hear has suggested a generalized form and obtained an expression for the yarn stre by substituting it in the analysis for small strains.

The above relationship for the prediction of yarn stress suggested by Hear is for large extensions and includes the yarn lateral contraction and no Hookean behavior. These expressions apply to the yarn stress-strain behavi up to the rupture of the first filament, that which is at the center of the yar and the most highly strained with extension equal to that of the yarn extensic ($\epsilon_{fb} = \epsilon_y$). This would then be followed by the catastrophic rupture of the who yarn; if the broken regions in the yarn do not contribute to the tension, tl stress-strain curve will drop down linearly, as shown in Figure 6.11.

It should be mentioned that this analysis did not take into account the effe of pressure due to transverse forces. This factor has been introduced by Trelo and Riding (17) in analyzing the mechanics of an extended twisted yarn by t energy method. This method involves the calculation of the energy of deform tion, which is obtained by equating the work done by all external forces extending the yarn to the elastic energy stored in the deformed filaments. Tl is a simpler method, since the energy is a scalar quantity and can be summ numerically, whereas the stress is a tensor and requires vectorial summatic Hearle (84) has shown that it is possible to work out the essential relatic of the energy method in a simpler and briefer form than that reported Treloar and Riding (17). The following relationships describe the predicti of mean yarn stress for extension of an idealized twisted continuous-filame yarn by the energy method.

Ex. 2020-062

$$\text{Specific tensile stress} = f_y = 2\int_0^1 f_f(\partial\epsilon_f/\partial\epsilon_L)\, x^d x$$

$$\epsilon_f = [(1+\epsilon_L)^2 \cos^2 \theta_o + (1 - \nu_y \epsilon_L)^2 \sin^2 \theta_o]^{1/2} - 1 \qquad (6.11)$$

$$\tan \theta_o = x \tan \alpha_o$$

$$\tan \alpha_o = 2\pi R_o T_o = 2\pi V_o^{1/2} C_o^{1/2} T_o$$

where

C_o = initial yarn linear density
T_o = yarn twist
V_o = yarn specific volume
ν_y = Poisson's ratio

and fiber specific-stress versus strain relation

f_f = function (ϵ_f) subject ot a tensile strain ϵ_L
$x = r_o/R_o$
r_o = radial position
R_o = yarn radius
θ_o = helix angle
α_o = surface twist angle.

The suffix o is used to indicate explicitly that initial values are to be taken. All values are in a consistent set of units.

The validity of equation 6.11 in predicting the stress-strain relationship of twisted continuous-filament yarns is shown in Figure 6.14*b*.

The case for the inclusion of transverse forces in the analysis for large extension has been dealt with by Treloar and Riding (17) using the energy method. Treloar (20) and Kilby (19) have included the idealized migration pattern of fibers within a yarn and conclude that it has little effect on the tensile properties of yarns.

ACTUAL OBSERVATION OF THE TENSILE BEHAVIOR OF CONTINUOUS-FILAMENT YARNS

Experimental investigations of the tensile behavior of twisted continuous-filament yarns have been reported by many workers and are summarized in Table 6.3. The results reported in the literature by various workers are in general agreement.

Before dicussing the load-extension behavior of twisted continuous-filament yarns, it must be pointed out that their tensile characteristics are profoundly influenced by the method of twisting: this controls the form of the twisted structure and to a certain extent affects the properties of individual filaments.

Ex. 2020-063

Table 6.3. Experimental Studies of Tensile Properties of Continuous Filament Yarns[a]

	Modulus
Maginnis (23)	Viscose rayon (sonic and static modulus)
Hamburger (24)	Acetate and nylon (sonic modulus)
	Tenacity and Breaking Extension
Platt (7)	Viscose rayon and acetate
Shrinagbushan (25)	Viscose rayon
Grover and Hamby (26)	Viscose rayon, acetate, nylon, Dacron, Orlon
Taylor et al. (27)	Viscose rayon, nylon, Dacron
Alexander and Sturley (28)	Nylon
Hearle and Thakur (28)	Viscose rayon, acetate, nylon, Terylene
Kilby (30)	Viscose rayon (effect of lubricant)
	Full Stress-Strain Curves
Hearle, El-Behery, and Thakur (31, 32)	Viscose rayon, acetate, nylon, Terylene
Treloar and Riding (33)	Viscose rayon
Riding and Wilson (34)	Rayon, nylon, polyester, triacetate, acrylic, PTFE

[a]From Hearle (5).

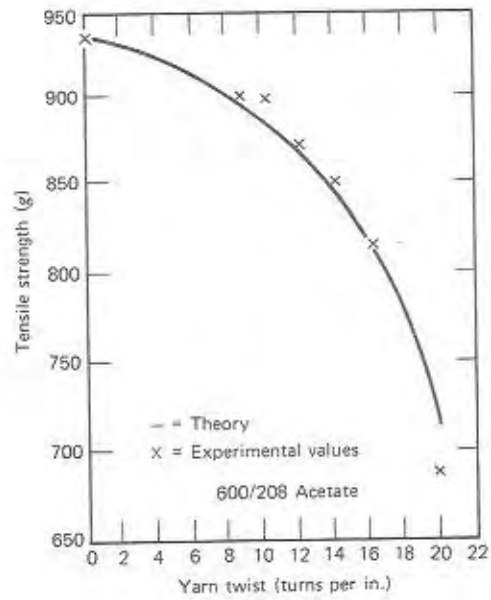


Figure 6.12. Yarn strength vs. twist. From Platt (7)

Ex. 2020-064

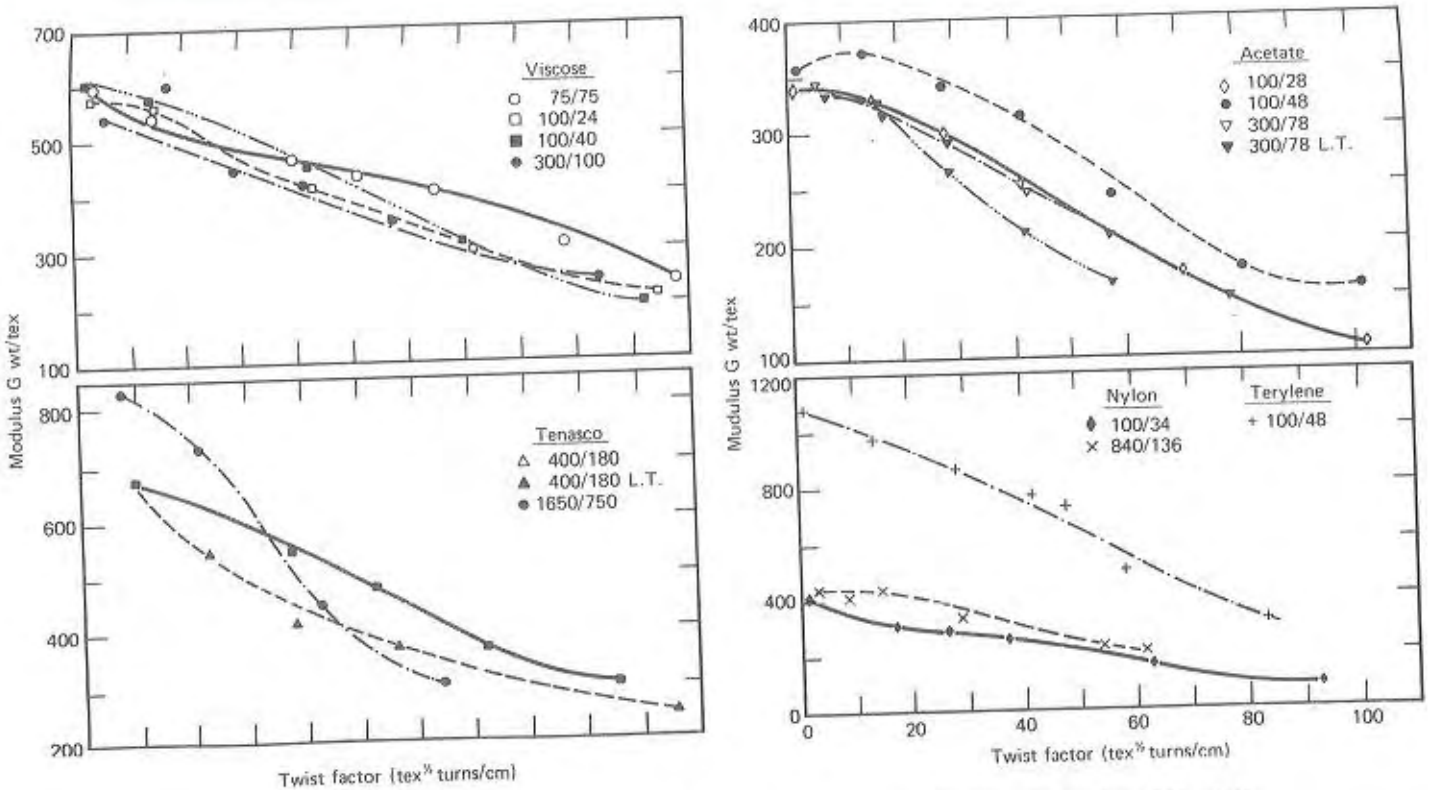


Figure 6.13. Variation of modulus with twist. From Hearle et al (31). Figures below yarn types refer to denier/number of filaments.

Ex. 2020-065

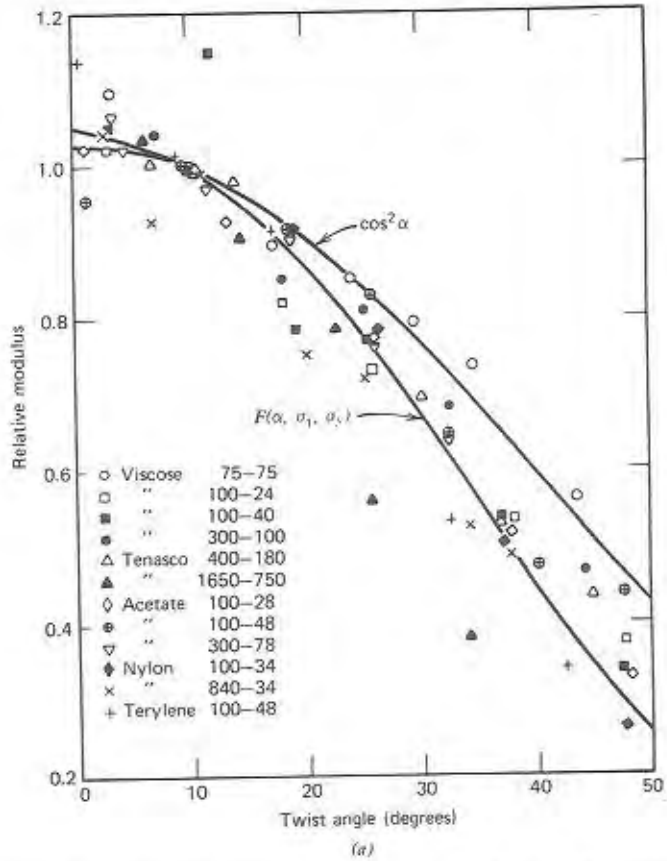
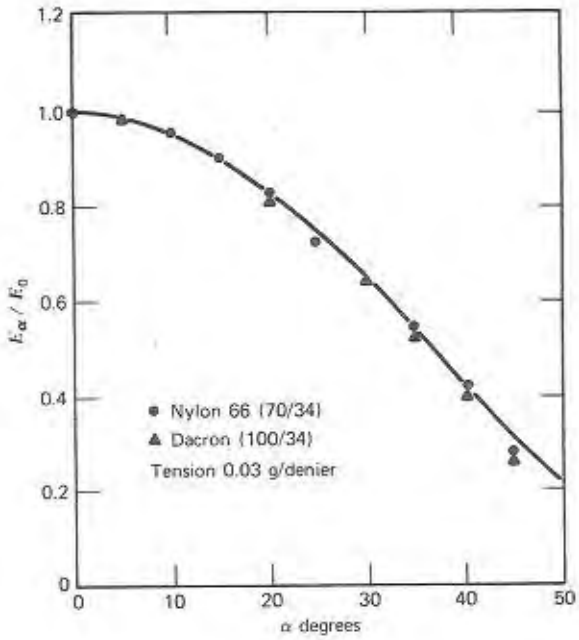


Figure 6.14(*a*). Comparison of experimental values of modulus with theoretical relations, namely $\cos^2\alpha$ from equation (6.3) and $F(\alpha, \sigma 1, \sigma_y)$ with $\sigma_1 = 0.5$ and $\sigma_y = 0.5$ from equation for normalized yarn stress. From Hearle and Hearle et al. (5, 31)

The individual load-extension curves also show some variability, as shown in Figure 6.15. For simple comparison, it is a common practice to obtain the average values of the tensile parameters (modulus, tenacity, breaking extension, work of rupture, etc.) and draw an average curve. The load-elongation properties of filament yarns are easily measured using any of the standard instruments mentioned earlier.

The agreement between the theoretically calculated relationship of the tensile strength and twist and the experimentally obtained values of strength has been demonstrated by Platt (7). Figure 6.12 shows a plot of yarn strength (of an acetate continuous-filament yarn) calculated theoretically from Platt's expres-

Ex. 2020-066



(b)

Figure 6.14(b). Experimental and theoretically calculated variation of yarns dynamic modulus with twist. From Zorowski and Murayama (87). E_α and E_0 is the ratio of modulus with surface twist angle α to modulus at zero twist angle. Points are experimental. Line is theoretical.

sion (variation of strength with $\cos^2 \alpha$) and the corresponding experimentally determined values as a function of twist level.

Hearle et al. (31) have reported the results of experimental investigations of the variation of modulus with twist factor for ordinary viscose rayon, high-tenacity viscose rayon, acetate, nylon 66, and polyester yarns. The results, shown in Figure 6.13, exhibit a decrease of modulus with twist as expected on the basis of the theoretically derived expressions. Hearle has also plotted the relative values of modulus (E_y/E_f) against twist angle, as shown in Figure 6.14*a*.

It is obvious from this plot that the simple expression ($E_y/E_f = \cos^2 \alpha$) exhibits the general trend, but the more elaborate expressions give the best agreement with the experimental results. A further demonstration of the change (decrease) in modulus with increasing twist for other yarns is shown in Figure 6.15. From observation of these curves, Hearle (5) remarks that the sharpness of yield point is markedly clear for low-twist yarns, whereas the high-twist yarns exhibit a poor transition. This behavior is attributed to the effect of the range of

Ex. 2020-067

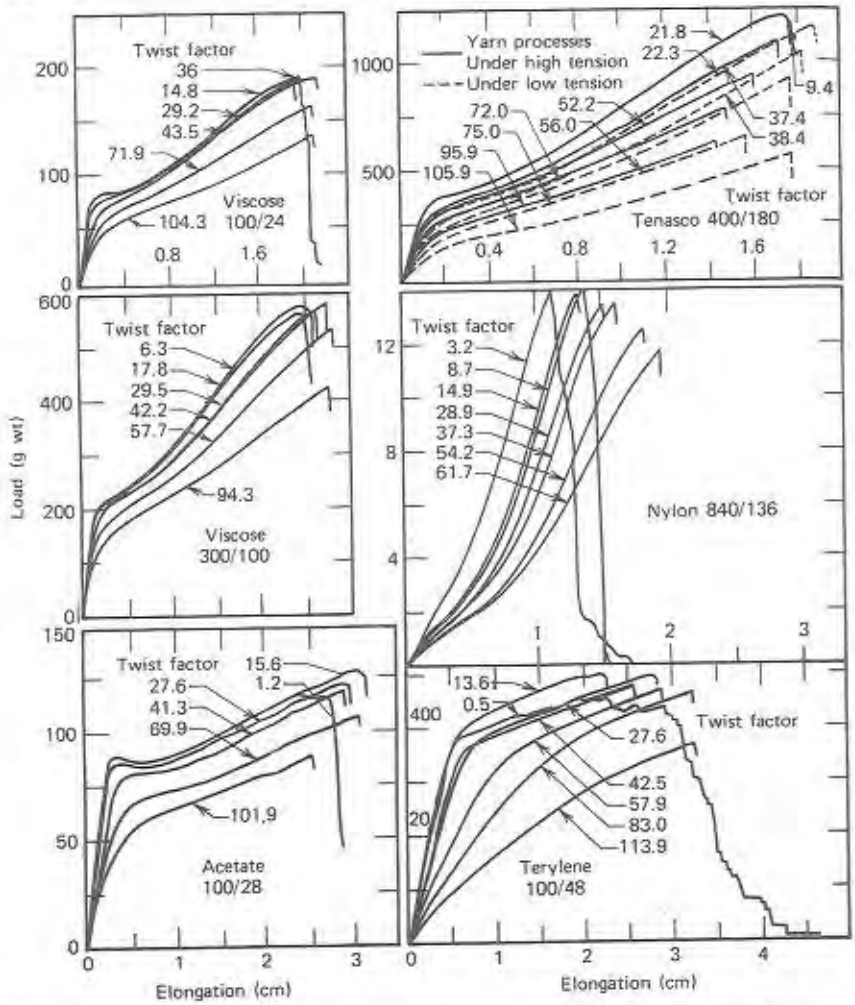


Figure 6.15. Some load-elongation curves of continuous-filament yarns From Hearle et al. (31)

filament extensions occurring in the highly twisted yarns. "When the central filament reaches the yield point, the outer filaments are still at a much lower extension. The sharp bend in the fiber stress-strain curve is thus spread out over a range of yarn extensions." The load-elongation curves for high-twist yarns do not show very good agreement with the predictions made by the theoretical expressions.

However, the observed behavior over the whole range of load-extension curves for yarns shows the best agreement with the predictions made by the energy

Ex. 2020-068

method developed by Treloar and Riding (17). Their experimental results (33) and those of Riding and Wilson (34) for a range of man-made continuous-filament yarns, for example, high-tenacity viscose, nylon, low-tenacity polyester, high-tenacity polyester, triacetate (tricel), polytetrafluoroethylene (Teflon), and Fortisan, are compared with the theoretically obtained curve in Figure 6.16. Their method of calculation requires the knowledge of geometric factors such as yarn twist and yarn radius for the application of the theory. It can be seen that there is some deviation from the theoretical prediction at low strains and high twist, which has been attributed to the presence of crimp.

RUPTURE BEHAVIOR OF CONTINUOUS-FILAMENT YARNS

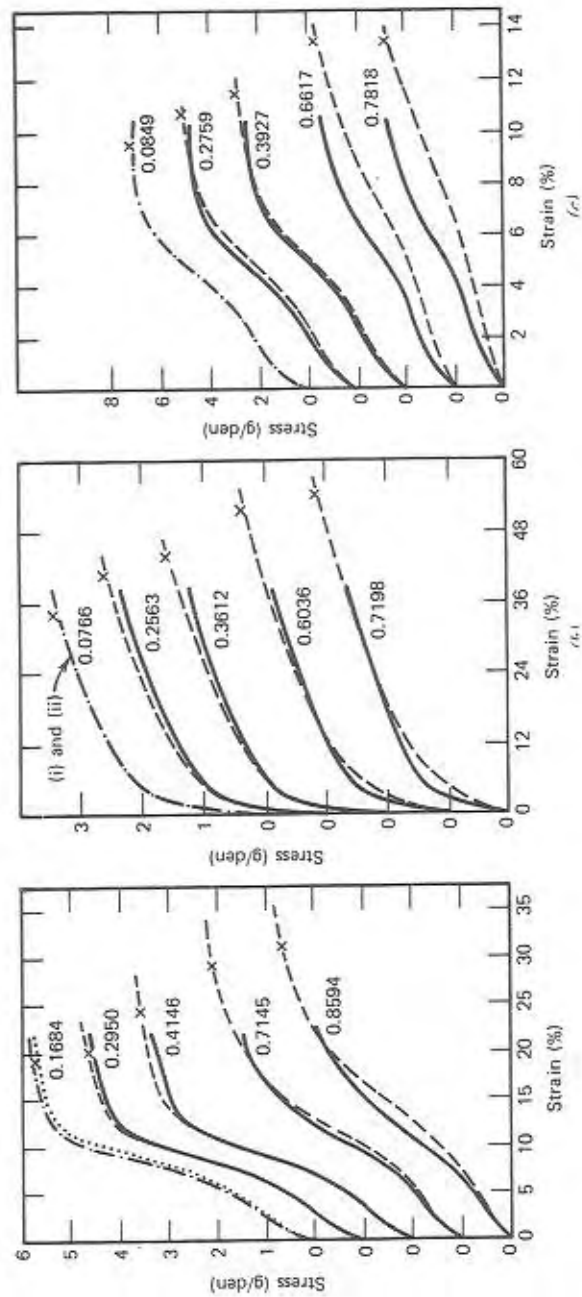
The rupture behavior of the whole twisted yarn structure is a complex one and therefore very difficult to treat analytically. The complications arise because of the following:

1. The migration behavior of filaments—affected by the conditions of twisting.
2. Level of local strains during twisting.
3. Local recovery and buckling behavior of filaments.

All these factors will contribute to the variation of the behavior of individual filaments in a given yarn structure. It has already been pointed out that Platt (7) and Hearle (5) have demonstrated a reasonably close agreement between the simple model of yarn tensile behavior and the actual tensile strength of yarn. However, it would be interesting to see whether these theories would explain the actual rupture, that is, the limitations and other related behavioral aspects in a twisted yarn structure.

Platt (7) suggests that, once the first break has taken place in twisted continuous-filament yarn, the rest of the rupture follows suddenly or catastrophically. On the other hand, the hypothesis advanced by Hearle (5) suggests the occurrence of two different mechanisms of rupture. The breakage observed in actual yarns shows that there is a difference between the nature of break in low-twist and high-twist yarns. The rupture in a low-twist yarn occurs in steps, with the individual filaments behaving independently of the others and each filament breaking when it reaches its breaking extension. This independent behavior results from the lack of the development of lateral pressure (a consequence of twist). On the other hand, in highly twisted yarns, the filaments are held together more coherently, resulting in a sharp break, as predicted by the theoretical analysis. Hearle has discussed both these mechanisms and conjectures that, in actual rupture, what happens is that "when a filament breaks, it ceases to be able

Ex. 2020-069


Stress (g/den)
Strain (%)
0.1684
0.2950
0.4146
0.7145
0.8594
(i) and (ii)
0.0766
0.2563
0.3612
0.6036
0.7198
0.0849
0.2759
0.3927
0.6617
0.7818

Ex. 2020-070

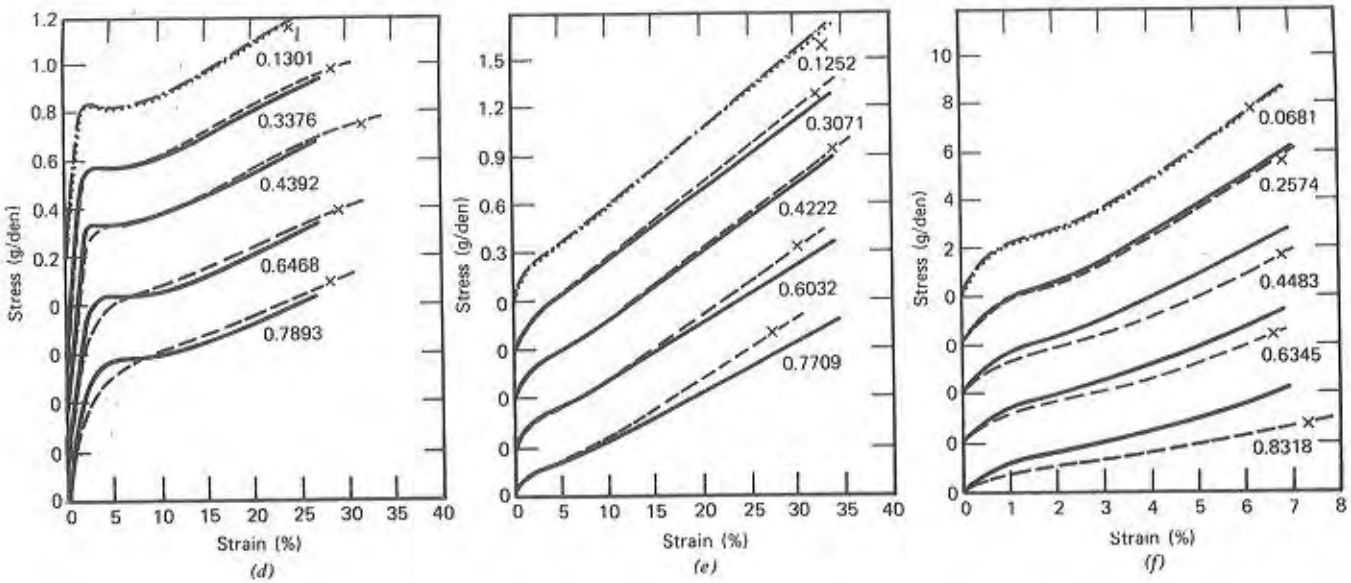


Figure 6.16. Comparison of theoretical and experimental stress-strain curves. From Riding and Wilson (34). i (-·-) Calculated curve for zero-twist yarn, equivalent to individual filament curve. ii (· · ·) Experimental curve for low (but not zero) twist yarn used as basis for calculation of other curves. (- - -) Experimental curves. (———) Calculated theoretical curves. (x) Breaking points. Numbers on curves are values of tan α. (*a*) Nylon, (*b*) low-tenacity Terylene (polyester), (*d*) Tricel (triacetate), (*e*) Teflon (polytetrafluoroethylene), (*f*) Fortisan.

Ex. 2020-071

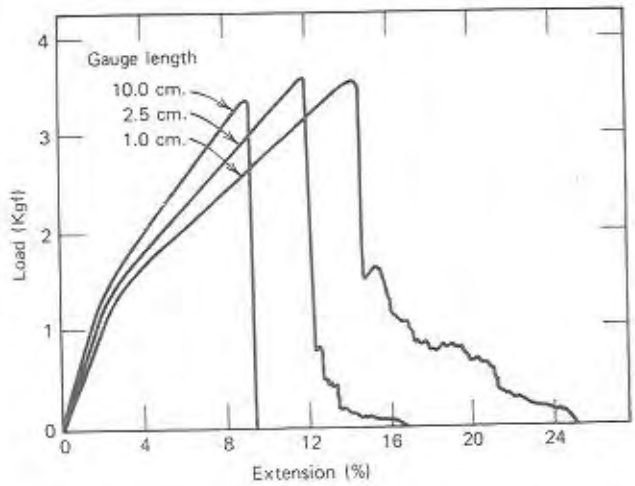


Figure 6.17. Effect of gauge length on load-extension curve of 1650 denier Tenasco yarn at twist factor of 67 tex$^{1/2}$ turns/cm. Rate of Extension of 40% per min. From Hearle and Thakur (29)

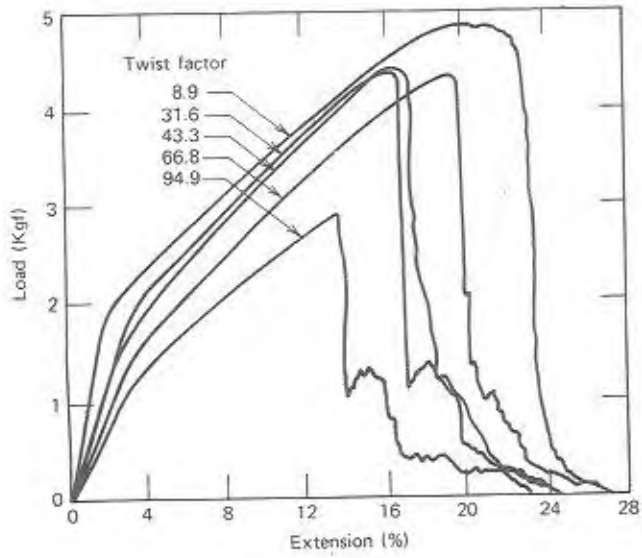


Figure 6.18. Load-extension curves of Tenasco yarns of various twist factors, tested at 1 cm gauge length and rate of extension of 40% per min. From Hearle and Thakur (29)

Ex. 2020-072

o support a load at the point of breakage, but, provided there is some friction, t will still remain an effective part of the yarn at positions remote from the point of break." Hearle has reported the effect of yarn twist and gauge length (test specimen), as well as the rate of extension on the observed rupture behavior of continuous-filament yarns. His results on Tenasco 1650/750 yarns are shown in Figures 6.17 and 6.18. It can be observed that, whereas the long specimen (10 cm) shows a sharp break, the 1-cm gauge length specimen depicts a long tail (higher extension), with a part of the yarn breaking sharply. The effect of twist on rupture can be seen in Figure 6.18. Whereas the high-twist-factor yarns (higher than 43 $tex^{1/2}$ turns/cm) show a sharp partial drop, the rupture point in low-twisted yarns has an extended form with complete absence of sharpness at the lowest twist factor (9 $tex^{1/2}$ turns/cm). Tables 6.4 and 6.5 give some additional information on the tensile properties of these yarns.

Hearle also points out that he was able to arrest the process of rupturing midway and stop the progress of the break. This can be seen in Figure 6.19, in which a series of twisted Tenasco yarns with interrupted breaks are illustrated.

On the basis of the observations made from the load-extension curves and the actual rupture behavior of yarns, Hearle states that "whereas for the long specimens and high ratios of extension the breakage is sharp and complete, for short specimens and low rates of extension the break occurs in a series of steps. The change from one mechanism to the other as the gauge length is altered is due to

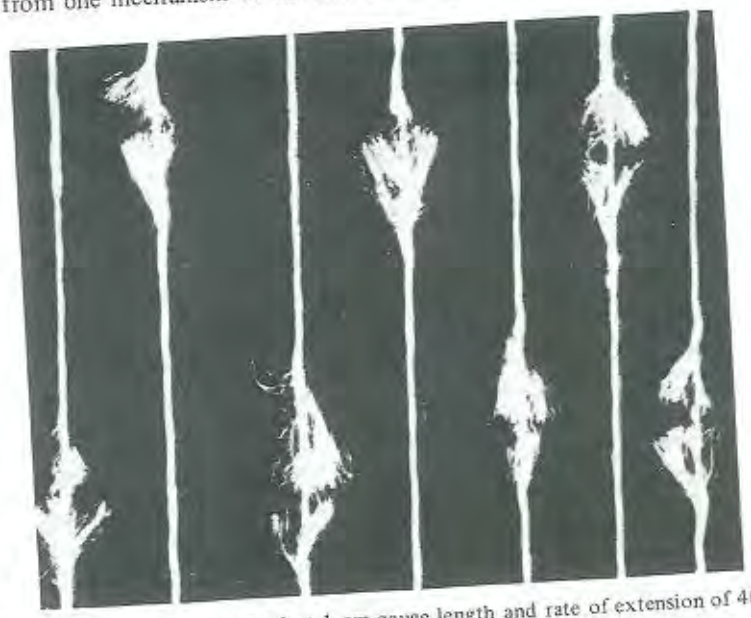


Figure 6.19. Tenasco yarns, tested at 1 cm gauge length and rate of extension of 40% per min, showing interrupted breakage. From Hearle and Thakur (29)

Ex. 2020-073

Table 6.4. Breakage of Ring-Twisted Viscose, 300/100[a]

Twist Factor ($tex^{1/2}$ turns/cm)	Twising Tension (g/tex)	Maximum Load at Break (g), Gauge Length, 1 cm						Load Immediately After Break (g), Gauge Length, 1 cm						Breaking Extension (%)		Breaking Load (g), G.L., 10 cm; Average of 10 Observations
		5 Observations					Average	5 Observations					Average	Average of 5 Observations, G.L., 1 cm	Average of 10 Observations G.L., 10 cm	
7.1	0.9	590	635	600	620	640	617	Continuous drop in load						35.4	22.7	602
18.1	0.9	600	600	610	615	605	606	210	110	120	160	120	144	27.2	24.7	605
17.5	1.8	580	625	610	585	540	599	100	220	130	290	110	170	35.4	25.3	622
17.0	2.7	590	600	580	580	600	590	80	200	160	100	cont.	135	33.5	22.8	609
41.9	0.9	580	620	595	620	580	599	100	180	210	160	120	154	29.5	27.2	598
39.4	1.8	600	615	580	590	600	597	40	110	170	200	200	144	33.6	20.5	569
37.2	2.7	590	585	615	610	605	601	cont.	cont.	cont.	240	200	220	22.5	13.7	592
57.3	0.9	540	540	530	545	540	539	190	280	280	225	80	211	26.7	25.6	532
53.2	1.8	540	555	535	555	585	554	180	260	cont.	290	200	232	27.4	20.7	550
49.9	2.7	560	530	540	520	520	534	120	340	280	240	280	252	26.4	15.8	536
73.7	0.9	450	480	450	480	465	465	190	180	170	200	100	168	27.7	21.6	433
72.4	1.8	470	405	420	490	420	441	280	280	280	220	220	256	22.7	20.7	430
66.5	2.7	500	495	470	500	520	497	200	200	300	240	260	242	26.3	15.7	481

[a]From Hearle (5).

Ex. 2020-074

Table 6.5. Breakage of Ring-twisted Tenasco, 1650/750, 12 tpi[a]

Rates of Extension	Breaking Extension (%)			Breaking Load (g)			Load Immediately after break (g)		
	4%	40%	400%	4%	40%	400%	4%	40%	400% per min
Gauge length									
	16.4	19.0	18.4	2050	2425	2750	1000	1000	1250
	16.6	20.6	16.0	2275	2700	2525	950	1000	1200
1 cm	22.2	19.4	18.0	2525	2425	2800	1000	1700	1000
Average	18.4	19.7	17.5	2283	2517	2690	983	1233	1150
	14.8	11.6	12.8	2400	2550	2950	1250	850	150
	12.8	13.2	14.4	2600	2900	3100	850	900	150
2.5 cm	12.0	10.4	14.4	2350	2400	3050	750	1100	100
	11.6	13.4		2450	2750		750	450	
	14.4	12.8		2400	3100		1000	750	
Average	13.1	12.3	13.8	2440	2740	3033	920	810	130
	10.2	10.7	12.0	2475	2725	3200	625	200	0
5.0 cm	10.0	10.1	12.4	2625	2600	3260	650	0	0
	10.4	11.6	10.4	2650	2900	1250	75	75	0
	10.1	11.5	10.8	2590	2850	2750	840	150	0
Average	10.2	10.9	11.4	2580	2770	3040	842	142	0
	8.1	8.5	7.6	2700	2900	2750	0	0	0
	7.9	8.5	8.8	2550	3000	2760	0	0	0
7.5 cm	7.7	8.2	8.8	2300	2800	3100	0	0	0
	7.9	7.5		2450	2750		0	0	0
	8.1	8.6		2225	2800		0	0	0
Average	7.9	8.3	8.4	2445	2850	2870	0	0	0
	9.7	10.6	11.6	2600	2600	2950	0	0	0
10.0 cm	9.2	9.9	11.2	2650	2500	2950	0	0	0
	9.1	8.5	11.6	2675	2575	3100	0	0	0
Average	9.3	9.7	11.5	2640	2555	3000	0	0	0

[a]From Hearle and Thakur (29).

the amounts of elastic energy stored in the shorter specimen being less, and insufficient to complete the breakage. Similarly, in slower tests, the stored elastic energy will have decreased due to stress relaxation." He then suggests five different modes of break propagation to explain that the "initial part of the breakage (which) remains steady, and never becomes less than half the whole yarn." These five different possible modes of breakage are shown in Figure 6.20.

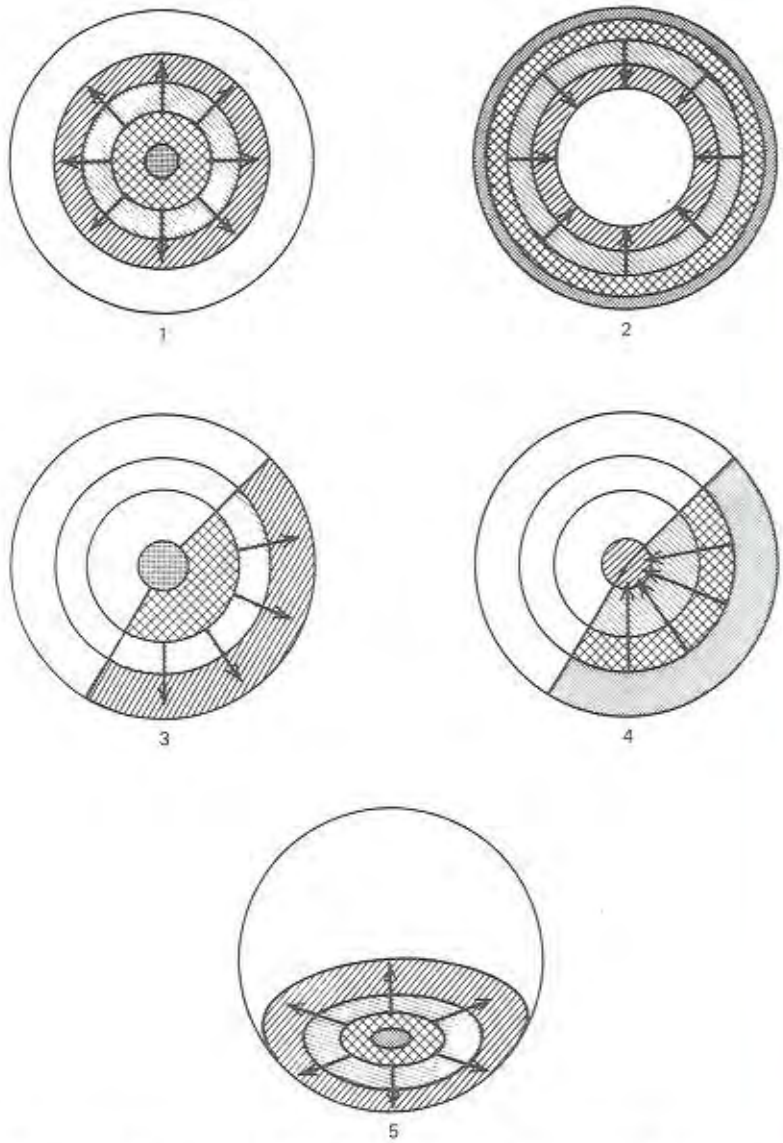


Figure 6.20. Modes of propagation of break, starting at black position and moving out from more heavily to less heavily shaded areas. White portion is left unbroken at end of first stage. From Hearle and Thakur (29)

Ex. 2020-076

To support his hypothesis, Hearle further argues in favor of the last mechanism on the basis of the considerations of buckling of the filament, the form of twisting, the change in filament behavior because of migration, and the influence of the twisting process on filament deformation.

The first mode shows the initiation of the break starting from the inside and spreading outward to stop midway through the yarn cross section (according to the first proposed mechanism). The second shows the break starting from the outside and moving inward. Neither of these mechanisms seems plausible, since there is no reason to expect the breaks to stop at the proposed position. The third and the fourth mechanisms, in which the break, assuming the asymmetry of the yarn structure, moves from the center to the outside and from the outside to the center, respectively, cannot be ignored altogether.

However, the fifth mode, in which the break is shown to start in the middle of one-half of the yarn and propagates outward, does show similarity with the observed appearance of a "pseudo-two ply structure" in which one part of the structure (one ply) ruptures and the other stays intact.

Further demonstration of actual rupture behavior has been reported by Backer et al. (35). They made model structures of 91 single twisted continuous-filament yarns under conditions of "no migration" and used mechanical tracer elements to identify the rupture mechanism. The yarns used for this purpose are 70/34 polyester filament yarns and 79s cotton yarns as tracer yarns, the latter dyed with different colors for easy identification. The cotton yarn is used for its low rupture elongation ($\simeq$ 8%) compared to the high rupture elongation of 30-35% for polyester yarns. This system is selected with the idea that the cotton yarn would break in the early stages of straining without influencing the total rupture of the surrounding polyester yarns. Backer et al. also state that this model system permits the study of the movement of rupture from cotton to cotton and from cotton to polyester. The other advantage of using such a structure is that it makes possible the experimental investigation of the distribution of strain and of the lateral pressure within the twisted structure as it is strained axially. The method used to record the location and the frequency of component rupture at each extension level consists of first drawing parallel lines in groups corresponding to the yarns in each layer of the yarn cross section. Each line in the model is assigned a corresponding number according to the position of the yarn in the yarn cross section, as shown in Figure 6.21. The marked number in the cross section refers to the position of cotton yarns; the unmarked refers to that of the polyester yarns. Their results obtained on a 2-cotton/89-polyester component model yarn twisted with a twist multiplier of 2.19 are shown in Figure 6.21. It is clear from the plot that, after straining the yarn to 11%, component #52 (located in the second ring from the core) suffered five breaks in 8 inches, whereas component #8 (in the outer or fifth ring) did not suffer any breaks; at 15% extension #52 and #8 showed 19 and 2 breaks, respectively; at 25% extension

Ex. 2020-077

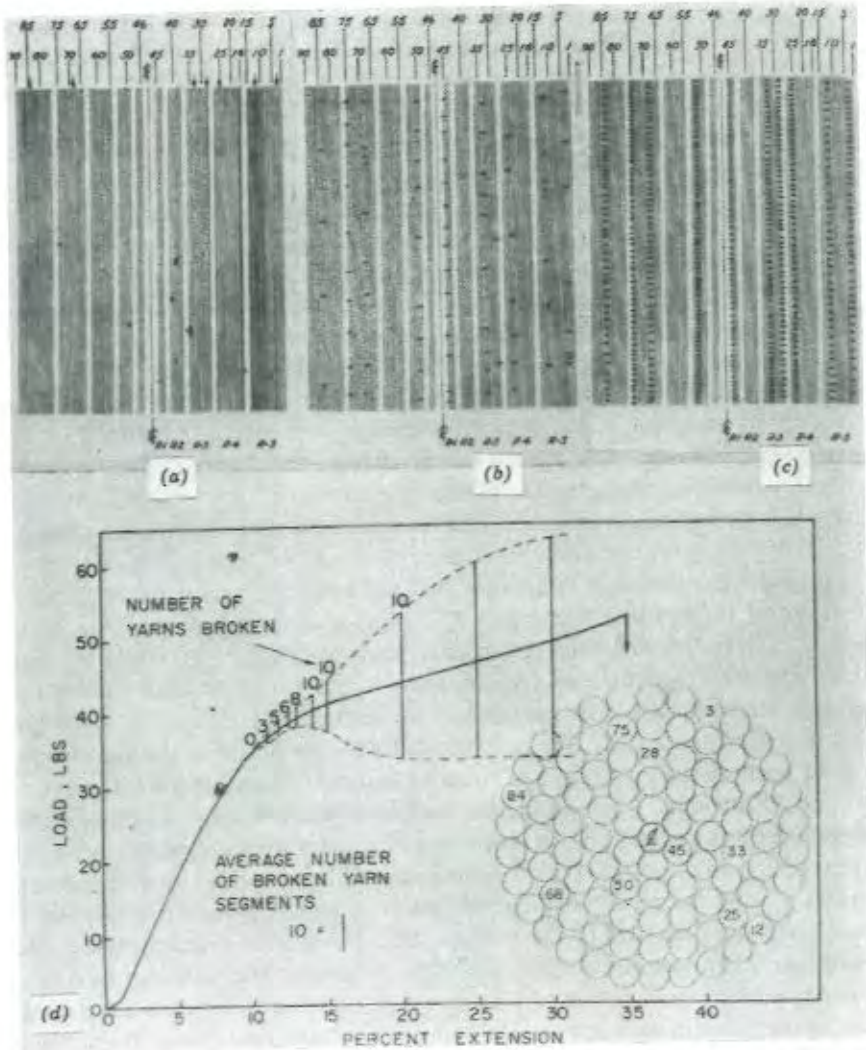


Figure 6.21. Stress-strain-rupture behavior of blended model yarns: 11% cotton/89% polyester, twist multiple = 4.37. (*a*) Rupture count at 11% extension, (*b*) 14%, (*c*) 30%, (*d*) stress-strain-rupture curve. From Backer and Monego (35)

Ex. 2020-078

they showed 44 breaks and 13 breaks in #52 and #8, respectively. The investigation also includes studies of the effect of component distribution, twist multiplier, and blend composition in the model yarns on the rupture mechanism. From their experimental investigation of the model yarns, Backer et al. (35) concluded that the first break invariably occurs in the yarns located in the central position. Moreover, the existence of multiple breaks in the cotton yarn invalidates the assumption that the individual filaments behave independently of each other and that the broken filament in a yarn ceases to contribute to the yarn strength.

Effect of Twist on Breaking Extension of Continuous-Filament Yarns

The theory put forward by Hearle (5) suggests that the breaking elongation of continuous-filament yarns remains constant and is not influenced by twist. However, the experimental results reported by Hearle and others do not agree with this hypothesis. Some experimental results for the breaking extension of continuous-filament yarns are shown in Figure 6.22. The results indicate that the breaking elongation of viscose rayon and Tenasco yarns does not show any regular or significant variation with twist. On the other hand, the breaking extension of acetate yarns first shows an increase to a maximum value and then decreases as the twist is increased. The behavior of a 100-denier nylon and Terylene (polyester), however, is just the opposite–it first decreases and then increases.

Hearle (5) has provided various possible explanations to account for the type of behavior mentioned above. These include:

1. The changed behavior of individual filaments caused by the filaments themselves being twisted in the yarn and under large transverse stresses.
2. The alteration of the properties of filaments as a result of the forces imposed on the filaments during the process of twisting; as a consequence, the filaments might suffer permanent extension.
3. Because of the migration of filaments from one helical layer to another, a redistribution of strains within the yarn can occur as a result of slippage when a yarn is stretched; the highly strained regions in the center layer will pull on less strained portions (outer layers) of the same filament. This can result in higher extension of the yarn. This type of behavior is highly likely in the case of low-twist yarns.
4. Twisting tension and the geometry of the twisting triangle plays an influential role in altering the breaking extension of the constituent filaments and eventually the yarn. A large part of the twisting tension is taken up in stretching the outer filaments to accommodate them more easily along the longer paths near the surface of the twisted yarn. After releasing

Ex. 2020-079

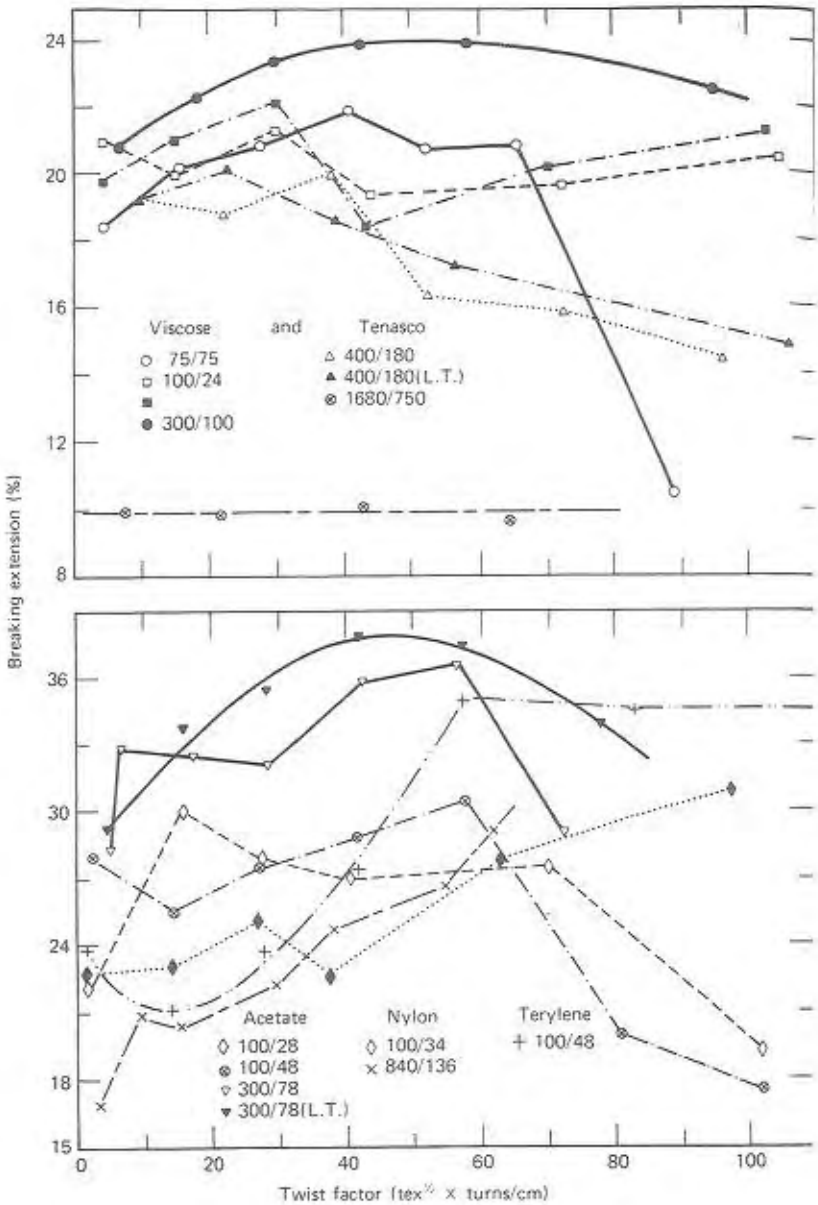


Figure 6.22. Variation of breaking extension with twist. From Hearle et al. (31)

Ex. 2020-080

the tension in the yarn, the outer filaments will contract (provided they have good elastic recovery), causing the inner (center) filaments to buckle. This type of mechanism is presumably the one that predominates in increased extension of nylon and polyester yarns made with high twist.

5. Buckling of filaments may occur during the twisting operation provided there is a lack of sufficient migration. However, the extent of the existence of such behavior is not precisely known.
6. There is a discernible variability in the properties of filaments in a yarn, and this will affect yarn breakage behavior, since breakage is determined by the single weakest point in each filament.

Hearle has further discussed this aspect in terms of twist and argues that twist will inhibit the influence (because of increased cohesion) of the weak place in one filament from extending beyond its near neighbor. Second, because of the differences in the path lengths, the outer filaments will be less extended than the center ones. Consequently, the breakage will initiate at or near the center of the yarn. In other words, the extension of the yarn will be determined by the minimum extension of a few filaments at the core, and not by the minimum extension of all the constituent filaments in the yarn cross section. Considering the whole situation statistically, it can be argued that, in general, the breaking extension will be higher than predicted.

On the basis of the above possilbe explanations, Hearle suggests that the increase in the breaking extension with increasing twist, at low twists, is perhaps attributable to the factor of variability. However, at higher twist, the behavior may be explained on the basis of the influence of tension during twisting. Thus fibers having poor recovery characteristics, for example, if they suffer permanent extension, will contribute to decreased breaking extension; on the other hand, fibers with good recovery behavior will cause the central filaments to buckle, thus increasing the breaking extension. Cellulose acetate fibers have poor recovery and therefore fall in the first group; nylon and polyester fall in the second group, and viscose rayon and Tenasco show behavior that falls in both groups.

Hearle has further theoretically analyzed the effects of buckling, deformation, and migration on the breaking extension and has compared the theoretical relationships with the experimental results. His experimental results for viscose, acetate, nylon, and Terylene, along with the theoretically predicted curves, are shown in Figure 6.23. He concludes that nylon and Terylene yarns show maximum buckling, whereas acetate at high twist factors gives evidence of appreciable permanent deformation. However, the viscose yarns behave in a manner that suggests the presence of perfect migration. Nevertheless, he goes on to suggest that this type of behavior could also be expected from a situation that

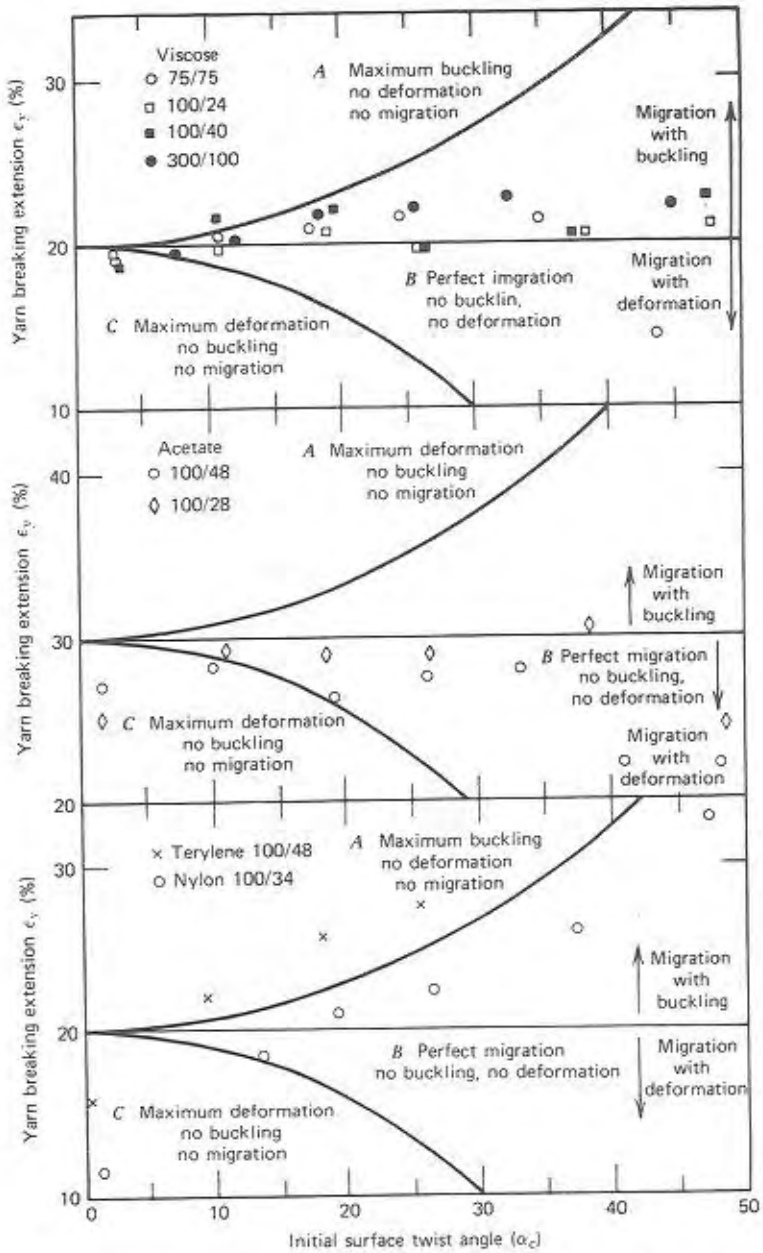


Figure 6.23. Comparison of theoretical and experimental values of breaking extension. From Hearle and Thakur (29)

Ex. 2020-082

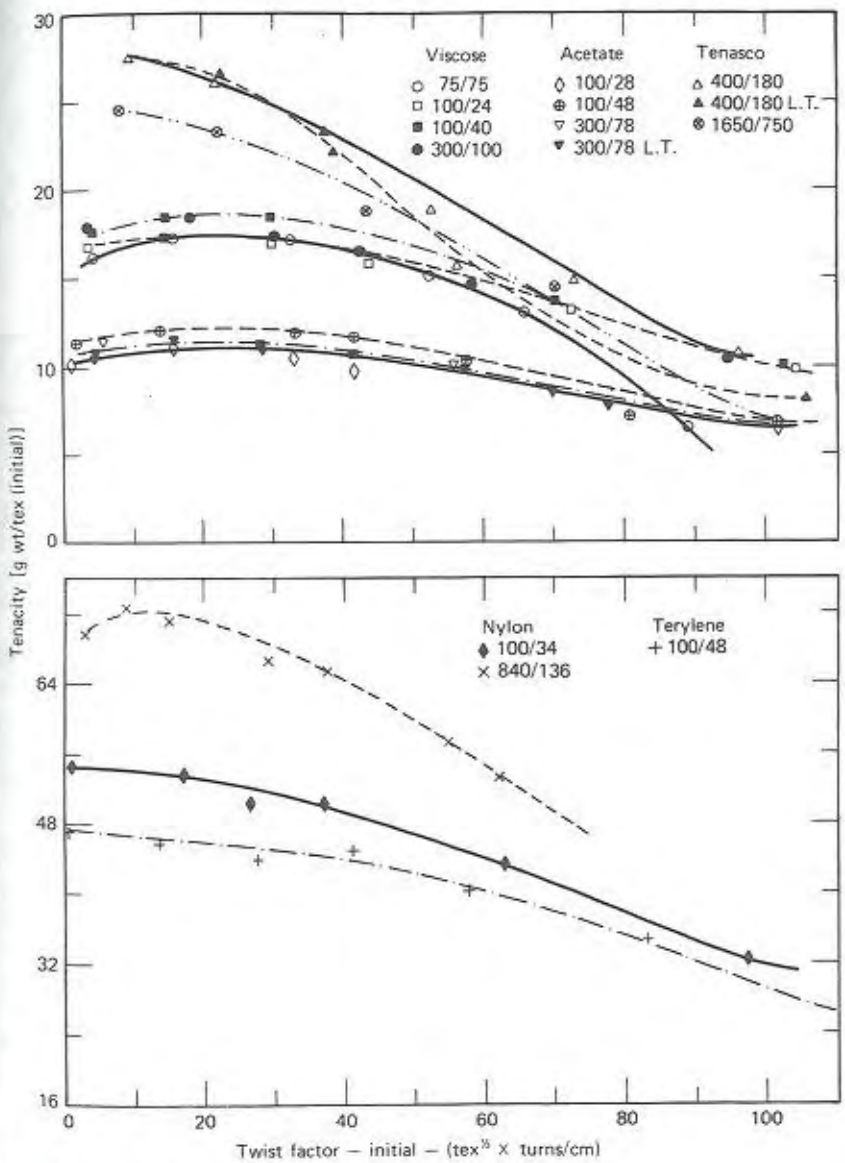


Figure 6.24. Effect of twist on tenacity. From Hearle et al. (31)

Ex. 2020-083

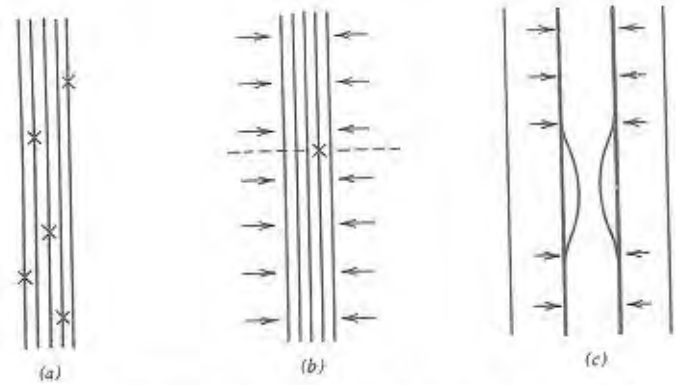


Figure 6.25. (*a*) Choice of weakest points for break of yarn without lateral pressure. Breaking load < (sum of weakest points of each filament). (*b*) Break located at one position in yarn with transverse forces. Breaking load = (weakest point of whole yarn). (*c*) Weak place in one filament supported by neighboring filaments under action of transverse forces. From Hearle (5)

would exist because of the combination of buckling and deformation even without the presence of migration.

Effect of Twist on Tenacity

Figure 6.24 shows the experimental variation of tenacity with twist (29). The tenacity, in general, first increases and then decreases with increase in twist. Hearle attributes the initial rise to the interaction of twist with the variability of the material; the twist will influence the sharing of the load by filaments in the immediate vicinity of the weak places in one filament, and it will also prevent the imitation of rupture solely confined to the filaments that happen to be in the highly strained location in the yarn. This phenomenon is shown diagrammatically in Figure 6.25. The decrease in tenacity as the twist is increased might be explained theoretically in terms of the effects of obliquity. Although the agreement between the theoretically predicted values and the experimental results is reasonable in trend, there is no perfect quantitative agreement (Figure 6.24). Some results obtained by Kilby (30) (shown in Table 6.6) indicate this discrepancy; his results indicate that the tenacity of lubricated high-tenacity rayon yarns decreases less rapidly with increase in twist than the trend observed for unlubricated yarns.

EFFECT OF PROCESSING FACTORS ON TENSILE PROPERTIES

In addition to the amount of twist, the tensile properties of yarns are also

Ex. 2020-084

Table 6.6. Properties of Lubricated 1650 Denier High-Tenacity Rayon Yarns[a]

Lubricant Content (%)	Tenasco 35			Tenasco Super 70			Tenasco Super 105		
	Twist Angle (degrees)	Relative Tenacity[b]	Breaking Extension (%)	Twist Angle (degrees)	Relative Tenacity[b]	Breaking Extension (%)	Twist Angle (degrees)	Relative Tenacity[b]	Breaking Extension (%)
0.15	0	0.90	9.2	0	0.87	11.0	0	0.85	10.8
	17	0.96	12.2	21	0.93	15.6	23	0.95	14.1
	45	0.35	11.3	46	0.36	14.6	52	0.43	16.0
0.66	0	0.86	8.0	0	0.83	6.8	0	0.86	10.0
	19	0.97	10.6	19	1.00	10.6	22	0.94	12.8
	43	0.55	13.0	46	0.64	16.4	51	0.51	15.6
1.97	0	0.69	6.7	0	0.77	7.0	0	0.89	10.4
	17	0.84	9.2	20	1.00	12.0	20	0.94	12.6
	51	0.41	9.6	41	0.6	15.7	52	0.48	15.5

[a]From Kilby (30).
[b]Relative to value at angle of 12.5°.

Ex. 2020-085

influenced by such factors as the method and form of twisting and twisting ten sion. The form and nature of twisting method affect the arrangement of fibers i the yarn, and they may also modify the properties of the constituent filaments The methods of twisting include:

1. Static twisting–in this process, the migration of filaments in a yarn i restricted once the yarn has been given a small amount of initial twist.
2. Continuous twisting–here migration will influence the yarn structure. Th type of continuous twisting, for example, ring twisting or uptwisting, wi also create differences.

Hearle et al. (31, 32) have reported a study dealing with the effect of twistin tension and the operation of twisting on the properties of yarns. Their investig tion is based on the following two types of experiments:

1. Yarns twisted on the same machine to the same nominal twist but diffe ent tensions.
2. Yarns twisted to the same nominal twist under almost identical tension b on different machines.

The results of the experiments on the effect of twisting tension on mechanic properties of yarns twisted on a ring doubler are shown in Table 6.7. The results indicate that the tensile moduli of viscose rayon yarns increase conside ably as the twisting tension is increased (from 0.9 g/tex to 2.7 g/tex). Howeve nylon and Terylene yarns are very slightly affected, which may be attributed t their higher elastic recovery behavior. On the other hand, Tenasco 1650/75 yarns do not follow the trend mentioned above; the tensile modulus decreas slightly with increasing tension at low twists but shows a slight increase at high twists. Hearle attributes this observation to the interaction caused by the hi linear density of this yarn, since a similar experiment on a Tenasco 400/180 ya shows behavior identical to that of viscose rayon.

Kilby (30) reports that the tension under which yarn is wound on the bobb causes a change in the physical properties of the yarn. He finds a considerab difference between the properties of yarn measured immediately after it has be removed from the bobbin and those measured after the yarn has been relax for sometime under standard conditions.

EFFECT OF METHOD OF TWISTING ON TENSILE PROPERTIES

The method or the process of twisting can influence the form of twisting (ribb type or cylindrical form) and the migration behavior of the filaments. The

Ex. 2020-086

Table 6.7. Effect of Twisting Tension on Mechanical Properties of the Yarns (Data Taken from Smoothed Curves)[a]

Yarn and Tester	Twisting Tension (g/tex)	Tensile Modulus (g/tex) at Twist Factors ($tex^{1/2}$turns/cm)of				
		5	10	20	40	60
Viscose	0.9	575	600	605	460	357.5
300/100	1.8	625	638	635	560	460
(Instron)	2.7	650	670	688	650	525
Tenasco	0.9	950	935	868	600	390
1650/750	1.8	965	935	840	590	418
(Instron)						
Nylon	0.9	460	460	450	357.5	230
840/136	1.8	480	490	473	370	250
(Instron)						
Terylene	0.9	1140	1100	1000	740	480
250/48	1.8	1080	1050	975	790	500
(Instron)	2.7	1175	1155	1080	825	–
		Tenacity (g/tex) at Above Twist Factors				
Viscose	0.9	–	17.8	17.8	16.5	14.1
300/100	1.8	–	18.6	18.6	17.0	14.2
(Uster)	2.7	–	17.8	18.8	17.7	14.7
Tenasco	0.9	–	25.5	25.6	23.0	18.4
1650/750	1.8	–	25.5	25.0	22.3	18.0
(Instron)						
Nylon	0.9	73.2	73.8	73.6	70.0	59.0
840/136	1.8	72.9	73.4	73.2	70.5	60.6
(Instron)						
Terylene	0.9	61.2	62.4	62.4	57.2	47.8
250/48	1.8	–	–	63.6	57.6	45.6
(Uster)	2.7	62.8	64.0	63.4	55.2	–
		Breaking Extension (%) at Above Twist Factors				
Viscose	0.9	–	23.7	25.2	22.4	20.8
300/100	1.8	–	20.3	20.4	17.8	16.7
(Uster)	2.7	–	17.8	18.0	14.1	13.6
Tenasco	0.9	–	9.6	10.2	10.8	10.1
1650/750	1.8	–	9.7	10.0	10.5	9.8
(Instron)						
Nylon	0.9	13.8	14.4	15.6	17.0	18.6
840/136	1.8	13.0	13.4	14.3	16.0	17.8
(Instron)						
Terylene	0.9	10.8	11.5	11.9	12.7	14.2
1650/750	1.8	–	–	11.9	12.3	13.2
(Uster)	2.7	10.3	11.3	10.9	11.5	–

[a]From Hearle et al. (32).

Ex. 2020-087

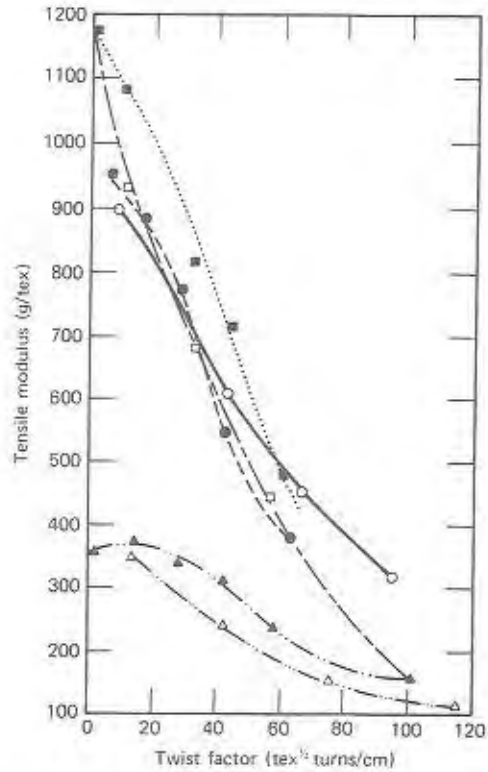


Figure 6.26. Effect of twisting methods on tenxile modulus. Hearle et al. (32) Tenasco 1650/750: (○) Up-twisted; (●) ring-twisted. Acetate 100/48: (△) Up-twisted; (▲) ring-twisted Terylene 250/48: (□) Up-twisted; (■) ring-twisted.

imposed changes in yarn structure cause differences in yarn properties. Hearle e al. (32) have reported a comparison of the properties of uptwisted and ring twisted polyester, Tenasco, and acetate yarns. Figures 6.26-6.28 show the effect of the method of twisting on the moduli, breaking extension, and the tenacity of these yarns.

The differences in the moduli and the breaking extensions of the acetate and Terylene (polyester) yarns spun on the uptwister and ring frame are obvious The ring-twisted acetate and polyester yarns generally show higher values of tensile modulus; the Tenasco yarns, however, do not show any appreciable difference with different methods of twisting.

The uptwisted acetate yarns have generally higher breaking extension than those of ring-twisted yarns (Table 6.5 and 6.8). Tenasco yarns do not show any discernible difference, whereas the Terylene yarns made on the uptwister have a

Ex. 2020-088

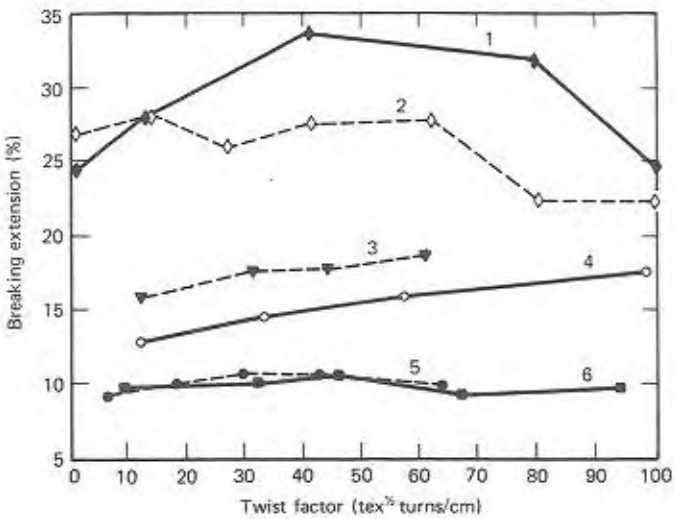


Figure 6.27. Effect of twisting methods on breaking extension. From Hearle et al. (32) Acetate 100/46: (◇) Doubler twisted; (◆) uptwister twisted. Terylene 250/48: (▼) Doubler twisted; (○) uptwister twisted. Tenasco 1650/750: (●) Doubler twisted; (■) uptwister twisted.

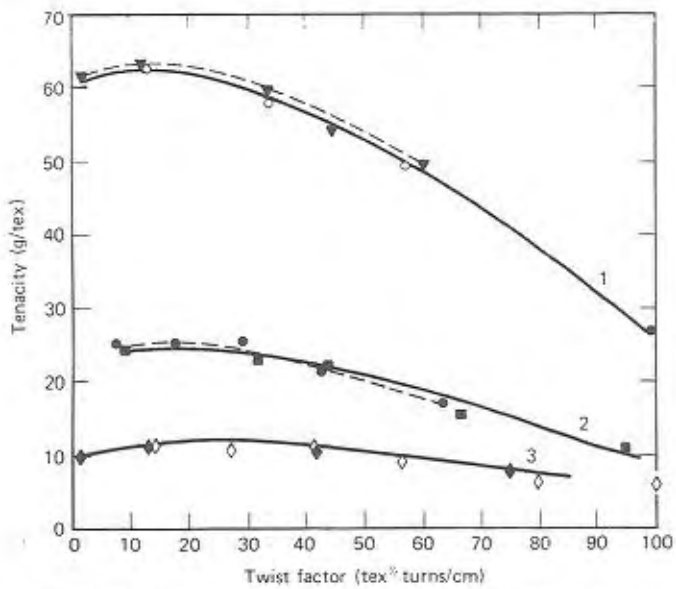


Figure 6.28. Effect of twisting methods on tenacity. From Hearle et al. (32) Terylene 250/48: (▼) Doubler twisted; (○) uptwister twisted. Tenasco 1650/750: (●) Doubler twisted; (■) uptwister twisted Acetate 100/48: (◇) Doubler twisted; (◆) uptwister twisted.

Ex. 2020-089

Table 6.8. Breakage of Uptwisted Tenasco 1650/750[a]

Gauge Length (cm)	Twist Factor ($tex^{1/2}$ turns/cm)	Average Breaking Load (g)	Average Breaking Extension (%)	Load Immediately After Break				
				Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
10	31.6	4650	10.09	Sharp drop				
	43.3	4526	10.76					
	66.8	3413	9.26					
	94.9	2603	9.53					
2.5	31.6	4654	11.89	800	1000	1200	300	900
	43.3	4374	11.61	2000	1500	1000	1100	800
	94.9	2686	10.44	1100	1200	1100	1400	800
1.0	31.6	4445	16.89	1200	cont.	1400	2900	1000
	43.3	4365	18.60	2000	2300	1600	1700	1000
	66.8	3557	13.96	1600	1400	1600	1800	1600
	94.9	2815	13.95	1200	1200	1000	1400	800

[a]From Hearle et al. (32).

lower breaking extension. Hearle (5) points out that "these differences in properties probably arise from differences in yarn structure, such as the form of twisting and the migration behavior of the filaments, as a consequence of the different restraints imposed on the yarn during the two different methods of twisting." In particular, it has been found that some ring-twisted yarns appear to twist as a "ribbon."

STAPLE YARNS

Introduction

The literature is full of reports of experimental investigations on the effects of various physical and mechanical properties of fibers and the yarn processing factors (twist, spindle speed, fiber parallelization, draft ratios, etc.) on the strength of spun yarns. It is not an exaggeration to say that tensile strength has been the most extensively studied property of spun yarns in the textile industry. The strength characteristic has been and is still the primary test used in the textile industry as a guide in comparing the performance efficiency of various processes in quality control, and in determining the end-use behavior of most textile products. This is in spite of the fact that it is difficult to find any correlation between yarn strength and the efficiency of subsequent processes such as winding, warping, beaming, ends down during spinning, slashing, etc. However, the tensile properties of yarns spun from staple fibers, because of their

Ex. 2020-090

complex structure, are still not fully understood. The complications in understanding the structural mechanics of staple yarns are primarily caused by two factors, namely, discontinuities in fiber length, and the slippage of fibers during extension. Factors such as twist and fiber migration in spun yarns acquire different dimensions, since they are the only reasons why a bundle of short fibers is held together in a linear assembly. The introduction of new types of fibers, the use of various blends compositions, and the new methods of yarn manufacture inject additional complexities and necessitate a thorough understanding of the mechanical behavior of spun yarns if one is to succeed in producing novel structures.

The problem of fiber cohesion was first recognized by Pierce (36), who suggested that the fibers in a yarn are held together because of "random tangle," which was later described by Morton (63) as "fiber migration." The subject of fiber migration in yarns is discussed briefly in Chapter 3.

The earliest attempt made to analyze the mechanics of staple yarns theoretically is attributed to Gégauff (6). He derived an expression for the variation of breaking load in a twisted fiber assembly by assuming that the yarn has a perfect helical geometry and that the twist in the yarn is enough to prevent any slippage. Later, Sullivan (64) carried out his analysis assuming the existence of an arbitrary pressure on the surface to account for the development of transverse presssure. In this analysis, he also introduced the concept of variability of fiber properties. In theory, he established that yarn strength increases first to a maximum value with increase in twist and then falls with subsequent increase in twist. This optimum value of twist is largely determined by the fiber length, fiber fineness, and the fiber coefficient of friction, in addition to the fiber strength. Among the earlier studies, the work of Platt (7), Gregory (65-69), Alexander (70), Shorter (71), and Holdaway (72) should also be mentioned.

Hearle (5) has carried out a more rigorous theoretical analysis of the mechanics of spun yarns. He suggests three levels of approach to studying the problem:

1. a purely qualitative descriptive treatment
2. a rough analysis with many approximations yielding an explicit equation for the variation of staple fiber yarn mechanical properties with twist
3. a full rigorous analysis of the behavior of an idealized model yielding a set of equations that require solving by numerical computation

Of these three approaches, the third is out of the scope of this work, and the reader is referred to the original work by Hearle (73). However, for the benefit of the reader, a simple account of the rough analysis is given here, and the qualitative treatment is discussed at length. The observed behavior of the tensile properties of staple yarns is discussed in terms of the structure (twist, etc.) and properties of the constituent fibers and ultimately linked to the qualitative explanation.

Ex. 2020-091

Approximate Theoretical Treatment

In this analysis, Hearle (5) considers yarn as a continuous-filament yarn. I including all other approximations, the derivation of the equation for the var tion of modulus with the twist predicts that the modulus varies as $\cos^2 \alpha$ (equ tion 6.3). Hearle then develops an expression for the reduction in tension in t fibers in the surface layers of the yarn. He obtains an equation for the me normalized tensile stress in the surface layer resulting from an imposed sm axial strain. The final expression has the form:

$$\frac{\text{Yarn modulus}}{\text{Fiber modulus}} = \frac{E_y}{E_f} = \cos^2 \alpha \ [1\text{-}K \operatorname{cosec} \alpha] \qquad (6.1$$

where

$$K = \frac{\sqrt{2}}{3L_f} \left(\frac{aQ}{\mu}\right)^{1/2}$$

The $\cos^2 \alpha$ term represents the effect of obliquity (twist) and the ($1\text{-}K \cos \alpha$) term gives the change in tension caused by fiber slippage; a is the fiber radi Q is the migration period, L_f is the fiber length, and μ is the coefficient friction. Hearle points out that, because of the severe approximations, a preci value of k is difficult to obtain; however, this simple treatment does indicate general how various factors affect the modulus of a staple-fiber yarn.

Qualitative Explanation of the Strength of Staple Yarns

The strength of a staple yarn is determined by various fiber properties and ya structural and processing parameters. It is known that, as yarn twist increas yarn strength increases to a manimum value, and any further increase in t former brings about a reduction in the latter. The twist at which yarn streng is maximum is called the optimum twist. One traditional explanation of t phenomenon of change in strength with twist is based on the combination slippage and breakage of fibers. This is shown diagrammatically in Figure 6.2 It is evident that a staple yarn with no twist (zero twist) has no strength, sin the fibers merely slide over one another when stretched. In the initial rising pa of the curve, the resistance to slippage increases, but the number of fibers th slip rather than break slowly decreases as the effect of twist in gripping the fibe increases. The downward trend at high twist is obviously caused by fib obliquity in the yarn; this is identical to the behavior of continuous-filame yarns. A further explanation of this view is given in the following:

1. At low twist, the effect of cohesion between the fibers outweighs t

Ex. 2020-092

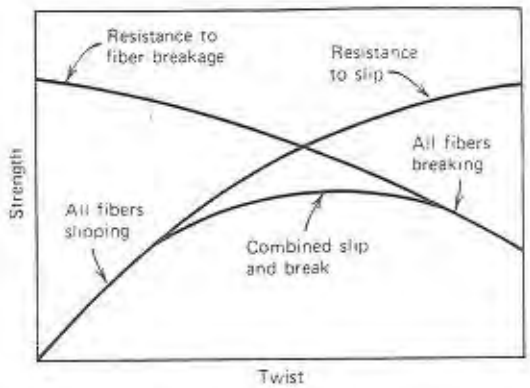


Figure 6.29. Traditional explanations of the effect of twist on strength of staple fiber yarns.

effect of obliquity, giving rise to increase in strength. This increase in strength is slow at first, up to the point at which fibers may just begin to break, and then increases rapidly as larger numbers of fibers break.

2. In the high-twist region, a further increase in cohesion no longer produces an increase in strength, since the majority of fibers break, whereas the increasing inclination of the fibers causes the strength to fall.

However, a close examination of this view indicates that the mechanism governing the twist-strength relationship of staple yarns is not so simple, and this view is incorrect. There will very likely be slippage near the ends of all the fibers, and practically all the fibers are gripped in the central region.

The other explanation, which does not take the effect of migration into account, suggests that the fibers in the outer layers slip, whereas those in the inner layers break, the transition between the breaking and slipping fibers shifting from the inner to the outer zone. This explanation assumes that some arbitrary cohesion in the outer layers causes the development of the transverse pressure. This interpretation does not appear plausible, because the gripping of fibers at low twist will occur if the length of the fibers is reasonably long and there is a high level of migration. Consider an ideal yarn in which all the fibers have similar migration behavior and all will be gripped at some places along their length. Now if the twist is raised to a level at which fibers grip one another, an increase of imposed load will not cause slip because, even though it increases the tension in the fibers that causes slip, it is also effective in the development of transverse forces that increase the frictional hold on the fibers, thus preventing them from slipping. This situation resembles more closely the

Ex. 2020-093

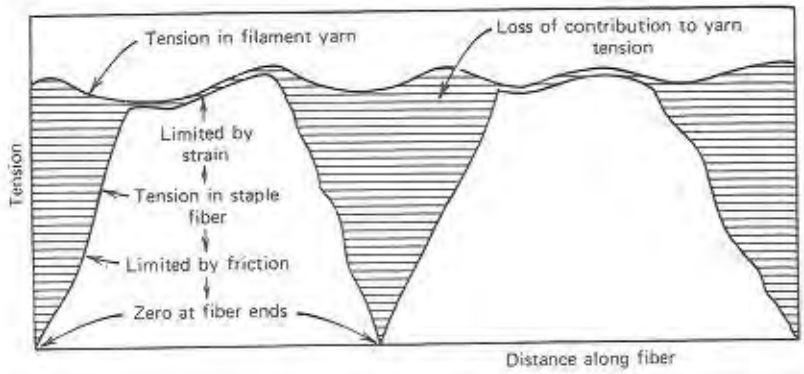


Figure 6.30. Comparison of tension along filament in a continuous-filament yarn and along fibers in the corresponding spun yarn. From Hearle (5)

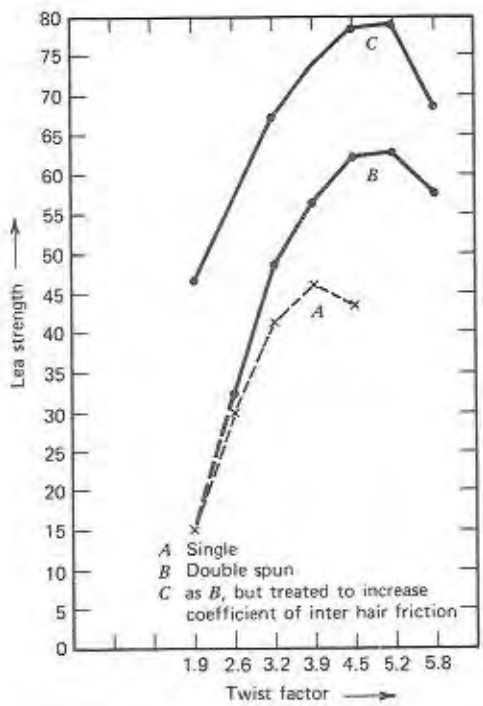
actual yarn structual behavior, but it still leaves the question of what happens in the regions of fiber ends where slip is liable to occur.

Hearle and El-Sheikh (74) have offered a modified qualitative approach regarding the behavior of spun yarns during extension in terms of the behavior of a continuous-filament yarn. It is assumed that the two structures are identical in all respects (fiber properties, etc.) except for the joining of the discontinuities at the ends of the fibers. Figure 6.30 shows the buildup of tension along the length of the filament when the yarn is subjected to longitudinal extension; the variation in stress is caused by the radial position of the filament imposed by filament migration. Hearle and El-Sheikh suggest that the loss in contribution to the total yarn tension is not so much caused by the slippage of complete fibers as by the failure of portions near the fiber ends to contribute to their fullest extent. Hearle suggests that yarn tension at a given extension or yarn modulus or yarn strength can be expected to vary with twist, fiber length, and fiber friction. Other factors that influence yarn tensile properties are:

1. The rate of fiber migration in yarn: this will have an effect on the rate at which the tension builds up in a fiber.
2. Fiber fineness: the buildup of tension in a fiber is proportional to the area of cross section of the fiber, whereas the frictional resistance to slip is proportional to the circumference and thus to the radius of the fiber. Obviously, the tension causing slippage increases as the square of the fiber radius, whereas the frictional resistance increases as the first power of the radius. Consequently, the greater the fiber radius (coarse fiber), the greater will be the tendency for the fiber tension to overcome the frictional forces resisting slippage. In other words, the finer the fiber, the stronger the yarn.

Ex. 2020-094

3. The number of fibers in a yarn cross section: this will affect the pressures generated at the points of interfiber contact in a yarn. Yarn count or size determines the number of fibers in a yarn; thus for a given fiber fineness, yarn size will affect the yarn strength. A very low number of fibers will produce a weak yarn. Goodwin suggests (75) that the minimum number of fibers needed for economical spinning of rayon staple yarn is 64-97, depending on fiber fineness and length. Stanbury and Byerly (38) have suggested a minimum of 20 fibers for worsted spinning.
4. Fiber packing density: this will determine the entanglement of fibers in a staple yarn.



(a)

Figure 6.31(a). Reproduction from Studies of Quality in Cotton by Balls (1928). "The inter-relation of twist, adhesion, and strength in singles yarn. Curve A shows the increasing "strength" of a yarn spun with increasing twists, its optimum being at 3.8 twist factor. In Curve B the hair-to-hair adhesion is increased by wet double-spinning for the softest single, thus adding turns up to the same total twists as in A. The optimum rises to 4.9 twist factor. For Curve C the same treatments as in B were preceded by an artificial modification of the hair surface, after the soft single had been spun. The coefficient of friction was thus increased, but the optimum twist is unchanged, though the "strength" is raised throughout."

Ex. 2020-095

Table 6.9. Other Experimental Studies of the Strength of Spun Yarns[a]

Reference	Title
Turner and Venkataraman (37)	A study of comparative results for lea, single thread and ballistic tests on yarns from standard Indian cottons
Stanbury and Byerly (38)	The relation between the strength, count, and twist of single worsted yarns
Millard (39)	Nylon staple on the cotton system: some properties of all nylon yarns
Platt et al. (40)	Factors affecting the translation of certain mechanical properties of cordage fibers into cordage yarns
Brown (41)	Correlation of yarn strength with fiber strength measured at different gage lengths
Dickson (42)	Structure and properties of cotton and synthetic single yarn
Ewald and Landstreet (43)	A new method for predicting cotton yarn strength from the observed strength of a single count
Fiori et al. (44)	Effect of single and ply twists on the properties of a 31/2 carded cotton yarn
Fiori et al. (45)	Effect of single and ply twists on the properties of a 15.5/2 carded cotton yarn
Fiori et al. (46)	Effect of cotton fiber strength on single yarn properties and on processing behavior
Fiori et al. (47)	Effect of single and ply twists on the properties of 31/2 or 15.5/2 carded cotton yarns
Platt et al. (48)	Factors affecting the translation of certain mechanical properties of cordage fibers and yarns into cordage strands and ropes
Bogdan (49)	The characterization of spinning quality
Fiori, Brown, and Sands (50)	The effect of cotton fiber strength on the properties of 2-ply carded yarns
Fori, Sands, Little, and Grant (51)	Effect of cotton fiber bundle break elongation and other fiber properties on the properties of a coarse and a medium singles yarn
Virgin and Wakeham (52)	Cotton quality and fiber properties Part IV. The relation between single fiber properties and the behavior of bundles, silvers, and yarns
Coulson and Dakin (53)	The influence of twist on the strength and certain other properties of twofold yarns
Coulson and Dakin (54)	The effects of their physical properties of singles twist; doubling twist, direction of doubling, traveler weight and spindle speed

Ex. 2020-096

Table 6.9. (*Continued*)

Reference	Title
Dakin (55)	The effect of twist and structure on the physical properties of some manifold yarns
Dakin (56)	The effect of twist on some physical properties of an 805/2/3 thread twisted Z/Z/S
Sreenivasan and Shankaranarayana (57)	Twist and tension as factors in yarn characteristics
Bandyopadhyay (58)	The optimum twist factor for jute yarns of various sizes and fiber qualities, and tex-tenacity relations at different twist factors
Nanjudayya (59)	Rupture strength of single yarns measured by ballistic method
Nanjudayya (60)	Strength of a cotton yarn in relation to its structure in the break region

[a]From Hearle (5).

Experimental Studies of Yarn Strength

Several experimental investigations concerning the strength of staple yarns have been reported in the literature. Some of the important studies are listed in Table 6.9. The following discussion is limited to the treatment of results that typify the experimental observations of the strength characteristics of staple yarns.

One of the earliest studies reported in the literature is by Balls (76) in his book "Studies of Quality of Cotton." The three most important chapters are Chapter 10–The Arrangement of Twist, Chapter 11–Hair Adhesion and Yarn Rigidity, and Chapter 12-The Strength of Yarn. These three chapters deal with the role of twist, fiber friction, and the variability in yarn element (yarn structure) on the tensile properties of cotton yarns.

The illustrations in Figure 6.31*a* and *b* show the results of the experiments reported by Balls. Figure 6.31*a* shows the effect of twist and adhesion on the skein strength of yarns, whereas Figure 6.31*b* demonstrates the effect on breaking load of removing twist by untwisting a yarn spun to a high twist. It is clear from the illustrations that the strength of a yarn rises to a maximum value as the twist is increased, followed by a downward trend with further increase. Balls suggests that, for the yarns shown in Figure 6.31*b*, the optimum twist factor ranges between 3.8 and 4.9 (roughly 40 $tex^{1/2}$ × t.p.c. and 50 $tex^{1/2}$ × t.p.c.), depending on the surface behavior of fibers. Balls also comments that the "initial tension of various yarns was such as to indicate that zero tension would correspond to a twist factor of 1.5." The trend exhibited by these experimental

Ex. 2020-097

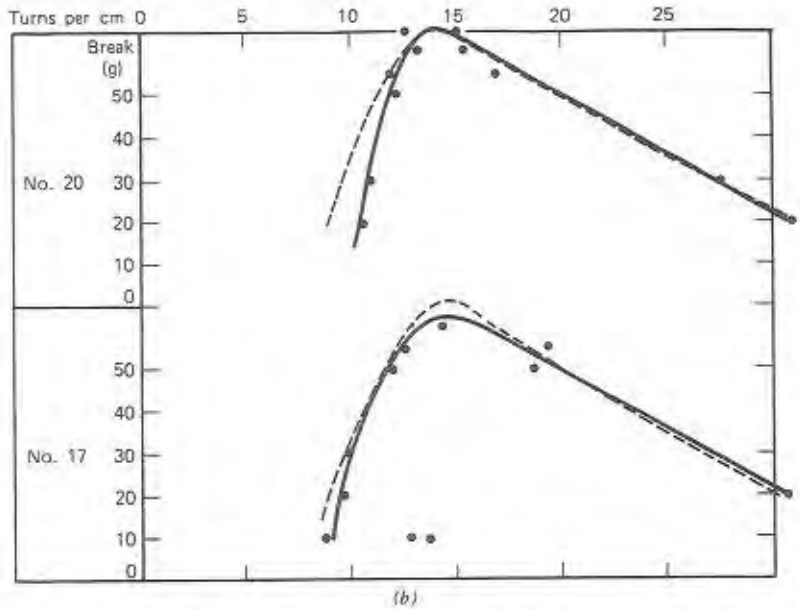


Figure 6.31(*b*). "Part of figure showing breaking loads of two cotton yarn samples at twists obtained by untwisting of yarn spun to high twist. The measurements were made on the twist-yield tester."

results is in conformity with the general predictions made by the qualitative hypothesis put forward by Hearle.

Balls also interested himself in finding out how fiber properties and yarn structure influence the load-extension and the recovery properties of single yarns. He devised an apparatus that he called an "Elastometer" capable of stretching a yarn at a fixed rate of extension. He studied the elasticity, extension, and permanent set of yarns and made a comparison of the properties of cotton and spun "artificial silk" yarns with the behavior of continuous-filament yarns. The results for extension, elasticity, and permanent set in the region of initial extension for various yarns are shown in Figure 6.32. It is clear that the staple fibers "artificial silk" yarn shows lower tension values and greater permanent set than the corresponding continuous-filament yarns. The effect of increase in twist in cotton yarns on the tensile properties is shown in Figure 6.33. As would be expected, the tension in cotton yarns, at a given extension, increases with increase in twist and then follows a downward trend at the highest twist. With the exception of yarns spun with the two lowest twist levels, the permanent set shows little change. The fibers in the low-twist yarns can easily slide over one another, which accounts for their higher permanent set and low breaking levels.

Ex. 2020-098

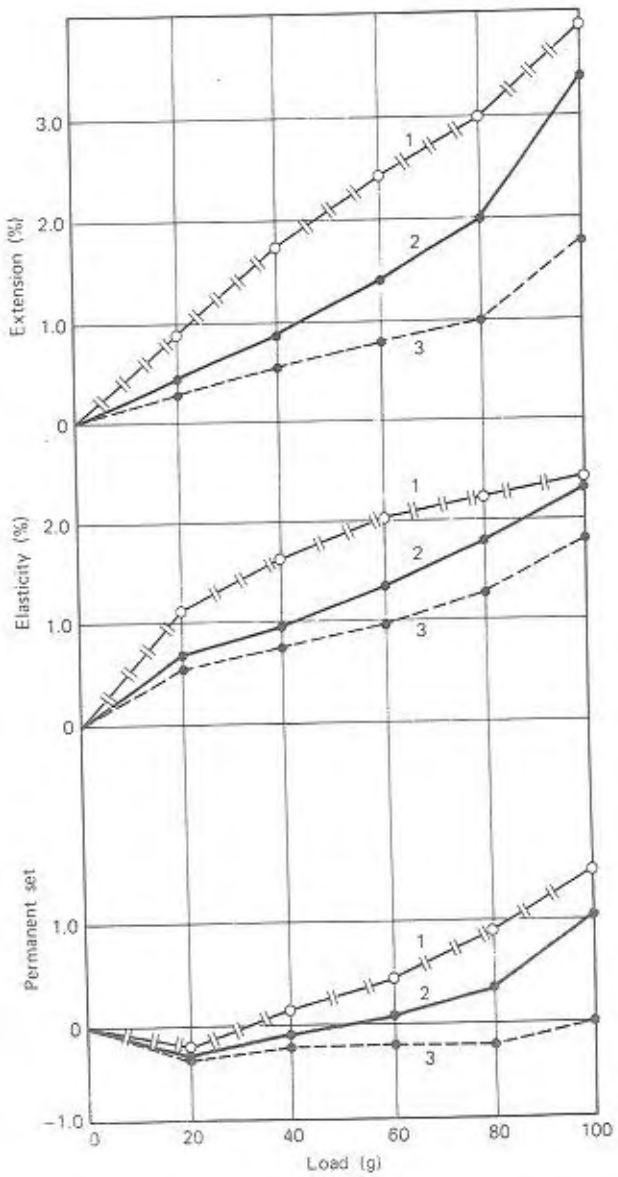


Figure 6.32. Load-extension and elasticity curves for yarns of similar twist and count: 1. cotton yarn; 2. rayon (artificial silk) fibers spun into yarn; 3. rayon (artificial silk) continuous-filament yarn. From Balls (76).

Ex. 2020-099

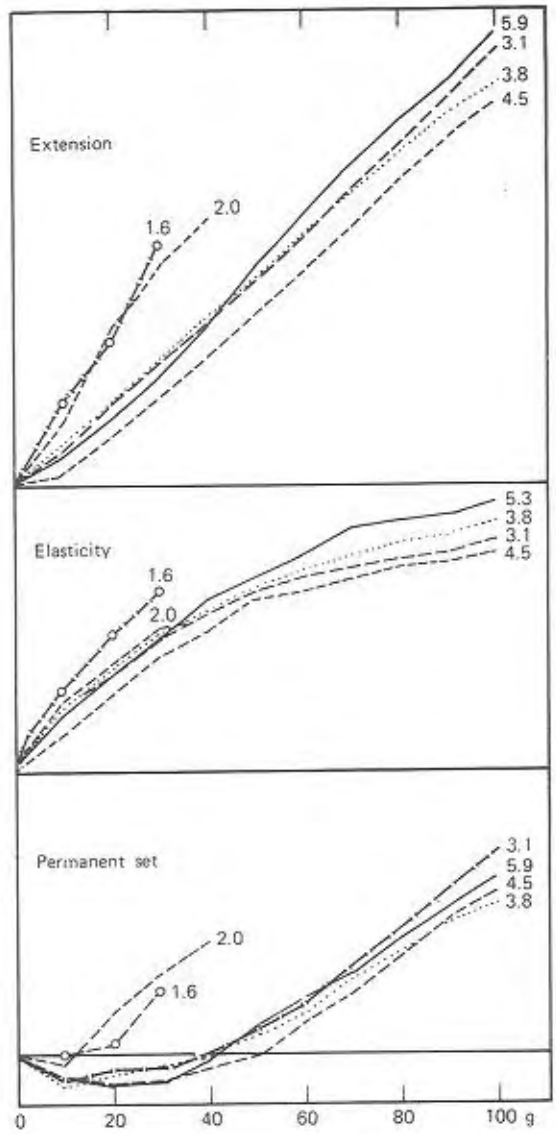


Figure 6.33. Load-elongation and elasticity curves for cotton yarns of different twi factors, expressed in (TPI/count$^{1/2}$). From Balls (76)

Ex. 2020-100

Platt (7) has reported a study of the effect of fiber length and twist on the load-extension properties of acetate yarns. Figure 6.34 shows the curves obtained by Platt. An examination of these curves reveals that the staple yarns show a lower tension at all points of extension and a significantly lower strength and breaking extension than the corresponding continuous-filament yarns. For the staple yarns, there is a smoothing out of the yield point. Increase of twist and decrease of staple length have the effect of causing a reduction of tension at a given extension.

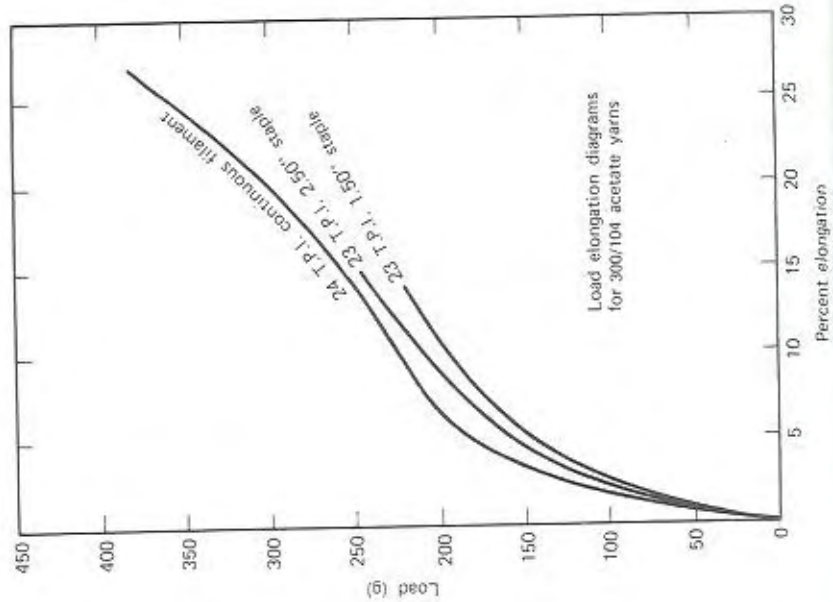
Goodwin (75) has reported an experimental study of the effect of twist on the strength of yarns made from three different fiber types. The skein break factor is maximum at the optimum twist factor and decreases gradually to zero at zero twist; however, Hearle (5) has pointed out that "in the absence of an indication of experimental points, it is not certain whether this is a valid deduction from the observations or merely a reflection of the traditional thinking." The elongation-at-break values show a rapid increase with twist (Figure 6.35) in the low twist region, but tend to level off above the optimum twist multiplier.

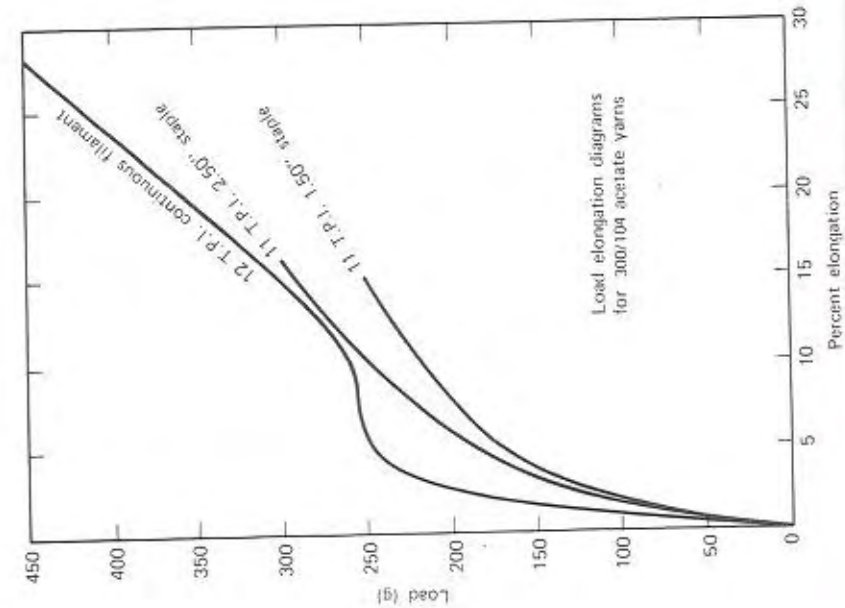
Another important study that has made a significant contribution to the understanding of the twist-yarn strength relationship is by Landstreet et al. (77). In this study, the authors have dealt with the problem of experimentally defining the overall shape of the twist-strength curve (extending from the low-twist region and beyond the area of maximum strength) for cotton rovings and yarns. Some of their results are shown in Figures 6.36 and 6.37. The results shown in Figure 6.36 are of twist-strength curves for seven rovings ranging from 0.5 to 10.0 hank made from Deltapine, 1 1/16 in. cotton. In addition to the number, the twist-strength relationship is also affected by fiber properties, roving age, position on the bobbin, and method of manufacture. In Figure 6.37 are shown the twist-strength curves for 4.0 hank rovings made from cottons differing widely in fiber properties. It is clear from this illustration that the strength increases slowly at low twist (depicting the behavior of the drafting forces of a low-twist roving), but when the twist is increased, the strength changes very rapidly, exhibiting the behavior of a twisted yarn. The results in Figure 6.37*a* show twist-strength plots for the rovings and yarns over a wide range of twist; Figure 6.37*b* shows the twist-strength curve in more detail in the area of maximum strength. These results also show good agreement with the qualitative predictions discussed in the previous section, with the exception of the points of inflection in the maximum strength region.

Holdaway (72) has presented a theoretical model for predicting the strength of single yarns. According to this theory, the mean strength of a yarn can be expressed by the following:

$$F = (\sqrt{M} - 0.0518\, d_m)^2 \;\; \psi\,(T_M) \qquad (6.13)$$

Ex. 2020-101


Load (g)
450
400
350
300
250
200
150
100
50
0
5
10
15
20
25
30
Percent elongation
Load elongation diagrams
for 300/104 acetate yarns
24 T.P.I. continuous filament
23 T.P.I. 2.50" staple
23 T.P.I. 1.50" staple


Load (g)
450
400
350
300
250
200
150
100
50
0
5
10
15
20
25
30
Percent elongation
Load elongation diagrams
for 300/104 acetate yarns
12 T.P.I. continuous filament
11 T.P.I. 2.50" staple
11 T.P.I. 1.50" staple

Ex. 2020-102

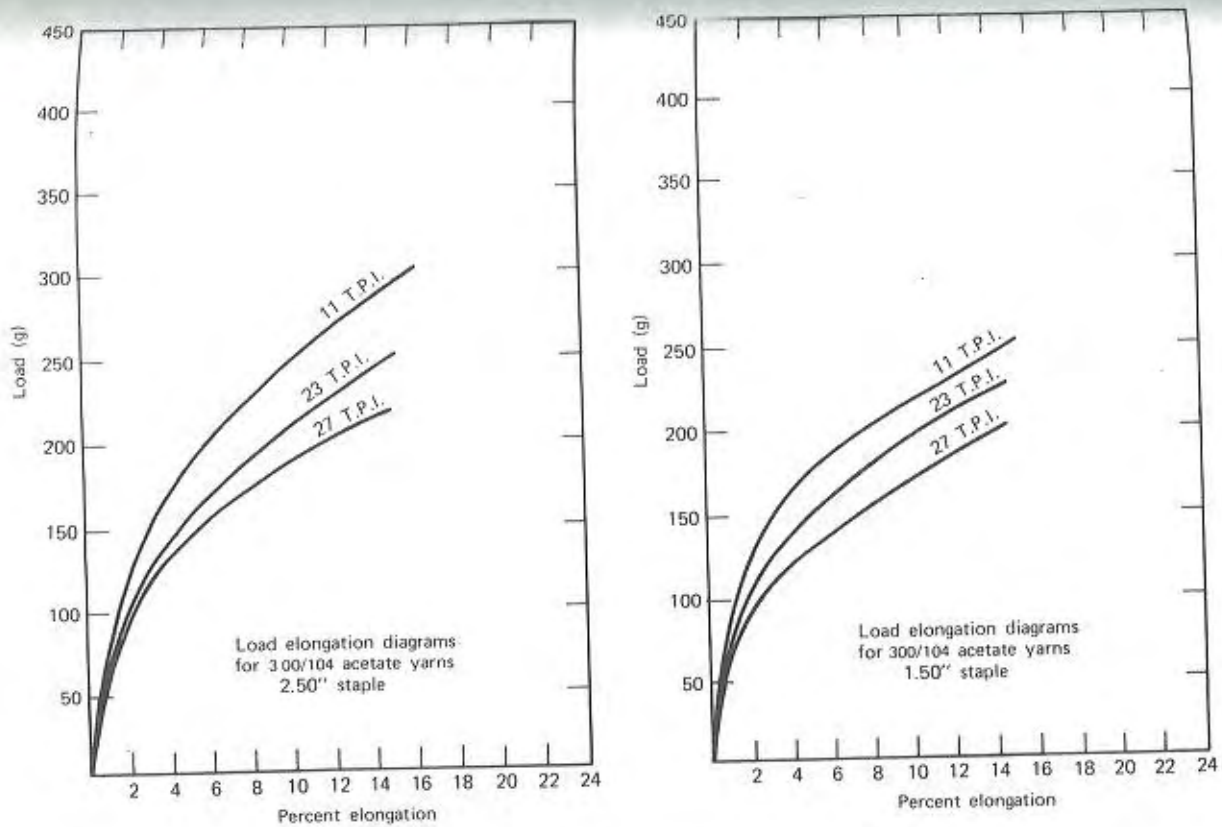


Figure 6.34. Load-elongation curves reproduced from Platt (7).

Ex. 2020-103

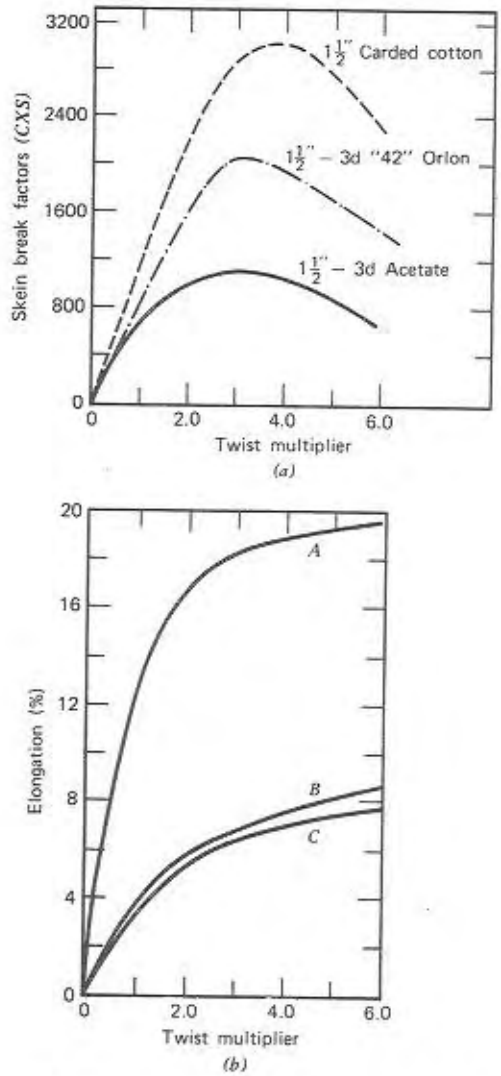


Figure 6.35. (*a*) Effect of twist multiplier on skein break factor of 20s/1 yarn (Courtesy J. A. Goodwin and Lowell Technological Institute), (*b*) effect of twist multiplier on elongation at break. A, 100%, 1½ in. 3 den Orlon 42; B, 100%, 1¼ in. carded cotton; C, 50-50 Orlon-cotton. (Courtesy Lowell Technological Institute.) From Goodwin (75)

Ex. 2020-104

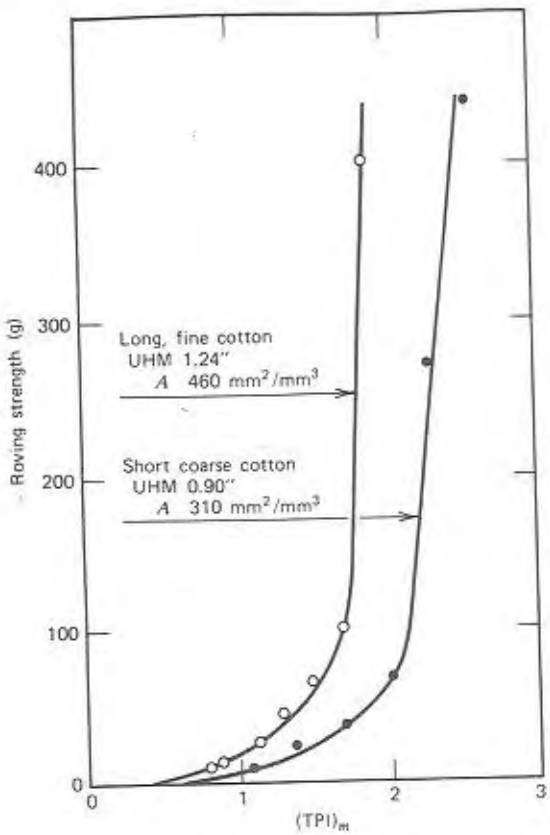


Figure 6.36. Results of Landstreet et al. (77) $(TPI)_m$ is the twist in turns per inch based on yarn length as supplied, $(TPI)_y$ is the twist in turns per inch actual twisted yarn, after twist contraction has taken place. The above diagram shows the twist-strength curves in the region of low twist and depicts the effect of fiber properties on the position of the curves for 2.0 hank roving.

where

F = mean breaking tension in g wt
M = linear density of the pretensioned yarn in tex,
d_m = mean diameter of the single fiber in microns
T_M = the effective twist factor
$= t(\sqrt{M} - 0.0518\, d_m)$
t = turns per inch

and

ψ = a function of T_M.

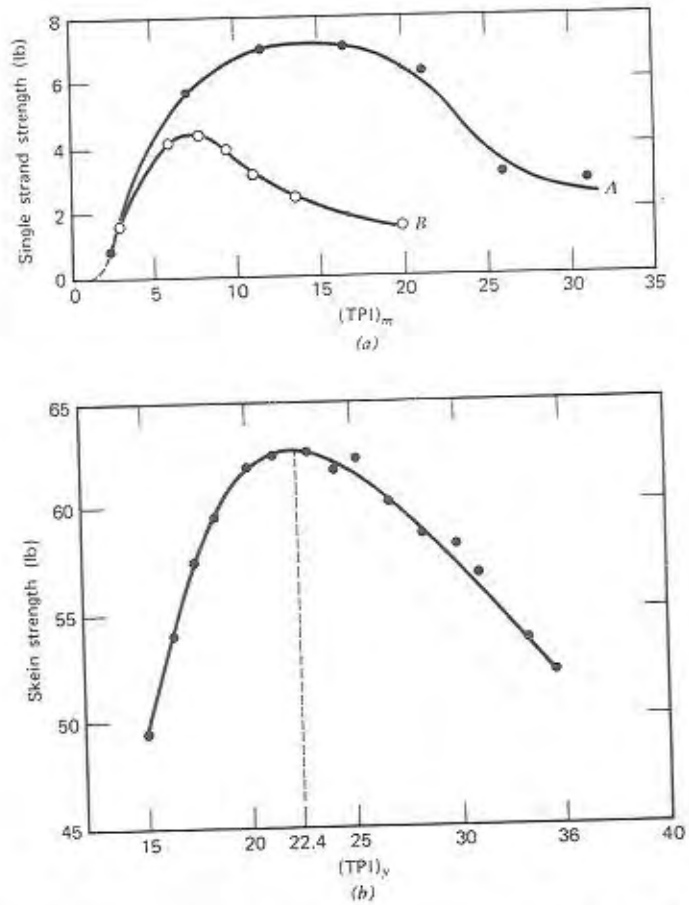


Figure 6.37. From Landstreet et al. (77) (*a*) Twist-strength curves developed over a wide range in twist. Curve A is for a 4s roving given successive increments of twist, becoming coarser due to contraction. Curve B is for yarn spun to an actual count of 4s at all twists, (*b*) twist-strength curve in the region of maximum strength.

In a later publication, Holdaway and Robinson (78) have reported that the theoretical model, in spite of the complexity of spun-yarn structure, is in good agreement with experimentally obtained values of yarn strength. The experimental study was made on worsted single yarns covering a wide range of counts and twists, and the strength and breaking extension measurements were made on a Uster automatic yarn-strength tester. The results of preliminary tests, in which 500 or 600 specimens were tested, demonstrated that the distribution of break-

Ex. 2020-106

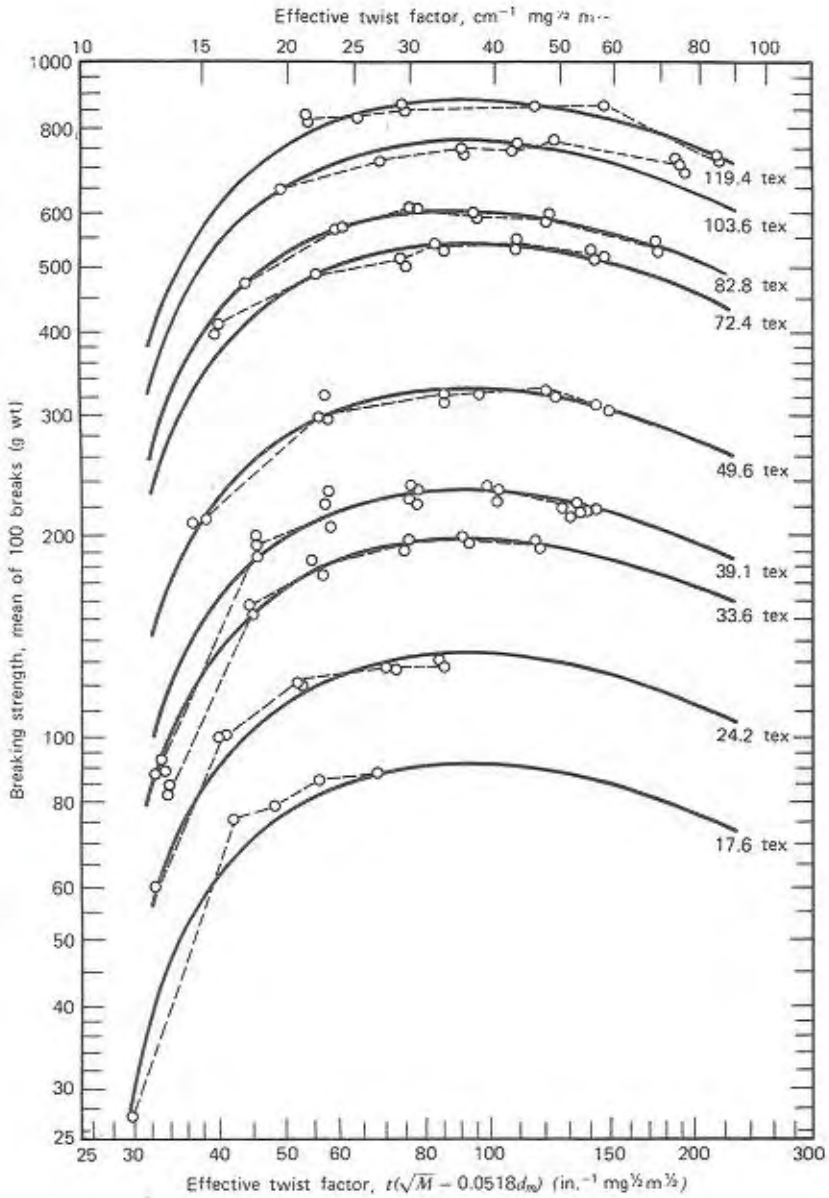
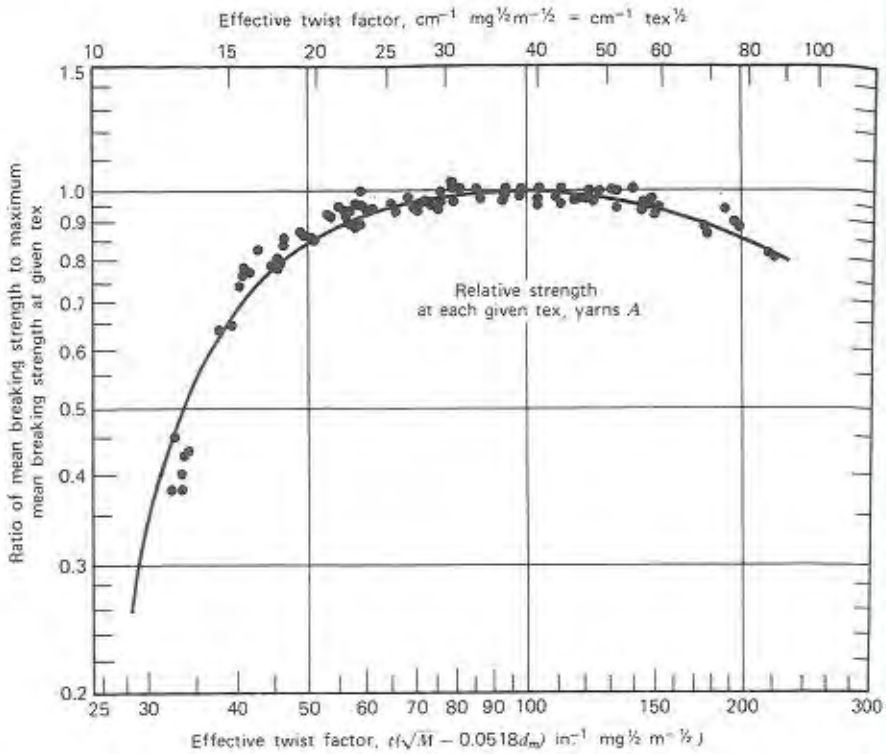


Figure 6.38. Reproduced from Holdaway and Robinson (72) Mean strengths of cap-spun 64s quality wool.

Ex. 2020-107



(b)

Figure 6.38(b). Reproduced from Holdaway and Robinson (72). Composite curve (data from (a) of relative strength.

ing loads is very close to normal except for two yarns of very low and very high twist that show deviation from the normal distribution.

The expression in equation 6.13 predicts that "for yarns of constant linear density, the mean strength will be a function of the effective twist factor." The actual linear density is replaced by an "effective linear density" given by the term $(\sqrt{M} - 0.0518\ d_m)^2$ "from which the outer layer of fibers has been removed to a depth of $d_m\ \mu$"; and the bulk density corresponds to the packing factor of 0.603. This explanation thus differs from the simple view that the breaking load is directly proportional to the linear density. Now if the results according to equation 6.13 are plotted as breaking load F vs. effective twist factor T_M on a logarithmic scale, this should produce curves, for various constant values of $\log_{10} T_m$, that have the same shape but are displaced parallel to the $\log_{10} F$ axis. This is shown in Figure 6.38*a*. On the other hand, if all the results from Figure 6.38*a* are plotted as the ratio of the mean strengths to the

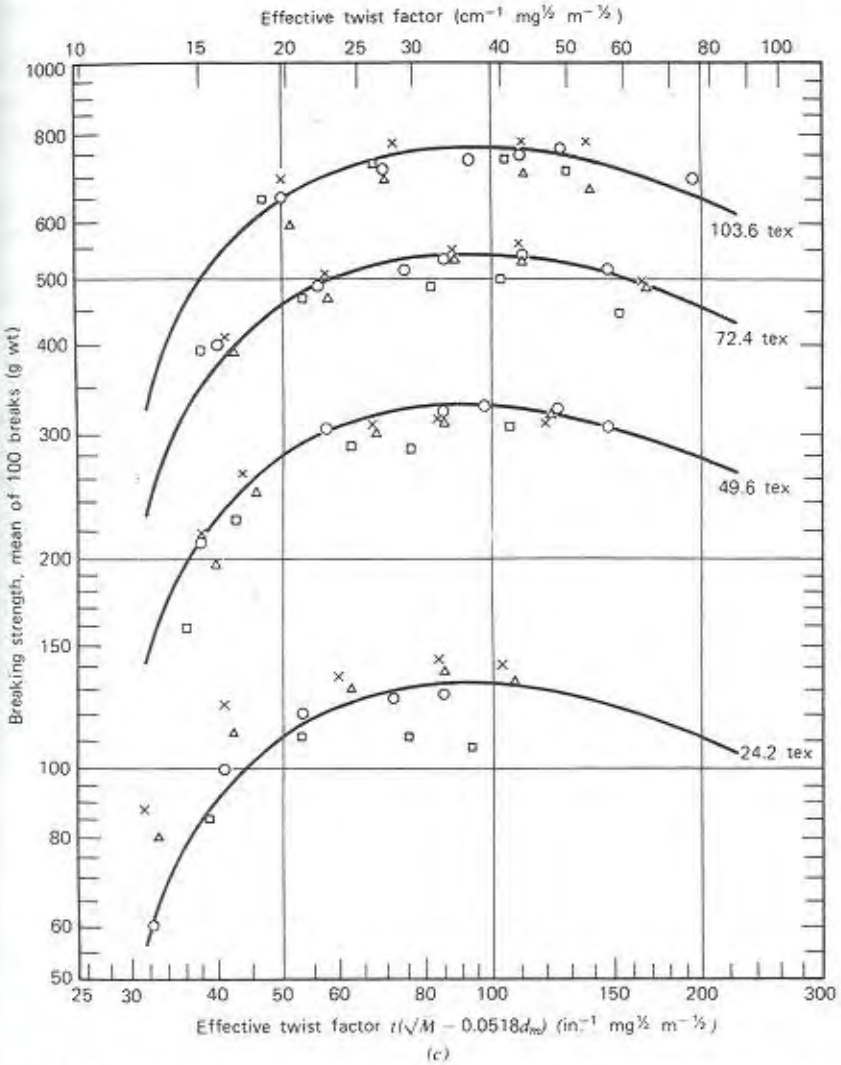


Figure 6.38(*c*). Reproduced from Holdaway and Robinson (72). Mean strengths of yarns from different wool qualities. (○) 64s (20.68μ); (□) 56s; (x) 64s (22.45μ); (△) 70s.

maximum strength values (relative strength) for each yarn count against the effective twist factor, a single curve is obtained, as shown in Figure 6.38*b*. This common curve can be used as a basis for predicting the strength of single yarns of a given fiber, provided an allowance is made to take into account the influence of effective linear density. Figure 6.38*a* demonstrates that the results for

Ex. 2020-109

yarns made from wool of different qualities are fairly close together when plotted in the same manner as Figure 6.38*c*.

Holdaway and Robinson report that it has not been possible to give a precise analysis of the factors that influence the extensibility of yarns to rupture. They state that "where fibers tend to slip rather than break, as in yarns of low twist, the mean length of fibers and the distribution of lengths will clearly be important. On the other hand, in yarns of high twist, where fibers mostly tend to break rather than slip, the yield characteristics of the single fibers will be important. With increasing linear density, there will be a statistical effect tending to reduce the frequency of premature breaks due to weaker-than-average fibers, and this will tend to increase the extensibility." Empirically, they demonstrate that yarn breaking extension varies as (0.71 × function of linear density), and this gives a moderately good fit with the experimental results illustrated in Figure 6.39.

There is one obvious factor that has not been taken into account in any of the work reported so far, and that is the "yarn irregularity," which has a profound influence on the strength of a yarn. It has been shown by Fiori et al. (44-46) that the irregularity of a yarn increases as yarn fineness increases, and Morton (79) has reported that an increase in twist increases yarn irregularity. However, it is known that the strength of a yarn is determined by the weakest place; thus an increase in the irregularity would cause the yarn to exhibit lower strength. In other words, for a better understanding of the structural mechanics of yarns, the breaking load should be expressed in terms of the count and twist at the point of rupture instead of the mean values for the whole yarn.

The relationship of yarn strength to its bulk (count) and twist has been very expertly dealt with by Gregory (65-69) in a series of papers on cotton yarn structure. He has tackled the problem of yarn irregularity along the length of a yarn in relation to its strength by examining artificial yarn elements. The strength of the twisted element is governed by its bulk and twist and by the properties of the constituent fibers (fiber length, fineness, and frictional characteristics). The approach adopted to make an artificial yarn element was to grip a length of roving at two points outside the length of the longest fibers separating the grips to produce a thin place at the middle. This method enables the production of yarn elements under controlled conditions and helps in studying the strength properties over a wide range of weights and twists.

Gregory has discussed a procedure to relate the measured breaking load to the weight and twist of the thin place in terms of the weight and twist of the whole yarn specimen between the grips. The method is similar in principle to the engineer's "necked" sample for strength testing. A typical plot of breaking length (count × strength, which is numerically equivalent to tenacity) against twist for yarn elements prepared from combed Giza 12, 6.75 hank rovings is shown in Figure 6.40. This illustration also shows the variation of count with twist. The maximum breaking length is well defined, and the slight reduction in

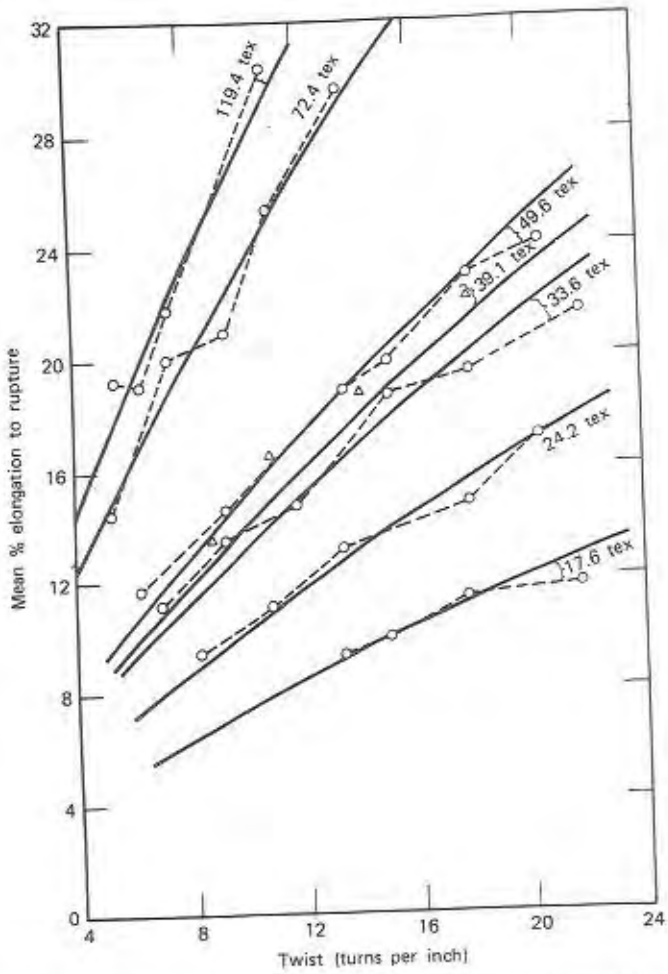


Figure 6.39. Breaking extension vs. twist. From Holdaway and Robinson (72)

count as the twist increases does not obscure the general trend observed for the variation of strength with twist. Gregory also reports that the yarn elements prepared from a particular cotton show a reduction in maximum strength as the count becomes finer. He found that the twist factors for maximum strength vary from 3.9 for the combed St. Vincent cotton to 7.5 for carded Bengals. The twist factors for maximum strength of yarn elements were found to be much greater than the twist factors to which the yarns from the cotton were normally spun.

From consideration of the influence of fiber properties on the twist required to produce maximum strength in twisted yarns, Gregory suggested that the twist

Ex. 2020-111

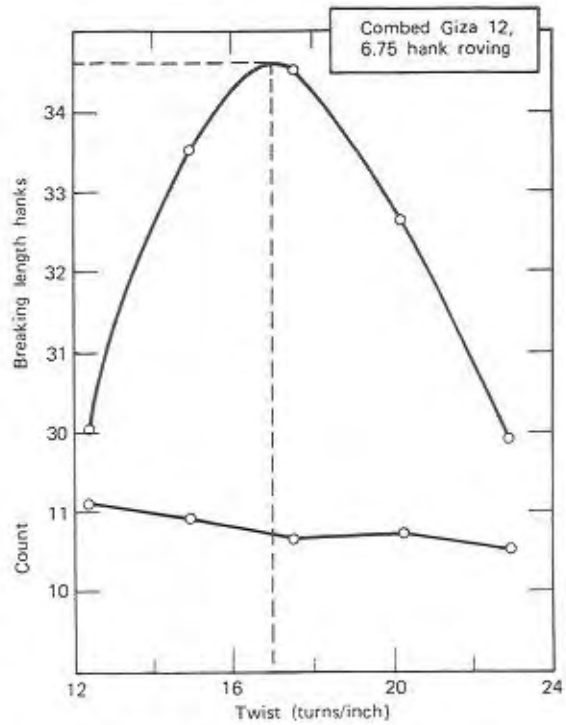


Figure 6.40. Effect of twist on the strength of artificial yarn elements. From Gregory (67)

factor for maximum strength is a function of the product of fiber length, L_1, coefficient of friction, μ, and surface area per unit mass, S. Empirically, the maximum strength is expressed in the form:

$$B = L_1 \ \mu S \tag{6.14}$$

where L_1 is a biased mean fiber length equal to $L + \sigma^2/L$
where

L = actual mean fiber length, and

σ = standard deviation of fiber length.

A plot of B vs. twist factor for maximum strength is shown in Figure 6.41. The dotted line is derived from Sullivan's (64) theoretical curves. The product $B = L_1 \mu S$ defines a critical pressure at which fibers just begin to break.

The concluding part of the study reported in this series of papers deals with a very important aspect that has a great practical value. It covers a very wide area

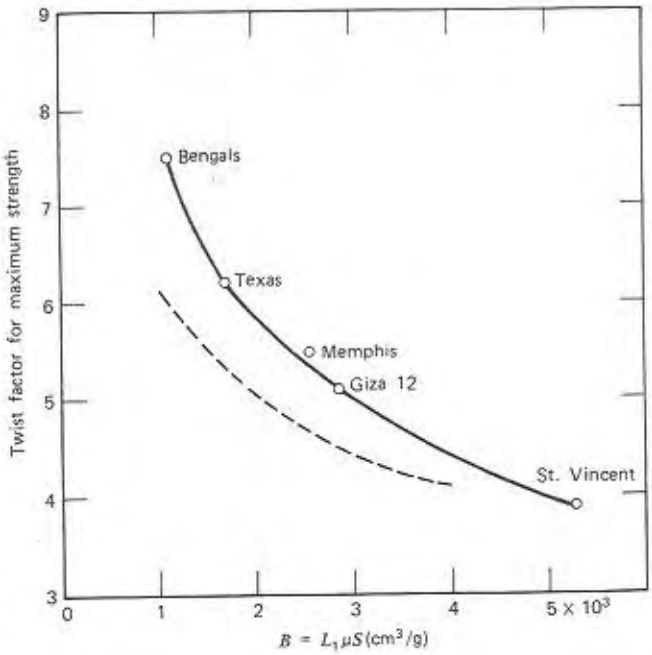


Figure 6.41. Gregory's (68) relationship of twist factor with a function of length, friction, and fineness. The dotted line depicts Sullivan's theoretical relationship.

Table 6.10. Comparative Values of Maximum Breaking Length for Different Cotton Fiber Structures (in kilometers, corrected to 10 sec break)[a]

Structure	Cotton				Range of Ratio St. Vincent
	St. Vincent	Giza 12	Texas	Bengals	Bengals
Single fibers					
1 mm test length	64.0	54.5	41.3	39.6	1.62
1 cm test length	40.7	38.9	27.6	21.1	1.93
Parallel bundle Pressley	47.8	39.7	34.5	32.3	1.48
Twisted yarn element	34.1	26.5	19.1	13.1	2.60
Cabled yarn	32.2	26.2	19.3	12.4	2.59
Cloth weft strip	29.0	20.2	14.0	10.4	2.79
Single yarn					
Single thread test	28.7	19.8	13.2	8.5	3.38
Lea test	24.3	17.8	10.2	5.6	4.34
Range of ratio, 1 mm fiber/lea	2.64	3.06	4.05	7.07	

[a]From Gregory (69).

Ex. 2020-113

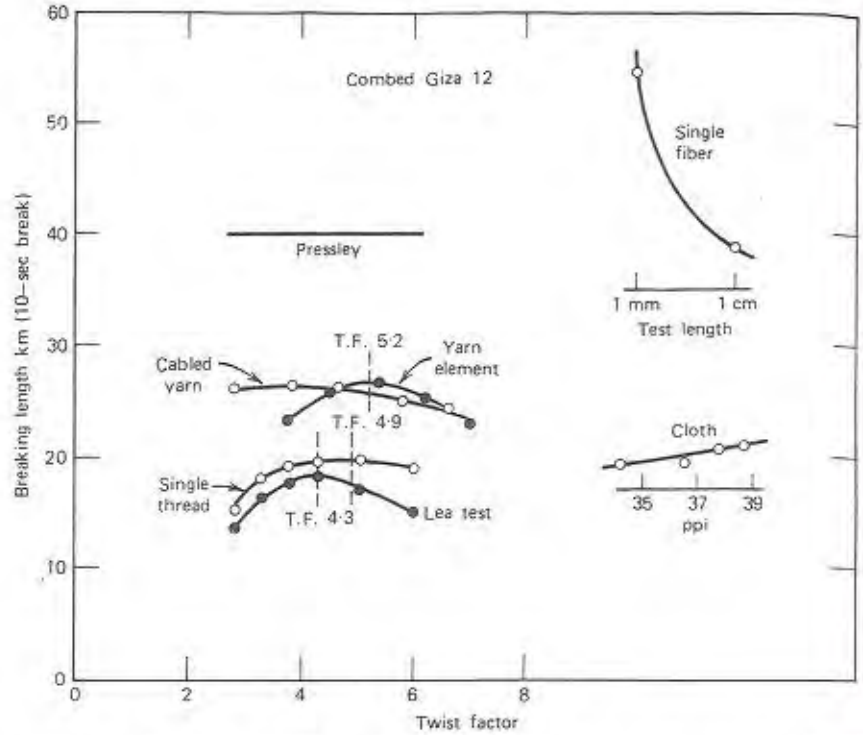


Figure 6.42. Maximum breaking length vs. twist factor for different structures made from cotton–85 count yarn. From Gregory (69)

in which a review is made of the strength of cotton fiber in a variety of textile structures, namely, single fiber, parallel bundles of fibers, twisted bundles of fibers, yarns (both singles and cabled), and cloth. Figure 6.42 shows typical curves for combed Giza 12 yarn spun in 8s (≃ 74 tex) single count, and the results for the comparison of cotton fiber structures of different types are listed in Table 6.10 and 6.11 and shown in Figure 6.43.

A recent study of the efficiency of fiber-to-yarn strength has been reported by Hurley et al. (61). The yarns were spun to cotton counts of 4.1, 6.2, 9.2, and 14 (≃ 144, 95, 64, and 42 tex), each with a twist multiplier of 3.5 (≃ 34 $tex^{1/2}$ × t.p.c). The results for the breaking force and intrinsic tenacity (yarn tenacity divided by the denier of the thin section in the region of rupture) are shown in Figure 6.44. The denier of yarn in the region of rupture was obtained on an 8-mm length by the Uster Evenness tester. Strength measurements were made on an Instron Tensile Tester and the Uster Single End Strength Tester. The results for the efficiency of fiber-to-yarn strength translation and the strength loss

Table 6.11. Breaking Lengths Expressed as Percentage of Pressley Value[a]

Structure and Text	Cotton			
	St. Vincent	Giza 12	Texas	Bengals
Single fiber: 1 mm	134	137	120	123
Pressley	100	100	100	100
Single fiber: 1 cm	85	98	80	65
Twisted yarn element	71	67	55	41
Cabled yarn	67	66	56	38
Cloth weft strip	61	51	41	32
Single yarn: single thread test	60	50	38	26
8s/3: low-twist single thread	57	47	36	23
Single yarn: lea test	51	45	30	17

[a]From Gregory (69).

factor are listed in Table 6.12. These results are in accord with the accepted view that the strength properties of the yarn are determined by the weakest place.

Other studies dealing with the variation of strength with yarn irregularity have been reported by Hamby et al. (80) and El-Behery and Mansour (62). In these studies, the single-end strength was measured on the Uster Dynamometer, and the yarn irregularity tests were made on the Uster Evenness tester. Some typical

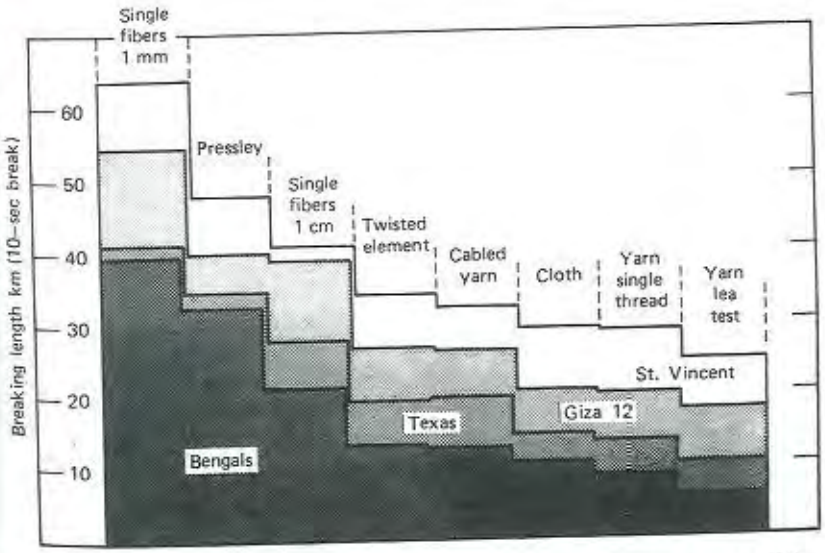


Figure 6.43. Strength relationships of different cotton structures. From Gregory (69)

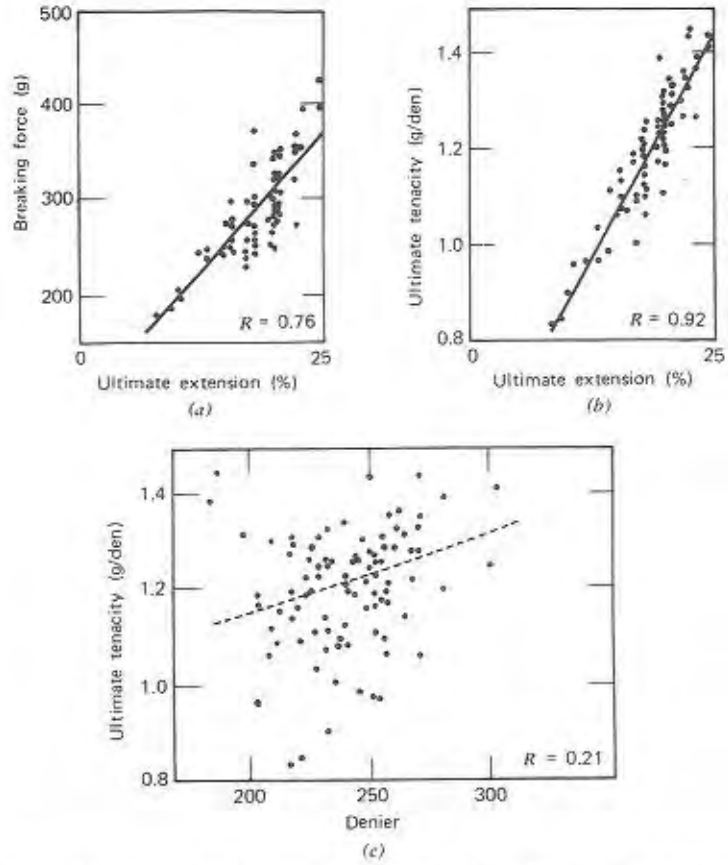


Figure 6.44. Variation of tensile properties of yarns–20-in length specimens broken on Uster Single end strength Tester. From Hurley et al. (61)

results for the variation of yarn strength with mass variation and yarn irregularity index are presented in Figure 6.45 (62).

Hearle and El-Sheikh (74) have reported a study of the tensile properties of twisted worsted and woolen rovings. They have discussed their experimental results in terms of the qualitative explanation of the behavior of spun yarns. A comparison of the experimental results with the equation developed for predicting the tensile properties of spun yarns by Hearle (73) has also been made. The experimental yarns were made by twisting the worsted and woolen roving on a continuous laboratory twister. This method helped to minimize the effects of yarn irregularity.

A typical load-elongation curve and the parameters used to characterize the tensile behavior of spun yarn are illustrated in Figure 6.46. Table 6.13 lists the

Ex. 2020-116

Table 6.12. Intrinsic Tensile Properties and Loss Factors for Some Acrylic Yarns[a]

Single-Fiber Properties[b]	Specimen Test Length (in.) 0.2	1.0
Denier	5.97 (14)	5.85 (13)
Ultimate Tenacity (g/den)	2.69 (13)	2.58 (15)
Ultimate Extensibility (%)		29 (22)

Yarn properties	Yarn Cotton Count 4.1/1	6.2/1	9.2/1	14/1
Skein strength, lb (120-yd skein)	603 (3)	360 (3)	212 (9)	106 (3)
Single end strength (g)	2148 (7)	1302 (9)	813 (10)	447 (18)
Intrinsic tenacity (T_i^c g/den)	2.17 (4)	2.10 (4)	2.07 (8)	2.16 (6)
Skein translation efficiency ($TE_{skeins}{}^c$ %)	44.6 (4)	42.5 (3)	37.7 (6)	29.7 (3)
Single end translation efficiency ($TE_{se}{}^c$ %)	60.8 (7)	55.6 (9)	51.6 (10)	43.2 (18)
Intrinsic translation efficiency ($TE_i{}^c$, %)	79.3 (4)	76.9 (4)	75.8 (8)	79.1 (6)
Skein loss factor (L_{skeins}, %)	34.7 (7)	34.4 (6)	38.1 (10)	49.4 (6)
Single end loss factor (L_{se}, %)	18.5 (23)	21.3 (25)	24.2 (22)	35.8 (22)

[a]From Hurley et al. (61).
[b]Tests carried out at 70°F, 65% RH and a rate of extension of 100%/minute.
[c]Based on single-fiber tenacity at a gauge length of 0.2 in.
Numbers in ( ) indicate the CV of the measurement.

Table 6.13. Spun Yarn Properties[a]

Twist Angle (degrees)	Linear Density (tex)	Yarn Crimp (%)	Yarn Modulus (g/tex)	At Max. Tension Stress (g/tex)	At Max. Tension Extension (%)	At Break Stress (g/tex)	At Break Extension (%)
10	271	1.5	21	0.4	2.8		
15	308	3.0	98	2.5	3.0		
20	270	2.9	127	5.4	6.8	3.9	15.6
25	285	3.5	124	6.8	30.6	6.6	33.1
30	274	3.3	130	7.5	23.1	7.4	29.4
35	276	4.4	86	7.1	31.5	7.0	32.4
40	330	3.7	55	7.9	47.2	7.9	47.7
50	436	1.3	10	4.6	66.5	4.6	66.6
			Yarn No. 4, Woollen				
15	183	0.9	13	1.1	21.7		
20	185	0.8	41	1.8	15.7	1.8	17.3
25	191	1.8	34	2.5	20.0	2.5	20.7
30	193	1.5	39	3.0	21.7	3.0	22.0
35	202	1.3	41	3.4	25.9	3.4	26.3
40	202	2.3	46	4.1	30.8	4.1	31.3
50	225	3.1	35	3.5	25.3		

[a]From Hearle and El-Sheikh (74).

Ex. 2020-117

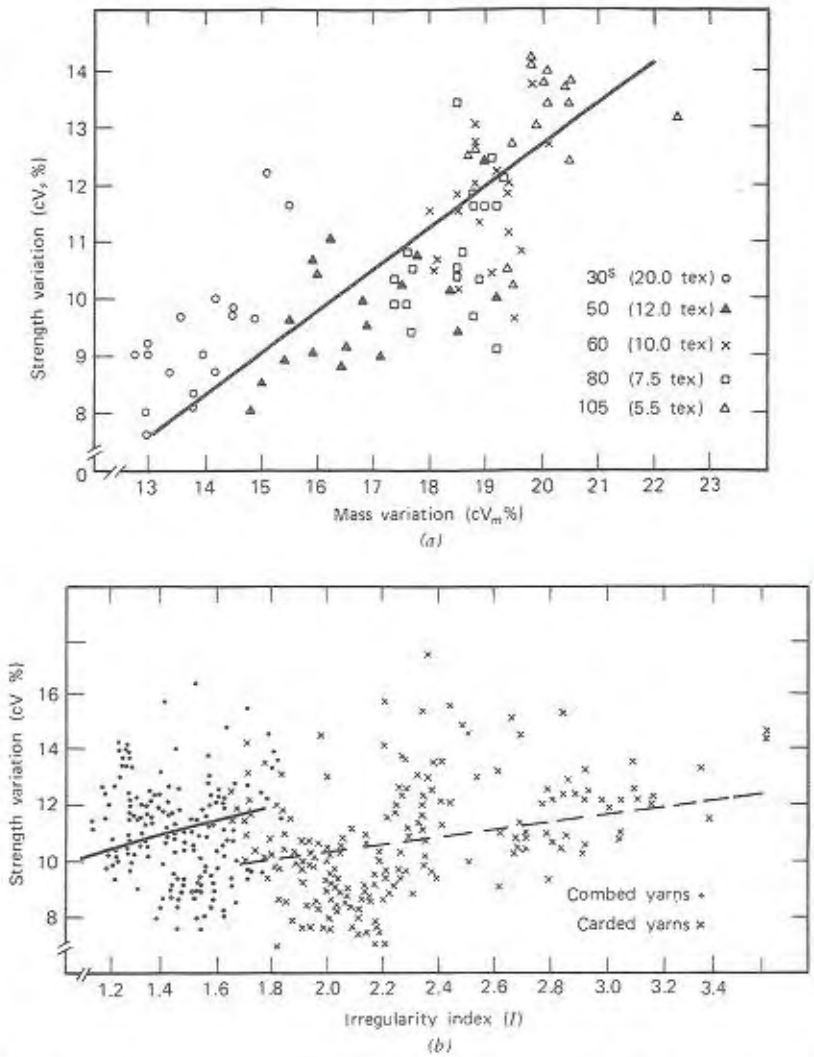


Figure 6.45. Typical results of El-Behery and Mansour (62). (*a*) Strength variation vs. mass variation for combed cotton yarns, (*b*) strength variation vs. yarn irregularity index for cotton yarns.

Ex. 2020-118

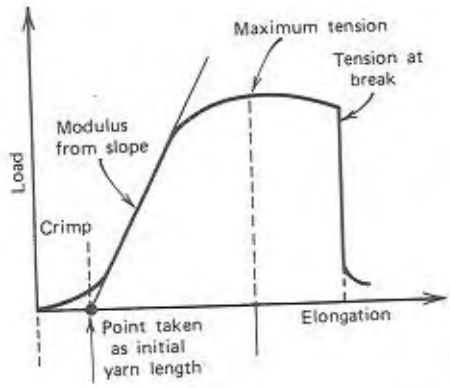


Figure 6.46. Representative load-elongation curve for a yarn. From Hearle and El-sheikh (74)

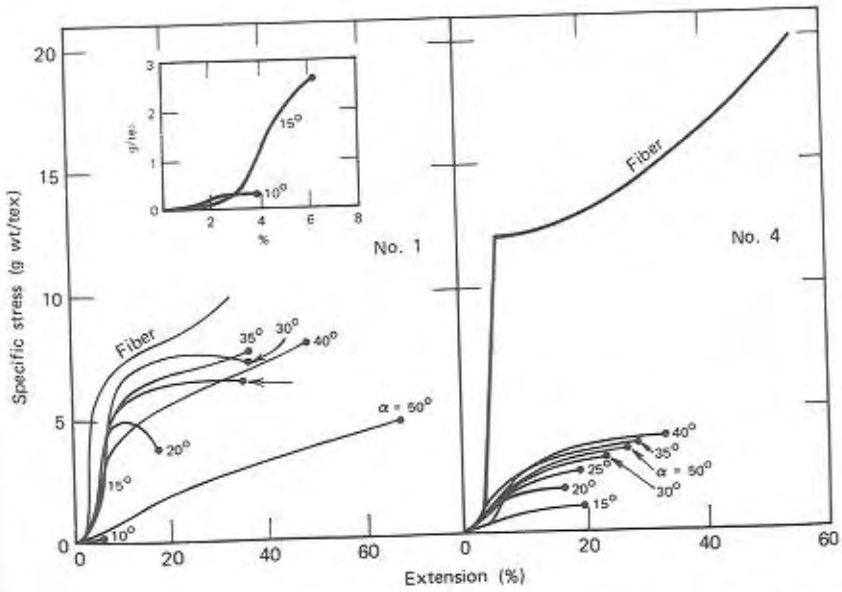


Figure 6.47. Stress-strain curves of yarn and fibers. No. 1. Worsted. No. 4. Woolen. From Hearle and El-Sheikh (74)

Ex. 2020-119

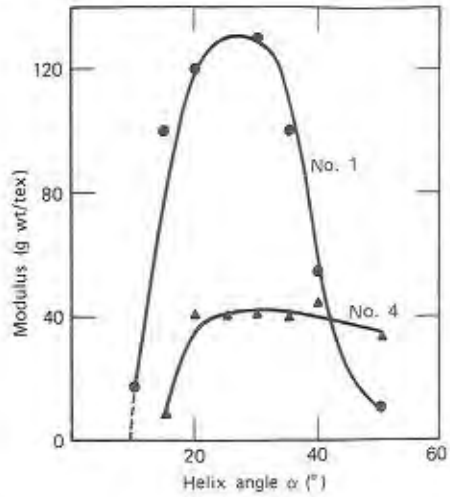


Figure 6.48. Variation of modulus with twist. From Hearle and El-Sheikh (74)

values of these parameters, and the corresponding stress-strain curves are illustrated in Figure 6.47. The plot of modulus vs. twist (twist angle) is shown in figure 6.48. It is evident from these relationships that the general trend of the curves in Figure 6.47 is similar to the form predicted in Figure 6.46.

Hearle and El-Sheikh (74) have presented arguments explaining the experimental results in light of a proposed theory, and for the sake of clarity their discussion is reproduced here.

In the worsted yarn No. 1 there is little resistance to slippage when the twist angle is 10°, but it subsequently builds up to achieve maximum effect at a twist angle of about 30°. Thereafter the yarn tension levels fall due to obliquity. The modulus of the woollen yarn No. 4, is much lower and this must be due partly to the more irregular fibre arrangement and partly to the greater proportion of short fibres. The twist angle for maximum modulus in the woollen yarn is nearer 40°, although the curve is very flat between 20° and 50°. In both yarns the minimum twist angle which is likely to be practically usable is about 20°.

In both yarns, the initial region of easy extension (called yarn crimp) generally increases in amount as the twist is increased.

Yarn tenacity, whether indicated by the maximum load or the load at which there is a sharp break, rises to a maximum value at around 40°. Breaking extension is low in the very weak yarns with low twist, and continues to rise steadily as twist is increased. This is similar to the behaviour of polyamide, polyester and acrylic filament yarns where the rising breaking extension has been attributed to the contraction of the yarn following the release of the twisting tension: in parti-

Ex. 2020-120

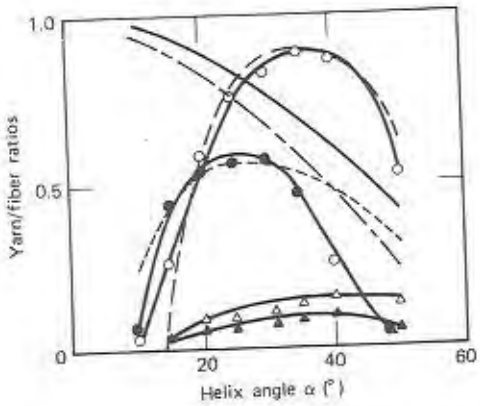


Figure 6.49. Comparison of theory and experiment. (●) No. 1, yarn modulus; (▲) No. 4, fiber modulus; (○) No. 1, yarn tenacity; (△) No. 4, fiber tenacity. (———) $\cos^2 \alpha$; (– —)F (α, σ_1, σ_y); (——–) $\cos^2 \alpha$ (1-0.122 cosec α); (– – –) 2.3 $\cos^2 \alpha$ (1-0.0.24 cosec α).

cular, fibres on the surface of the yarn following a longer path are assumed to be under strain during twisting, and then subsequently to contract to their unstrained length with a resultant buckling of the centre fibres. This allows an additional extension of the centre fibres before they come under strain and are extended to break. This behaviour is not shown by filament yarns with poor elastic recovery (where permanent deformation occurs); but in view of wool's good elastic recovery it is not surprising that it is now shown up by wool yarns.

Figure 10 (6.49) shows a comparison between the experimental results and theoretical relations. The variation of modulus of the worsted yarn shows a good agreement with the relation previously discussed, with K equal to 0.133, except for a rapid fall at high twist angle. However, the best relation $F(\alpha, \sigma_1, \sigma_y,)$ for continuous filament yarns, does decrease more rapidly from the $\cos^2\alpha$ relation used in the approximate theory.

The ratio of yarn tenacity to fibre tenacity in the worsted yarn rises to a much higher value than would be expected theoretically. Indeed it approaches a value of 1 at a twist angle of 40°. This means that the fibres in the twisted yarn are acting as if they were much stronger than appears from single fibre tests. This must be due to the fact that weak places in the fibres are being supported by the grip of neighboring fibres: they will not be extended to the local breaking extension and will be able to contribute to yarn tension. Another way of regarding the mutual support effect is to note that in single fibre tests each fibre can break at its own weakest place, but in a coherent yarn the break must occur at a particular point along the length of the yarn. The theoretical relation can be empirically modified to include this effect by putting:

Ex. 2020-121

$$\frac{\text{Yarn tenacity}}{\text{Fibre tenacity}} = A \cos^2 \alpha \, (1 - K \operatorname{cosec} \alpha)$$

where A is the ratio of effective fibre strength to measured fibre strength. This equation shows a reasonable fit with A = 2.3 and K = 0.24.

The same arguments do not apply to the modulus which is determined by strain all along the fibre, and not by the effect of an isolated weak place.

The woollen yarns show much lower moduli and tenacities and it is difficult to apply the theory in a meaningful way.

Hearle and El-Sheikh (74) conclude:

. . . that the tensile behaviour of twist worsted yarns can be explained by the effects of obliquity, which have been worked out for continuous filament yarns, combined with the effects of fibre slippage, which cause a loss in contribution to yarn tension. Yarn properties approach those of filament yarns more closely as yarn twist, fibre length, and fibre friction increase. At very low twists the forces generated are inadequate to cause the yarn to be a self-locking structure. The investigation shows that the idealised cylindrical helical yarn structure forms a

Table 6.14. Twist Factors at Optimum Yarn twist [a] ($tex^{1/2} \times$ turns/cm)

			Tensile Test[b]		Fatigue Test[c]	
Yarns	Linear Density (tex)	Spinning System	Maximum Strength	Maximum Elongation	Maximum Strength	Maximum Elongation
1	35.7	Conventional[d]	50.6	50.6	55.3	42.7
2	35.7	Open-end	54.7	54.7	58.5	47.4
3	25.0	Conventional	49.3	49.3	56.2	40.4
4	25.0	Open-end	57.2	57.2	63.2	47.4
5	20.0	Conventional	49.3	49.3	56.2	40.4
6	20.0	Open-end	56.9	56.9	64.8	53.7
7	16.7	Conventional	48.7	48.7	53.7	42.7
8	16.7	Open-end	55.9	55.9	63.2	52.5
9	31.3	Conventional	47.4	47.4	52.1	39.5
10	28.6	Open-end	55.3	55.3	56.9	53.7
11	20.0	Conventional	47.4	47.4	53.7	39.5
12	20.0	Open-end	54.7	54.7	61.6	50.6

[a] From Barella (83).
[b] Pendulum-type strength tester.
[c] Fatigue tests were carried out at 250 cycles/min.: relative extension 1.66% with a load of 2 gf/tex on a Comptiss apparatus.
[d] Ring spun yarns.

Ex. 2020-122

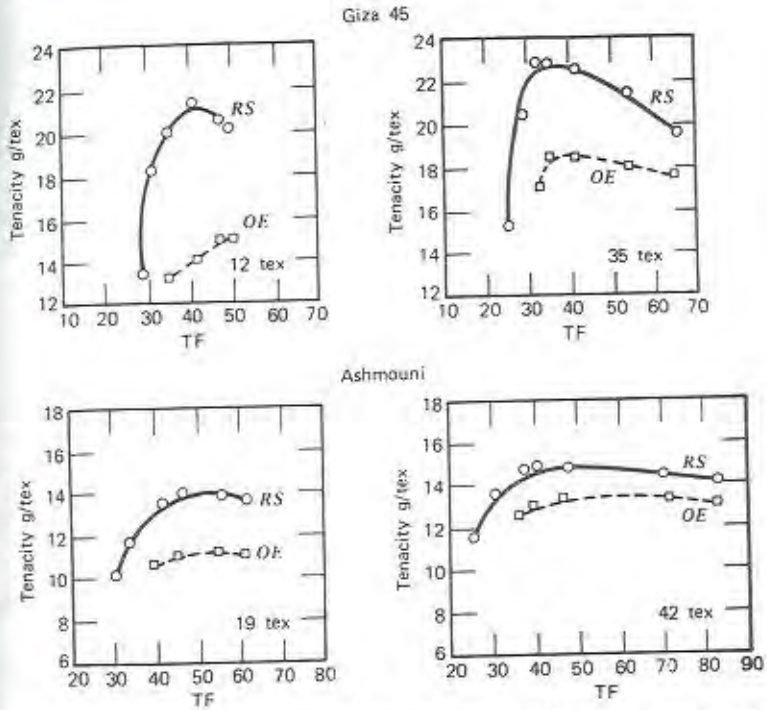


Figure 6.50. Reproduced from Sultan and El-Hawary (82). Yarn tenacity vs. twist (T.F.–tex$^{1/2}$ × turns/cm.)

reasonable model for theoretical study, provided that the important property of fibre migration is included.

This discussion of the structure and the mechanical properties of staple yarns would not be complete without a reference to open-end spun yarns, which form a significant part of the textile scene. The open-end spun yarns have a distinct structure that differs from that observed in ring-spun yarns. The most basic structural differences that are observed are in the fiber extent, fiber migration, and the fiber-packing density, which collectively determine the tensile behavior of yarns. Hearle et al. (81) report that open-end yarns (spun on the air vortex and drum machines) have a relatively high proportion of hooked and entangled fibers, which tends to reduce the fiber extent. This has a detrimental effect on the tenacity of yarns. Because of the mechanism of formation (Chapter 9), fiber migration in an open-end spun yarn tends to be more local, and the yarn is made up of layers. This aspect of the structure affects the degree of fiber interlocking (discussed in the last chapter) within the body of a yarn, which in turn

Ex. 2020-123

influences the tensile and other physical characteristics of the yarn. Sultan and El-Hawary (82) have reported a study on the comparison of the properties of open-end spun yarns and the ring-spun yarns from two Egyptian cottons. Figure 6.50 shows the twist-strength curves of open-end and ring-spun yarns. It is clear from the results that the twist-strength curves from the open-end spun yarns are flatter in the region of maximum strength. The twist factors for maximum strength for these yarns are generally higher by about 12% than the corresponding ring-spun yarns. These results are in agreement with those reported by Barella (83), as shown in Table 6.14 (in which the results for the optimum twist for maximum strength for open-end and ring-spun yarns are listed). The breaking extension of open-end spun yarns is also found to be 10-40% higher than for the corresponding ring spun yarns made at the same twist factor. These differences in properties result from variations in structural parameters discussed earlier.

REFERENCES

1. Backer, S. in Hearle, J. W. S., P. Grosberg, and S. Backer (Eds.), *Structural Mechanics of Yarns and Fabrics*, Volume 1. Wiley-Interscience, New York, 1969.
2. Gregory, J., *J. Text. Inst.*, 1953, 44, T515.
3. Meredith, R., *J. Text. Inst.*, 1945, 36, T107.
4. A.S.T.M., *1971 Book of ASTM Standards*, Part 24, Textile Materials–General Methods and Definitions, American Society for Testing and Materials, Philadelphia.
5. Hearle, J. W. S., in Hearle, J. W. S., P. Grosberg, and S. Backer (Eds.), *Structural Mechanics of Fibers, Yarns, and Fabrics*, Volume 1. Wiley-Interscience, New York, 1969.
6. Gegauff, C., *Bull. Soc. Ind. Mulhouse*, 1907, 77, 153.
7. Platt, M. M., *Text. Res. J.*, 1950, 20, 1.
8. Platt, M. M., *Text. Res. J.*, 1950, 20, 665.
9. Hearle, J. W. S., *J. Text. Inst.*, 1958, 49, T389.
10. Sullivan, R. R., *J. Appl. Phys.*, 1942, 13, 157.
11. Grosberg, P., *J. Text. Inst.*, 1963, 54, T223.
12. Hearle, J. W. S., H. M. A. E. El-Behery, and V. M. Thakur, *J. Text. Inst.*, 1961, 52, T197.
13. Treloar, L. R. G. and J. W. S. Hearle, *J. Text. Inst.*, 1962, 53, T446.
14. Treloar, L. R. G., *Brit. J. Appl. Phys.*, 1962, 13, 314.
15. Wilson, N. and L. R. G. Treloar, *Brit. J. Phys.*, 1961, 12, 147.
16. Wilson, N., *Brit. J. Appl. Phys.*, 1962, 13, 323.
17. Treloar, L. R. G., and Riding, G., *J. Text. Inst.*, 1963, 54, T156.
18. Symes, W. S., *J. Text. Inst.*, 1959, 50, T241.
19. Kilby, W. F., *J. Text. Inst.*, 1964, 55, T589.
20. Treloar, L. R. G., *J. Text. Inst.*, 1965, 56, T359.

21. Treloar, L. R. G., *J. Text. Inst.*, 1965, **56**, T477.
22. Wilson, N., *Brit. Appl. Phys.*, 1965, **16**, 1889.
23. Maginnis, J. B., *Text. Res. J.*, 1950, **20**, 165.
24. Hamburger, W. J., *Text. Res. J.*, 1948, **18**, 705.
25. Shrinagbhushan, *Text. Digest*, 1956, **17**, 4.
26. Grover, E. G., and D. S. Hamby, *Textile Processing of Synthetics–Continuous Filament*, School of Textiles, North Carolina State College, 1956.
27. Taylor, J. R. et al., WADC Technical Report No. 52-55, March 1952.
28. Alexander, F. J., and C. H. Sturley, *J. Text. Inst.*, 1952, **43**, Proc. 1.
29. Hearle, J. W. S., and V. M. Thakur, *J. Text. Inst.*, 1961, **52**, T49.
30. Kilby, W. F., *J. Text. Inst.*, 1964, **55**, T589.
31. Hearle, J. W. S., H. M. A. E. El-Behery, and V. M. Thakur, *J. Text. Inst.*, 1959, **50**, T83.
32. Hearle, J. W. S., H. M. A. E. El-Behery, and V. M. Thakur, *J. Text. Inst.*, 1960, **51**, T229.
33. Treloar, L. R. G. and G. Riding, *J. Text. Inst.*, 1963, **54**, T156.
34. Riding, G. and N. Wilson, *J. Text. Inst.*, 1965, **56**, T205.
35. Backer, S. and C. J. Monego, *Text. Res. J.*, 1968, **38**, 762.
36. Pierce, F. T., *J. Text. Inst.*, 1926, **17**, T355.
37. Turner, A. J. and V. Venkataraman, *J. Text. Inst.*, 1931, **22**, T197.
38. Stanbury, G. R. and W. G. Byerley, *J. Text. Inst.*, 1934, **25**, T295.
39. Millard, F., *J. Text. Inst.*, 1951, **42**, T168.
40. Platt, M. M., W. G. Klein, and W. J. Hamburger, *Text. Rex. J.*, 1952, **22**, 641.
41. Brown, H. M., *Text. Res. J.*, 1954, **24**, 251.
42. Dickson, J. B., *Text. Res. J.*, 1954, **24**, 511.
43. Ewald, P. R., and C. B. Landstreet, *Text. Res. J.*, 1954, **24**, 1064.
44. Fiori, L. A., J. J. Brown, and J. E. Sands, *Text. Res. J.*, 1954, **24**, 267.
45. Fiori, L. A., J. J. Brown, and J. E. Sands, *Text. Res. J.*, 1954, **24**, 428.
46. Fiori, L. A., J. J. Brown, and J. E. Sands, *Text. Res. J.*, 1954, **24**, 503.
47. Fiori, L. A., J. J. Brown, and J. E. Sands, *Text. Res. J.*, 1954, **24**, 526.
48. Platt, M. M., W. G. Klein, and W. J. Hamburger, *Text. Res. J.*, 1954, **24**, 907.
49. Bogdan, J. F., *Text. Res. J.*, 1956, **26**, 720.
50. Fiori, L. A., J. J. Brown, and J. E. Sands, *Text. Res. J.*, 1956, **26**, 296.
51. Fiori, L. A., J. E. Sands, H. W. Little, and J. N. Grant, *Text. Res. J.*, 1956, **26**, 553.
52. Virgin, W. P. and H. Wakeham, *Text. Res. J.*, 1956, **26**, 177.
53. Coulson, A. F. W. and G. Dakin, *J. Text. Inst.*, 1957, **48**, T207.
54. Coulson, A. F. W. and G. Dakin, *J. Text. Inst.*, 1957, **48**, T258.
55. Dakin, G., *J. Text. Inst.*, 1957, **48**, T293.
56. Dakin, G., *J. Text. Inst.*, 1957, **48**, T321.
57. Sreenivasan, K and K. S. Shankaranarayana, *Text. Res. J.*, 1961, **31**, 746.
58. Bandyopadhyay, S. B., *Text. Res. J.*, 1963, **33**, 9.
59. Najundayya, C., *Text. Res. J.*, 1965, **35**, 795.
60. Najundayya, C., *Text. Res. J.*, 1955, **36**, 954.
61. Hurley, R. B., R. G. Duby, and C. R. Pfeifer, *Text. Res. J.*, 1968, **38**, 1174.

Ex. 2020-125

62. El-Behery, H. M. A. E. and S. A. Mansur, *Text. Res. J.*, 1970, **40**, 896.
63. Morton, W. E., *Text. Res. J.*, 1956, **26**, 325.
64. Sullivan, R. R., *J. Appl. Phys.*, 1942, **13**, 157.
65. Gregory, J., *J. Text. Inst.*, 1950, **41**, T1.
66. Gregory, J., *J. Text. Inst.*, 1950, **41**, T14.
67. Gregory, J., *J. Text. Inst.*, 1950, **41**, T30.
68. Gregory, J., *J. Text. Inst.*, 1953, **44**, T499.
69. Gregory, J., *J. Text. Inst.*, 1953, **44**, T515.
70. Alexander, E., *Text. Res. J.*, 1952, **22**, 503.
71. Shorter, S. A., *J. Text. Inst.*, 1957, **48**, T99.
72. Holdaway, H. W., *J. Text. Inst.*, 1965, **56**, T121.
73. Hearle, J. W. S., *Text. Res. J.*, 1965, **35**, 1060.
74. Hearle, J. W. S. and El-Sheikh, Papers of Third International Wool Textile Conference, Institute Textile de France, 1965, p. 199.
75. Goodwin, J. A., Press, J. J. (Ed.), *Man-Made Textile Encyclopedia*, Chapter V-3, Textile Book Publishers, New York, 1959.
76. Balls, W. L., *Studies of Quality in Cotton.* Macmillan, London, 1928.
77. Landstreet, C. B., P. R. Ewald, and J. Simpson, *Text. Res. J.*, 1957, **27**, 486.
78. Holdaway, H. W. and M. S. Robinson, *J. Text. Inst.*, 1965, **56**, T168.
79. Morton, W. E., *J. Text. Inst.*, 1930, **21**, T205.
80. Hamby, D. S., W. C. Stuckey, B. Gast, and R. J. Hader, *Text. Res. J.*, 1960, **30**, 435.
81. Hearle, J. W. S., P. R. Lord, and N. Senturk, *J. Text. Inst.*, 1972, **63**, T605.
82. Sultan, M. A. and I. A. El-Hawary, *J. Text. Inst.*, 1974, **65**, T194.
83. Barella, A., *J. Text. Inst.*, 1972, **63**, T226.
84. Hearle, J. W. S., *J. Text. Inst.*, 1969, **60**, T95.
85. Konopasek, M. and J. W. S. Hearle, *J. Text. Inst.*, 1974, **65**, T217.
86. Cheng C. C., J. L. White, and K. E. Duckett, *Text. Res. J.*, 1974, **44**, 698.
87. Zorowski, C. and T. Murayama, *Text. Res. J.*, 1967, **37**, 852.

Ex. 2020-126

12

Textured Yarns

INTRODUCTION

The texturing of thermoplastic yarns has been one of the most exciting developments in the field of textile processing. This process has completely revolutionized the use of nylon and polyester yarns in the men's and women's apparel, rug, and carpet, and hoisery and knitting industries. This can be realized from the fact that the total volume of textured yarns produced in the United States increased from 63 million pounds in 1968 to 744 million pounds in 1972. It is expected (1) that by 1978, stimulated by such developments as improved machinery, introduction of draw texturizing techniques, new and improved yarn types, and the expected population growth, the total demand for textured yarn will increase to almost 2 billion pounds. This chapter deals with the various texturing processes currently used in industry as well as the behavioral characteristics of the textured yarns.

TEXTURING AND ITS PURPOSE

Most natural fibers have a certain amount of crimp and waviness that helps to impart some degree of bulkiness, a property considered very desirable in textile fabrics. However, because of the way they are manufactured, most synthetic polymer fibers have a smooth surface and circular cross section, and when these continuous-filament yarns are woven into fabrics, they feel slippery to the touch and clammy when worn next to the skin. Nevertheless, synthetic filament fabircs have an attractive appearance, offer excellent wear, and can be washed and dried easily. But they lack warmth, comfort, and dimensional stability properties

Ex. 2020-127

characteristic of fabrics made from natural fibers. Some of the aesthetic and comfort characteristics could be developed in fabrics by using synthetic fibers in crimped and staple form. Spun yarns (from staple fibers) are inherently bulky and have fuller appearance. Staple yarns also have good heat insulation and comfort characteristics. These properties result mainly from the large volume of air entrapped between the interstices of the yarn.

As is evident, achieving such characteristics involved an additional process of crimping and then cutting or breaking the continuous filaments into staple fibers to make yarns with improved bulk and warmth characteristics. To utilize the synthetic fibers more advantageously in their continuous-filament form, new techniques have been developed that modify their structural characteristics to make them bulkier (imparting texture) and fuller in appearance without converting them into staple fibers. Consequently, continuous-filament yarns are subjected to a modifying process, the purpose of which is to introduce permanent waviness (crimp), loops, coils, and wrinkles and thereby to modify the geometry of the constituent filaments. In addition, this process also imposes certain structural changes that become apparent in the modified tensile and other related properties of the filaments.

This process has the effect of modifying the geometry and structural characteristics of the constituent filaments of a yarn. In other words, the geometric shape of the filaments is deformed by either bending them or inserting crimps, loops, and curls into them by a number of means to provide a higher specific volume to the yarns (to make them bulkier). Thus they acquire many of the characteristics associated with spun staple yarns. The process by which this kind of modification in the character of continuous-filament yarns is achieved is known as "texturing" or "texturizing."

Concomitant with the changes in the bulk characteristics of yarns are other advantageous effects:

1. Texturizing helps improve the pill and crease resistance and confers better dimensional stability, fuller and better appearance, and greater durability.
2. Textured yarn fabrics have better shape retention ability than those made from straight filament yarns.
3. Flexibility is a very important property desired in textile yarns and fabrics. It depends on the ability of the filament (in the outer layer) to deform (extend) easily. A straight filament is comparatively less flexible than a crimped, looped, and curly filament. This ease of deformation of filaments is a function of their bending and torsional rigidities determined by the linear density of the filament and the geometry of the filament in the yarn. In a texturized yarn, filaments lie in all sorts of geometrical configurations and are loosely packed so as not to inhibit their relative movement. This technique confers better flexibility and extensibility to yarns and ulti-

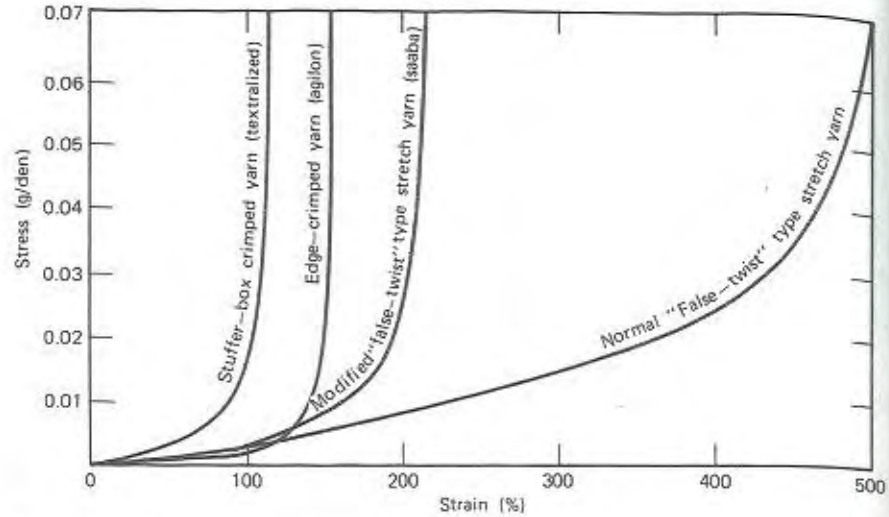


Figure 12.1(*a*). Stress-strain curves of stretch and bulk yarns (steam-relaxed 2-ply 70/34 nylon yarn) in the crimped region only.

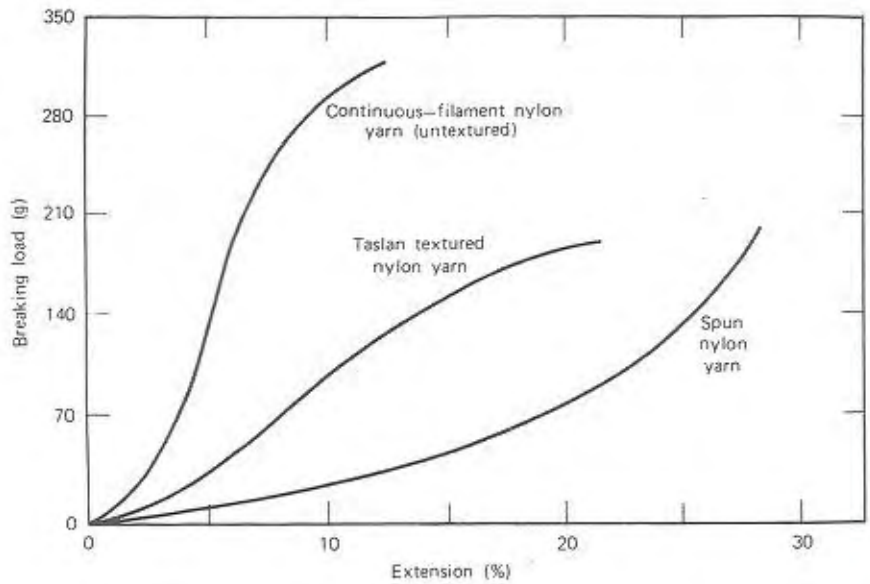


Figure 12.1(*b*). Load-extension behavior of untextured and textured continuous filament nylon yarn.

Ex. 2020-129

mately to fabrics made from them. The extensibility of various textured yarns is illustrated in Figure 12.1.

4. Texturizing results in softer yarns. Other factors being equal, the softer the yarn, the better its covering power.
5. Textured yarn fabrics are easy to wash, and they dry readily.
6. They reflect the high abrasion resistance, strength, and toughness of the thermoplastic polymer fibers from which they are made.
7. Most of the thermoplastic synthetic fibers have very low moisture content as compared to cellulosics and other natural fibers. However, the air entrapped between the interstices of the textured yarns retains moisture and thus makes the texturized yarns have fairly good comfort characteristics.
8. They provide higher covering power because of increased bulk.

CLASSIFICATION OF TEXTURED YARNS

Textured yarns may be classified into three major groups:

1. stretch yarns
2. modified stretch yarns or set yarns
3. bulk yarns

Stretch yarns are characterized by their high extensibility and good recovery, but possess moderate bulk in comparison with the other two classes of textured yarns. Stretch yarns, used extensively in stretch-to-fit garments in which extensibility and recovery from stretch are of primary importance, are produced mainly by the false-twist and by the edge-crimping (Agilon®) processes.

Modified stretch yarns may be defined as those with characteristics intermediate between stretch and bulk yarns. They are produced by modifying the stretch characteristics, usually by an additional heat treatment, after which they retain some stretch but have increased bulk. This modification treatment stabilizes the yarn structure and its bulk and stretch characteristics. The modified stretch yarns may be produced from stretch yarns by either of the following two methods:

1. In one method, stretch yarns may be modified by overfeeding them by as much as 30% or more into a heated zone in which they are stabilized in dry heat (process used on the yarn texturing machine to produce modified "stretch" or "stabilized" yarns).
2. The stretch yarns may be first soft wound in packages and then heat set or stabilized either in an autoclave in steam or during the dyeing process (the resulting yarns are usually called set yarns).

Ex. 2020-130

The modified stretch yarns are used in applications in which a lower degree of stretch and better hand and appearance are demanded. These yarns are generally used in knitted fabrics because they impart excellent stitch clarity, greater smoothness, and softness of handle, as well as better bulk and low extension under low loads. The low level of shrinkage of modified stretch yarns has favorable consequences when their dyeing behavior is considered.

Bulk yarns are characterized by their high bulk with moderate stretch and are used where bulk and fullness of hand are of greater importance than extensibility. However, bulked yarns generally possess adequate recovery characteristics. They are mostly used in carpets, upholstery, and garments requiring warmth and comfort characteristics. Bulked yarns are produced by air texturing, stuffer box, knit-de-knit, gear crimping, twist texturing, and various other types of crimp texturing processes.

Following is a brief discussion of the various types of filament yarns used for manufacturing textured yarns and the implication of the processing factors involved in modifying the resultant yarn structure. For detailed discussions of the various processes and the structural and morphological changes brought about by texturing, the reader is referred to the source material listed at the end of the chapter.

FIBERS USED IN TEXTURING

In the early years of development of textured yarns, nylon was the only fiber used in quantities that might be termed significant in terms of the total production of all fibers. In the early 1950s, processing techniques were developed to crimp nylon continuous-filament yarns by using the conventionial throwster's machinery to insert twist, subsequently setting the twist by heat treatment techniques, and finally untwisting the yarn. This method of twist-heat set-untwist in separate operations is very expensive and has low productivity. In subsequent years, new continuous methods of texturing continuous-filament yarns, such as false twist, stuffer box, edge crimping, etc., were developed, which increased productivity as well as improving the quality of the yarn produced. With the addition of other thermoplastic fibers in the field of textile applications during the following years, the scope for the use of texturized yarns was enhanced. Today, in addition to nylon, such fibers as polyester, acetate, and polypropylene are extensively used in the texturized form.*

One major problem in the use of false-twisted textured (continuous process) thermoplastic yarns is their dye nonuniformity, which produces an effect known

*More recently, a patent was granted to the Japan Exlan Company and Toyo Boseki K.K., both of Japan, for the production of textured acrylic yarns.

as "barré" in the fabric. Acetate, on the other hand, suffers from the two major disadvantages of "voids" and "shading" effects in the yarn. Voids are caused by twist slippage through the spindlette or by broken filaments trapped by the twist. Shading may result from variations in yarn quality or from uneven processing conditions.

Polyester offers good aesthetic properties as well as excellent wear characteristics. Although polyester yarns also suffer from the problem of "barré" in dyed fabric, those invovled in the texturing industry are making a concerted effort to ensure the production of quality yarns. The major factors that affect this nonuniformity in the material are end-to-end temperature variations, tension in the thread line, heater zone parameters, and take-up package density. Some improvements in the quality of the textured yarns have resulted from post-treatments and from various other stabilization techniques now being employed in the industry.

In addition to the conventional types of thermoplastic fibers presently used in the production of textured yarns, there have been some efforts made recently to introduce new varieties of yarns in this area. One such development is the introduction of reinforced textured acetate yarns. This yarn is produced by reinforcing the freshly extruded acetate fiber with either a nylon or polyester or polypropylene filament at the cup of the spinning chamber. This process results in a stabilized acetate yarn that has excellent resistance to laundering and possesses good bulk retention as well as hand characteristics.

The filament denier and the total denier of the yarn used will depend on the type of machine used and the desired end-use applications. The lower denier yarns (ranging between 15 and 30 denier with 3 to 5 denier per filament) are extensively used in hosiery applications, whereas medium (40-200 denier) denier yarns are used in men's and women's outerwear. The most commonly used deniers are 70, 100, and 150. Heavy denier yarns (500 denier and above) are used in industrial applications.

METHODS OF PRODUCTION

Basically, three major processing techniques are used in the production of stretch yarns:

1. The Helenca® process–This is the conventional batch-type method of producing stretch yarns. Helenca is the registered trademark of Heberlein and Cie A-G, Switzerland.
2. The false-twist method–This is the most versatile and most widely used method of producing stretch-type textured yarns. Some of the false-twist machines presently being used in the industry are those made by Scragg,

ARCT, Barmag, Leesona, Heberlein & Co., Mitsubishi, Berliner, and Platts to name a few (2).

3. The agilon process—The agilon process is highly suitable for processing low-denier hosiery yarns.

The Conventional (Helenca®) Twist-Heat Set-Untwist Process for Producing Stretch Yarns

The earliest method to produce permanent torque-crimp thermoplastic yarns was developed and patented by Heberlein Patent Corporation of Switzerland. This is a discontinuous process and involves the following three basic steps:

1. uptwisting to insert a high twist
2. heat-set or yarn-set (by the application of heat) to set the yarn in its twisted configuration while still on the bobbins
3. detwisting to remove the twist

The complete process for discontinuously texturing thermoplastic yarns is achieved by five primary steps followed by two or three secondary steps, as illustrated in Figure 12.2.

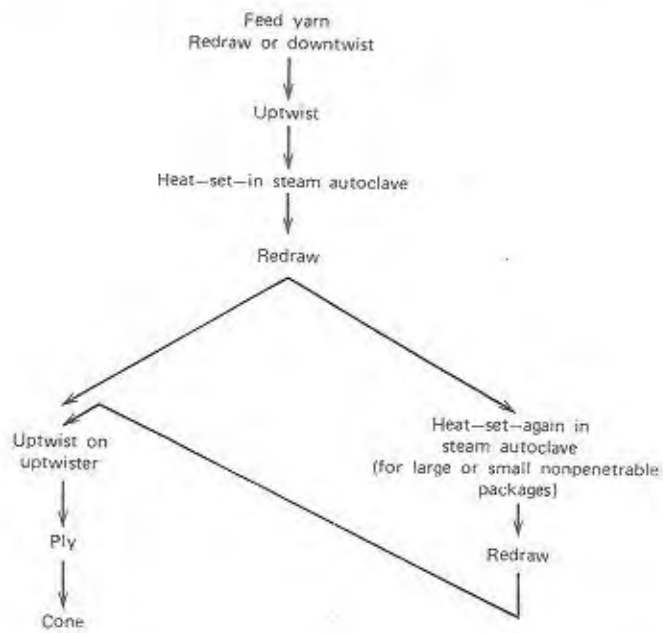


Figure 12.2. Helenca Process.

REDRAW

The feed yarn is wound or downtwisted on a redraw machine to produce packages suitable for use on an uptwister.

UPTWIST

The packages from the redraw machines are creeled on the uptwister, and the yarn is uptwisted at high speed. The twist inserted in the yarn is very high, varying from 47 to 114 turns per inch (1850 to 4448 tpm) depending on the total denier. The twist in a 70-denier nylon yarn is in the neighborhood of 74 tpi or 3000 tpm. The approximate twist can be calculated by the following relationship:

$$\text{TPI} = \frac{7000}{\text{Denier} \div 60} + 20$$

It is essential that the thread line tension during twisting and winding be kept as uniform as possible. However, the nature of the process is such that certain variations in tensions between bobbins and within the various locations of the bobbin are bound to occur. Tension in the yarn is maximum near the chase and when it approaches the top of the bobbin. These variations in tension can cause changes in the quality of texture, which in most cases show up as faults in the dyed and finished fabric.

HEAT SETTING

The twisted yarn packages are placed in an autoclave in which they are heated in steam under pressure to high temperatures for a considerable length of time. The temperature generally varies from 115 to 130°C at pressures between 25 and 50 pounds above the atmosphere for a period of approximately 1 hr. The function of this particular step is to impart to the yarn the highest possible "memory" of the highly twisted state.

REDRAW

After the yarn has been heat-set in its twisted condition (under high stress developed as a result of thermal shrinkage), the bobbins are allowed to cool so the yarn can stabilize. It is then redrawn onto large packages. The yarn at this stage may be heat set again and then redrawn and transferred onto uptwisters.

UNTWISTING

The redrawn heat-set yarn is untwisted on an uptwister to remove the twist completely (zero twist) or to some other desired level. In the latter case, the residual torque* caused by unremoved twist will cause the yarn to bulk, and the

*"Torque" yarns are characterized, by their tendency to rotate when hung freely.

unbalance torque created through untwisting will impart stretch characteristics to the yarn.

DOUBLING

In most cases, the stretch yarns produced by this process are plied in such a way that an end previously thrown in an S direction is generally plied with another end twisted in a Z direction with the same number of turns per unit length. This plying process results in a fully balanced, no-torque yarn (one having no tendency to rotate when hung freely) that does not lose its bulk and stretch characteristics. The plying or doubling twist generally varies within the range of 3 to 7 tpi (1 to 3 turns per centimeter) depending on the denier of the yarn. The direction of the doubling twist (whether S or Z) in yarns depends on such considerations as their intended use in weaving twill constructions. To achieve the best results in yarn bulk and stretch, it is preferable that the final twist in single yarn after doubling be either zero or in the direction opposite to the processing twist.

CONING

To facilitate further processing, the yarn is treated with 2-5% of lubricating oil during coning.

Stretch yarns produced by this method appear as in Figure 12.3. The modifications imposed by this process generally result in the yarns having the following characteristics:

1. Heavy-denier yarns acquire stretch up to 300% and more, whereas the fine denier yarns may extend from 400-500%.
2. Their bulk increases up to 300%.
3. They have excellent recovery from stretch.
4. They generally have crisper hand and possess higher crimp, and greater elasticity and elongation.

Figure 12.3. View of a typical stretch nylon yarn textured by the conventional twist-heat set-untwist technique.

These properties are generally affected by such factors as filament denier, total yarn denier, filament cross-sectional shape, and whether the yarn is used in

singles or plied form. The effect of various factors is discussed in more detail in another section. However, it must be pointed out that the lower total denier yarns generally have higher stretch potential; the fewer the number of filaments in a yarn of a given total denier (i.e., changing filament denier), the greater its stretch and resistence to extension, and the better its recovery. Filament number (as well as filament denier) also affects the hand and strength-retention behavior; higher-filament denier yarns have crisper hand and retain a higher proportion of the original strength.

In addition to the detrimental effect of variation in tension during uptwisting on the quality of textured yarn, the heat-setting process itself, for many reasons, can cause variations in crimp, crimp retention, and dyeing behavior of the finished yarn (resulting in barré effect). The application of moisture and heat tends to cause shrinkage in thermoplastic yarns. If the yarn is not allowed to shrink freely, the shrinkage tension (force) would cause the yarn to elongate, thereby affecting the stress-strain characteristics of the yarn. These variations are distinctly visible between that portion of the yarn near the core (barrel of the bobbin) and the layers on the outside. The layers near the barrel of the bobbin are unable to shrink, whereas the outside layers can shrink by moving inwards.

The other cause of variation in this process is uneven heating of the outside and the inside layers of the yarn. The yarns wound next to the flanges of the bobbin would be subjected to a different heat treatment.

False-Twist Method

The false-twist method is the most important and the most widely used technique for producing textured yarns. The yarns produced by the conventional twist-heat set-untwist (three-stage) process generally have excellent characteristics; however, there are certain inherent drawbacks in the process itself. These disadvantages include:

1. Slowness of the process. Table 12.1 shows the production rates of various texturing processes used in the industry (11). It can be seen that the batch process has the lowest production rate when compared to all the other processes. This is because of the limitations imposed by the spindle speed of the uptwister and the batch orientation of the process itself (an uptwister spindle running at 10,000 rpm will produce approximately 1 lb per 168-hr week).
2. The process requires extra care in handling the packages to avoid mixing of yarns.
3. Uniformity is difficult to control between packages and lots.

To overcome the above-mentioned objections, the continuous false-twist method is employed extensively in the production of stretch and modified

Ex. 2020-136

Table 12.1. Typical Rates of Production for Various Types of Textured Nylon Yarns (11)

Type Textured Yarn	Yarn Output Speed (ft per min)	Yarn Output Speed (m per min)	Production 70 den./ Spindle or Position/ 168 hr. Week (lbs)	Production 70 den./ Spindle or Position/ 168 hr. Week (kg)
Agilon (stabilized type) yarn produced on the *Hobourn* No. 2110 edge-crimp machine	180	54.9	2 ply-19 5 ply-24	2 ply-8.6 5 ply-10.9
C-B-Tex[a] (knit-de-knit) yarn	1983	604.4	134	60.8
Taslan yarn	300	91.4	19	8.6
Textralized yarn	1200	365.8	63	28.6
Turbo Duotwist yarn	1000	304.8	52.8	24.0
Conventional *Helanca* stretch yarn produced by the twist-heat-set-untwist batch method	–	–	Less than 1	0.45
False-twist type stretch yarn[b] (assuming a twist level of 78 tpi or 3071 tpm):				
45,000 rpm	48	14.6	2.5	1.1
100,000 rpm	107	32.6	5.6	2.6
150,000 rpm	160	48.8	8.4	3.8
180,000 rpm	192	58.5	10.1	4.6
210,000 rpm	224	68.3	11.8	5.4
240,000 rpm	256	78.0	13.5	6.1
270,000 rpm	288	87.8	15.2	6.9
300,000 rpm	321	97.8	16.9	7.7
330,000 rpm	353	107.6	18.6	8.4
360,000 rpm	385	117.3	20.3	9.2
400,000 rpm	427	130.1	22.5	10.2
500,000 rpm	534	162.8	28.1	12.8
750,000 rpm	791	241.1	42.2	19.1
1,000,000 rpm	1068	325.7	56.2	25.5

[a]Trademark of Textile Machine Works, Reading, Pa.

[b]Output of a false-twist spindle is directly proportional to the spindle's speed and to the denier being textured. Thus for any given spindle speed, a yarn of lower denier (which requires more turns per inch) must be run at a slower yarn speed and therefore at a corresponding lower rate of production.

stretch yarns (set). The false-twist method combines all three stages, namely, twisting, heat setting, and untwisting in one continuous operation. Furthermore, the twist in the yarn is inserted with the spindles revolving at very high speeds, in certain cases up to 800,000 rpm. In friction twisting, the yarn rotates at a speed equivalent to a spindle type machine at up to 4 million rpm. Such high-speed operations permit very high rates of production.

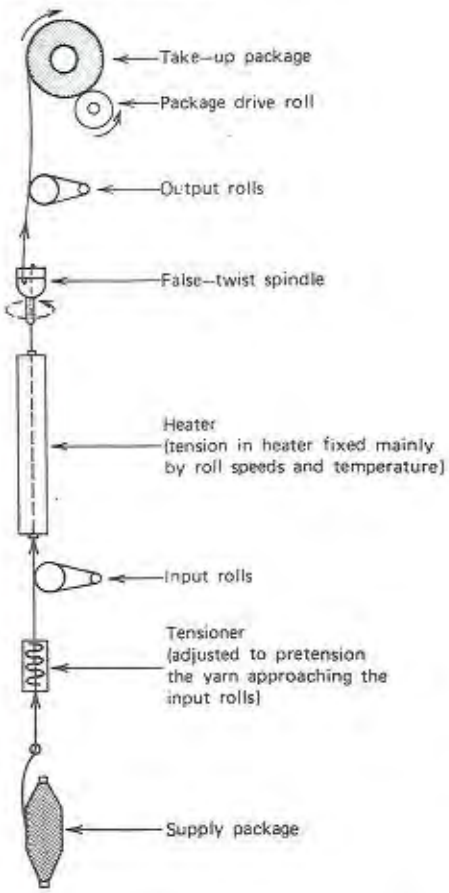
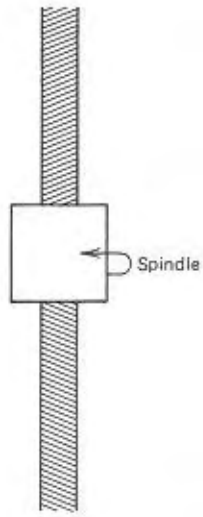


Figure 12.4. Line diagram showing the path of a yarn through a false-twist texturing machine.

It is out of the scope of this book to describe in detail all the principal false-twist-type yarn machines currently used for manufacturing stretch and modified stretch yarns. Although there are many variations in the design and the overall layout of different types of machines, they perform essentially the same function. The general principle of the false-twist texturing process is illustrated in Figure 12.4. The yarn is drawn from the supply package, fed at controlled tension over the heater and through the false-twist spindle, and finally wound on a package. The twist in the yarn is set when it is between the input feed roll and the false-twist spindle, by heating and cooling before it leaves the false-twist spindle.

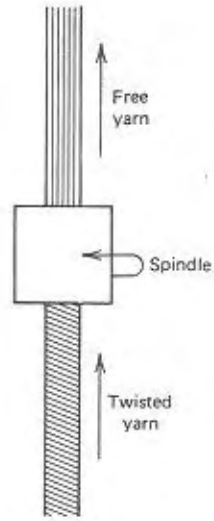
To explain the principle of the false-twist process, reference is made to line diagrams in Figure 12.5*a*. Here the yarn is held at both ends and twisted in the center by a false-twist spindle. This action would impart S twist on one side of

Ex. 2020-138



(a)

Figure 12.5(*a*). Insertion of false twist in a stationary yarn.



(b)

Figure 12.5(*b*). False twist in a moving yarn.

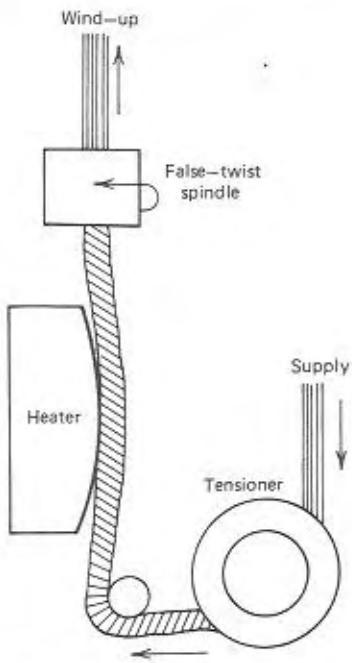


Figure 12.6. Illustration showing the principle of false-twist texturing.

Ex. 2020-139

the spindle and Z twist on the other side. However, if the yarn is running continuously while the false twist spindle is inserting twist continuously, the twist on the input side of the spindle (after passing through the spindle) will cancel the twist on the output side (because of the equal and opposite nature of the twist). This is shown in Figure 12.5*b*.

The next step in this process is to apply heat to soften the thermoplastic material to make it easily pliable; it is then deformed by twisting it in its softened state (to allow the stresses in the filaments to decay) and then by letting the yarn cool before untwisting it under relatively high tension. This is illustrated in Figure 12.6. The torsional forces are high enough to cause some significant changes in the geometry of the filament cross-sectional shape (Figure 12-7) in addition to the modifications in the morphology (orientation and crystallization) of the polymer material. Textured yarn thus produced has some residual torque in either the S or Z direction, depenting on the direction of rotation of the spindle. The extent of crimp and the latent crimping power of individual filaments in a false-twist yarn vary along the length of the yarn, and the crimp amplitude (size) is a function of radial position of the filament within the yarn. The radial position of the filament in turn is decided by the migration pattern imposed by the degree of twist and by the tension at which the twist is imparted. An idea of the crimp dependence, that is, of frequency and the ampli-

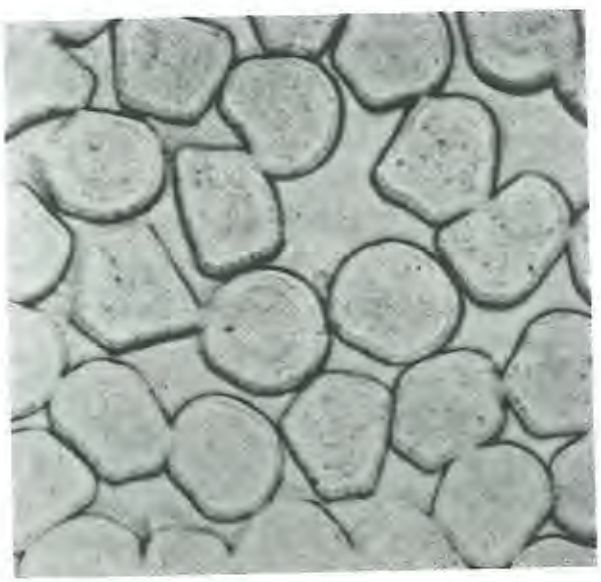


Figure 12.7. Deformed cross section of nylon filaments caused by the application of twist during their passage over the heater.

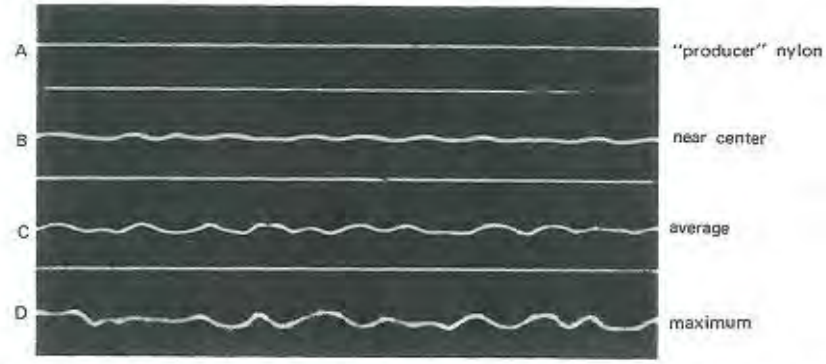


Figure 12.8. Longitudinal views of filaments from a 70 den/32 fils, nylon yarn, showing the differences in crimp due to the radial position in the yarn. A filament from untextured yarn; B, near center; C, middle layer; D, near the surface.

tude in a filament on its radial position in the yarn, can be obtained from the illustration in Figure 12.8; it shows variation in crimp in filaments caused by their location in the hot zone. The overall appearance of a 70-denier, 17-filament nylon stretch yarn produced by the false-twist yarn method is shown in Figure 12.9.

The productivity of a false-twisting machine depends on the spindle speed, provided the twist is kept constant. It is for this reason that much effort over the past twenty years has gone into the development of a spindle that can rotate yarn at ultrahigh speeds and still meet high performance standards. There are basically two types of twisting techniques used on false-twist texturing machines:

1. twist tube (spindle) or magnetic pin
2. friction twisting
   a. bush type
   b. stacked disc type

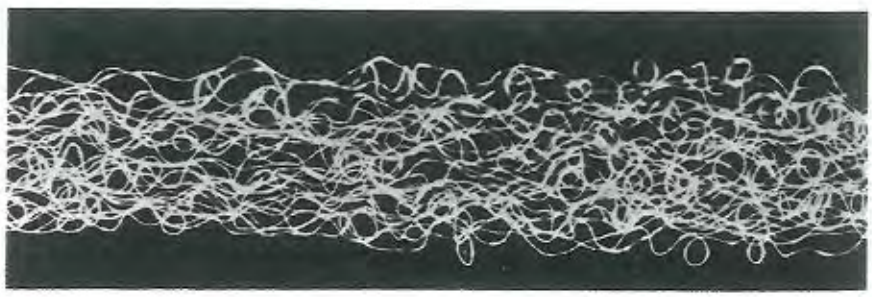


Figure 12.9. Photomicrograph of a 70 den-34 fil false-twist textured nylon yarn.

Ex. 2020-141

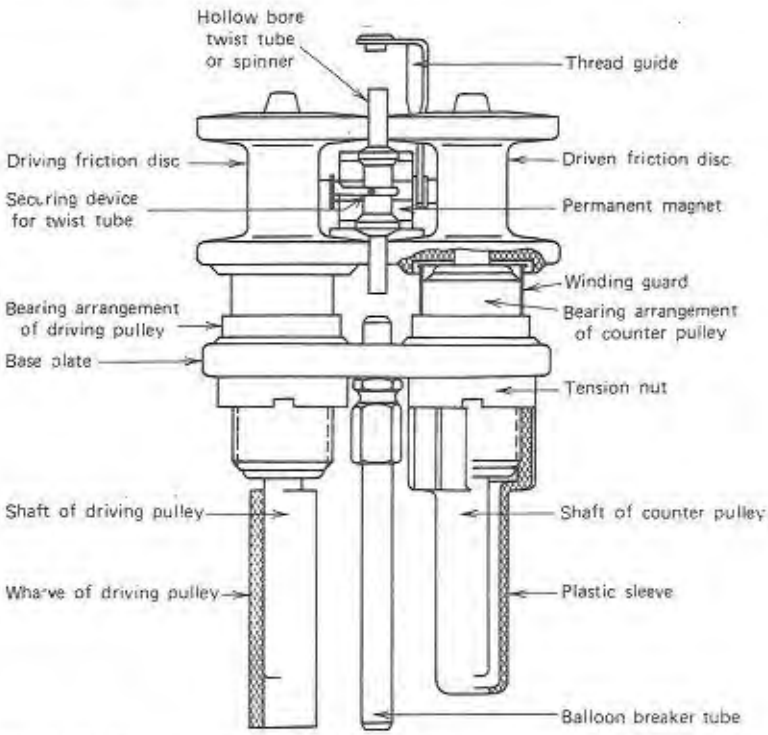


Figure 12.10. Schematic showing Type MFD FAG single-unit magnetic spindle. (Courtesy: Schäfer Industriegesellschaft M.B.H.)

Spindle or Pin Twisting

The earliest spindle used on the Fluflon® (trademark of the Leesona Corporation) machine was of the ball bearing type, which rotated at a speed of 45,000 rpm. Today, spindles of the magnetic pin type run around 800,000 rpm (MFD-800 Kugel-Fischer type). One such magnetic pin type spindle, Type MFD FAG (Schafer Industriegesellschaft GMBH, Schweinfust), is shown in Figure 12.10. A twisting spindle consists of a tube with a pin or a pulley fixed at one end. The yarn passes through the tube along its axis and is threaded around the pin, as shown in Figure 12.11. This arrangement ensures positive insertion of twist when the spindle rotates. The theoretical twist in the yarn can be calculated by the simple relationship between spindle (twist-head) and yarn speeds (wind-up).

$$\text{Twist per unit length} = \frac{\text{spindle speed (revolutions per unit time)}}{\text{yarn speed (length per unit time)}}$$

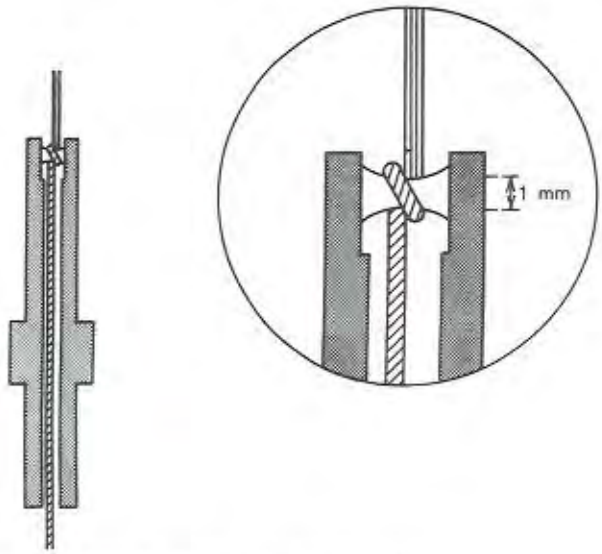


Figure 12.11. Yarn threading through a pin-type spindle.

The twist thus obtained is called "flat" twist. However, the actual twist in a yarn when it is still in the heater is somewhat different (generally more) than the calculated one. The fact that the amount of twist inserted in the yarn controls the production can be seen in Table 12.2, in which some typical production figures for three twist-head speeds are given (3).

Table 12.2

Denier	Twist (flat)	30,000 rpm		60,000 rpm		140,000 rpm	
		ft/min	lb/168-hr	ft/min	lb/168-hr	ft/min	lb/168-hr
30	100	25	056	50	1.28	117	2.61
60	80	31.3	1.28	62.6	2.56	147	6.00
100	70	35.7	2.14	71.4	4.28	167	10.00

FRICTION (BUSH-TYPE) TWISTING

Friction twisting, as the name implies, inserts twist into the yarn by frictional contact with a rotating head or a bush, as shown in Figure 12.12*a* and *b*. The yarn attains twist by rolling inside the moving inner surface of a hollow tube of plastic or rubber. The inner diameter of the cylinder is considerably larger than that of the yarn, which means that one revolution of the tube produces a very

large number of rotations in the yarn, neglecting any slippage. Consequently, the yarn can be fed at relatively high linear speeds at comparatively low rotational speed of the twisting unit. Twisting rates of up to 4 million rpm are claimed commercially, which would correspond to the bush speeds of 20,000-25,000 rpm. However, one great disadvantage of this system is the large amount of slippage, up to 50%, that occurs during twisting. This results in uneven crimping of the yarn as compared to the pin-type spindle (positive twisting) false-twist process. But, because of the higher production rates possible, this system is of increasing commercial importance in producing fine-denier textured yarns.

A major drawback of the bush is its gradual wear, which ultimately affects the yarn quality. The wear of the bush material is affected by higher running speeds and the processing of heavy denier yarns.

STACKED DISC-TYPE FRICTION TWISTING

A second type of friction twisting device commonly used in the industry is the stacked disc-type friction unit illustrated in Figure 12.12*b*. Other disc-type units commonly used in the industry are also shown in Figure 12.12. In the stacked disc principle, the yarn is twisted by frictional contact with the outer surface of the disc sets located on three shafts. The axis of the shafts are positioned on the apex points of an equilateral triangle.

The diameters of the stacked discs are such that they overcap in a fashion that imparts to the yarn desired angle of contract with discs for the most efficient twist insertion. There is a critical relationship between the diameter, the thickness, and the position of discs that must be satisfied for the most efficient twisting operation. The stacked disc-type generally has nine discs. With this type of arrangement, the angles of contact of 1000-1300 degrees can be realized effectively. In other words, in principle it should be possible to twist yarns by stacked discs using wear-resistant friction surfaces with a low coefficient of

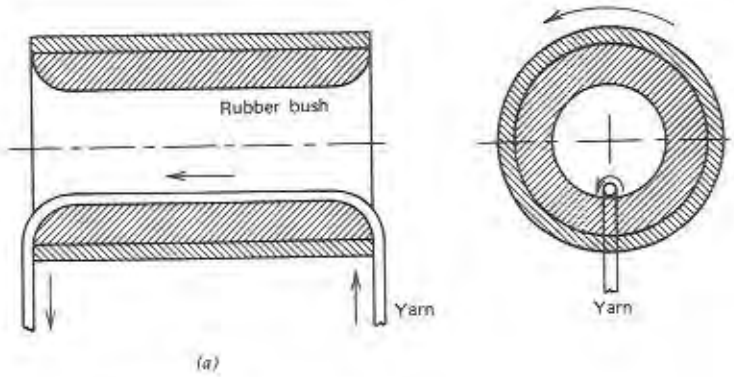
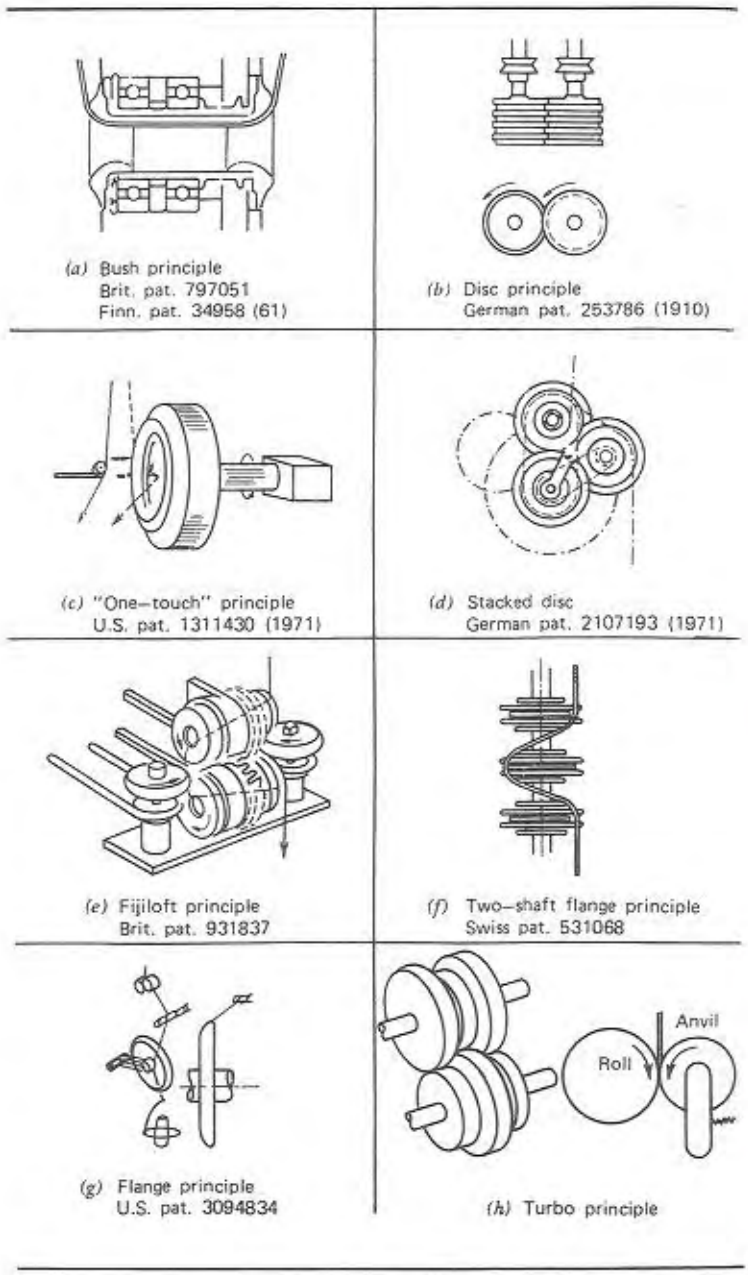


Figure 12.12(*a*). Principle of friction twisting.

Ex. 2020-144



(a) Bush principle
Brit. pat. 797051
Finn. pat. 34958 (61)

(b) Disc principle
German pat. 253786 (1910)

(c) "One–touch" principle
U.S. pat. 1311430 (1971)

(d) Stacked disc
German pat. 2107193 (1971)

(e) Fijiloft principle
Brit. pat. 931837

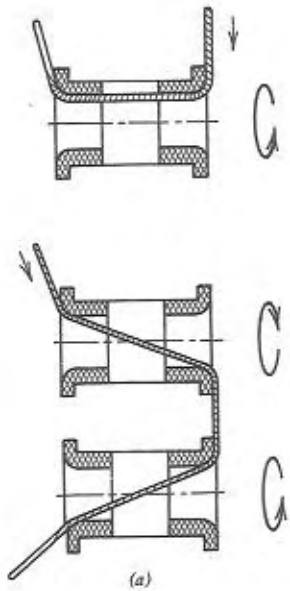
(f) Two–shaft flange principle
Swiss pat. 531068

(g) Flange principle
U.S. pat. 3094834

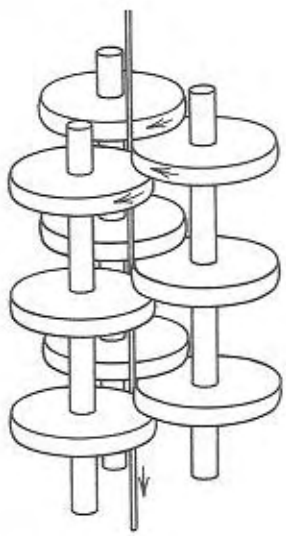
(h) Turbo principle

Figure 12.12(*b*). Construction principles of friction twisting devices.

Ex. 2020-145



(a)



(d)

Figure 12.12(*b*). Continued.

Ex. 2020-146

friction such as metals and ceramic (the torsional moment α to the production of the coefficient of friction of the surface and the contact angle). However, in practice this does not work, and a friction surface with a high coefficient of friction (rubber or a plastic) gives desirable results. Some reasons that account for the unworkability of low-friction surfaces are:

1. If the last friction surface does not have a high initial moment, the emerging false twist textured yarn will have a disturbed cross-sectional shape—ribbon-like instead of the more desirable circular shape.
2. The initial contact that the yarn makes with the twisting device is critical. It is believed that a large portion of the twist is inserted in the yarn at the instance of first contact. This is true for both the bush- and the disc-type friction units.
3. Generally, all metal, metal oxides, or ceramic surfaces cause extensive damage to the filaments.
4. The pores in the metal and ceramic surfaces are clogged by monomers and spin finishes stripped off the yarn, thereby altering the frictional characteristics of the surface and thus the twist insertion.

Friction surface materials such as rubber and polyurethane are commonly used for both bush- and disc-type twisting. Discs have a tendency to wear slower than bushes. Heavy-denier yarns can be processed easily on disc-type units, since they offer less wear and more flexibility (in denier range).

Recently, Turbo Machine Co. announced the development of a simple device that has proved highly successful in controlling the yarn slippage and thus the twist uniformity during texturing. They claim that the yarn produced with this unit installed on the texturing head has a lower tendency to have tight spots.

Principle of Friction Twisting

The principle of friction false twisting has been described by Arthur and Weller (3). They have discussed two devices that may be used in friction twisting, as illustrated in Figure 12.12. The first is of the bush type as mentioned earlier, and the second uses a moving band. Using a rubber-lined bush of approximately 5/8 in. internal diameter, they carried out experimental studies to investigate the effect of the principal variables that might influence twist during friction twisting. These variables included (1) twist head speed, (2) yarn speed, (3) yarn tension (4) wrap angle, and (5) yarn denier. The yarn twist values reported are based on the untwisted yarn length. (The twist was determined by removing a length of yarn and then untwisting in a twist tester under a tension equal to that used in the operation.) Their results showing the relationship between the twist in the yarn (t) and the ratio of yarn speed (μ) and twist head speed (the speed of the inside twist-tube surface, s) for various yarn speeds are plotted in Figure 12.13.

Ex. 2020-147

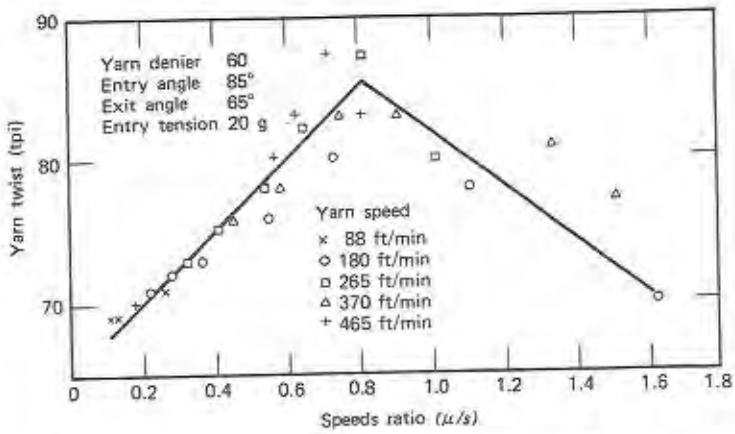


Figure 12.13. Yarn twist versus speeds ration. From Arthur and Weller.

It can be seen that there is an optimum value of (μ/s) at which twist is at a maximum level. The optimum value of (μ/s) would depend, among other factors, on the surface characteristics of the lining material used in the twist tube. Arthur and Weller have reported the optimum twisting efficiency for nylon 6 and nylon 66 yarns at $\mu/s = 0.81$ for natural rubber with carbon black filler as the lining material. The significance of the maximum is that the torque required to twist the yarn is just sufficient to overcome the frictional force on the surface of the yarn. Any deviation from this point would cause instability in the torque-twist characteristics of the yarn: increasing torque-twist (movement toward lower μ/s value) behavior caused by a decreasing value of the coefficient of friction would result in lower twist. Another advantage of the bush-type (friction) twisting head is its self-adjusting property over a wide range of yarn deniers, which is evident from the straight-line relationship observed between twist and the reciprocal of the square root of the linear density (twist factor = twist $\times \sqrt{\text{tex}}$) over the range of 30-840 denier. These authors also report a linear relationship between twist and the sine of the entry angle (defined as the angle made by the ingoing yarn path with the twist head axis) and suggest that, for optimum crimp, an entry angle close to 90° is suitable.

Thwaites (4) has recently reported a theoretical analysis of the mechanics of friction twisting and has derived expressions that relate variations of twist factor, yarn tension, and yarn path (entry and exit angle) through a false-twist spindle. His experimental results and theoretical predictions show a reasonable agreement and confirm the findings of Arthur and Weller. However, the effect of the change of the frictional properties of the bush material on the processing behavior and the torque-twist characteristics of yarn during texturing is still not fully understood and needs further study. This is essential if progress is to be made in improving the regularity of the friction-twisted textured yarns.

Ex. 2020-148

Factors Affecting the Stretch Characteristics of False-Twist Textured Yarns

The false-twist texturing process is used to produce crimped yarns covering a very wide range of properties. These include such yarn characteristics as rough appearance to softer and smoother silk-like qualities, high skein shrinkage, and varying amounts of stretch before and after relaxation. However, specific yarn properties, such as texture, softness, cover, and stretch, among others, could depend on a number of materials and processing variables. These variables can be grouped into the following three categories:

1. Material variables
   a. filament denier
   b. filament count and yarn denier
   c. cross-sectional shape of filament
   d. spin finish
   e. luster
   f. mechanical properties of parent yarn
2. Machine variables: this includes the machine design factors
   a. heater type
   b. heater length
   c. heating mode: conduction, convection, radiation
   d. feed system
   e. type of spindle—pin or friction (bush) type, fluid twisting, duo-twisting
   f. winding or take up mechanism
3. Processing (texturing) variables
   a. heating and cooling rate
   b. amount and direction of twist
   c. spindle speed
   d. yarn take-up speed
   e. heat zone thread line tension
   f. post-treatments such as second heater, autoclave (steam) setting

MATERIAL VARIABLES

Filament Denier and Number

The individual filament denier and the number of filaments for a given total denier of yarn have a profound effect on the textured yarn crimp rigidity, as well as on the stretch and bulk characteristics. The crimp rigidity, that is, the latent retained energy or torque, increases directly with the diameter of individual filaments. This is because the coarser the filament, the higher the torsional energy required to distort (or twist) it and the greater the retained energy after twisting and setting. The torsional stress in a filament is proportional to the fourth power of its radius (square of denier). It follows, therefore, that

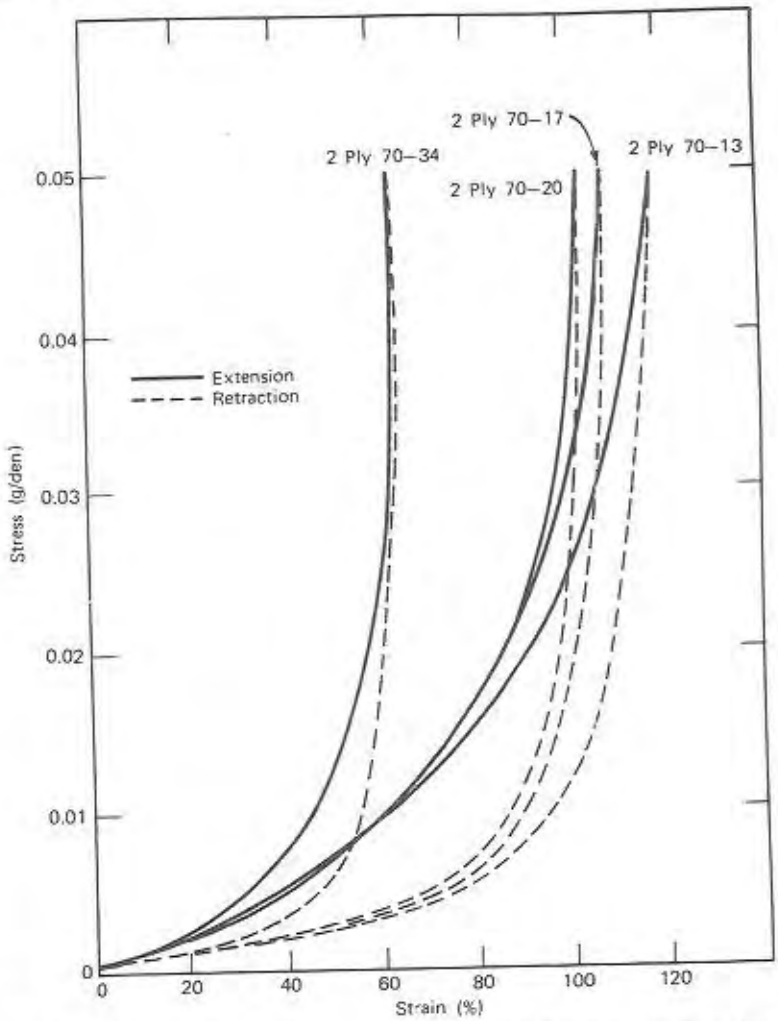


Figure 12.14. Extension-retraction curves (third cycle) for 2-ply, 70-den, false-twist textured nylon yarns.

the fewer the number of filaments in a stretch yarn for a given denier, the higher its stretch potential and resistance to extension, and the faster its recovery from extension. On the other hand, larger-diameter filaments produce textured yarns with crisper or harsher hand but retaining a higher percentage of their original strength, as can be seen from Figure 12.14 (5). This shows the effect of filament denier on the stress-strain characteristics of a typical 2-ply 70-denier false-twist stretch nylon yarn. It is clear from the illustration that the extension at the

Ex. 2020-150

point of crimp removal and the energy of extension and retraction increases with decreasing number of filaments (increasing filament denier).

Total (Yarn) Denier

Yarns are generally twisted with a constant twist factor during false twisting. It follows that the finer-denier yarn will be twisted to a higher twist angle and consequently will have a greater stretch potential. For example, for a given filament denier, a 70-denier yarn will develop higher stretch potential than a 100-denier yarn.

Cross-Sectional Shape

In addition to the regular circular type, synthetic filaments come in various cross-sectional shapes, such as trilobal, triangular, and dog-bone. The torsional rigidity of a filament varies directly with the shape factor, which has a value of unity for a circular cross section and decreases as the polygonal shape approaches a triangle. Textured yarns made from multilobal cross-sectional shapes tend to have silk-like hand and appearance. They also have greater covering power than the corresponding circular filament yarns with the same individual filament and total denier.

Spin Finish

Thermoplastic yarns are generally given a spin finish after spinning to make them amenable to further processing. The requirements from the point of view of processing, such as texturing, include:

1. correct fiber frictional properties at all stages of processing
2. control of static electrification at all stages of processing

It is believed that a spin finish, generally created by a lubricating additive, affects the deformability of filaments during twisting because of decreased friction between the filaments. An absence of spin finish would cause high frictional resistance between filaments and thus would prevent them from being twisted as desired and would result in very high thread line tension. This could then result in filaments with kinks and snarls, which are undesirable for a smooth appearance. On the other hand, spin finish can affect the free movement of the yarn around the pin and can hamper the performance of the twist trapper.

Properties of the Parent Yarn

The physical properties and the chemical nature of filaments (polymer type) would affect such factors as the thread line tension, temperature, the twist that must be adjusted during false twisting, the setting or the dwell time on the heater, and the degree of permanency of crimp. The role of the physical

properties of the parent yarn in influencing the behavior of textured yarn can be best understood from the relationship between the yarn retractive force (5) and the yarn parameters, as indicated by the following expression:

$$\frac{F}{D} = \frac{CEd}{A^2} \tag{12.1}$$

where

F = the retractive force of the yarn
D = the total yarn denier
C = a constant
E = filament elastic modulus
d = filament denier
and A = diameter of the filament helix.

It can readily be seen that the retractive force is directly proportional to the product of modulus and denier. Thus a material with lower tensile modulus will have lower retractive force, provided all other factors remain constant. For example, since the modulus of polyester (PET) is generally higher than nylon 66, which in turn is higher than nylon 6, the retractive force for a given total denier and filament would vary in the order $F_{PET} > F_{N66} > F_{N6}$. It is clear from equation 12.1 that, by manipulating the filament denier, it is possible to produce yarns from nylon 6, nylon 66, and polyester with similar retractive force for a given total yarn denier. It is known that a 70/24 nylon 66 yarn has retractive force similar to a 70/24 nylon 6 yarn.

It is recognized that torque-crimped nylon 66 as well as nylon 6 yarns have very good stretch and recovery, texture, covering power, etc. On the other hand, polyester yarns present some difficulty in retaining their torque-crimp memory if the parent yarn is not properly drawn and the textured yarn not adequately relaxed. These aspects are discussed in more detail in the following sections. However, it must be pointed out that the fabrics made from properly textured and relaxed polyester yarns are believed to have better texture or hand, better cover, and better crease-resistance characteristics than similar fabrics woven or knitted from nylon yarns.

Polypropylene yarns generally require longer dwell time in the heat zone, necessitating the use of longer heating, which to some extent slows down the production rate. However, polypropylene yarns have very good torque-crimp memory, provide excellent covering power, because of low specific gravity, yield a very pleasing "apparent" effect of lightness of hand.

MACHINE VARIABLES

There are more than a dozen manufacturers of yarn-texturing machines. Each machine has its unique design features, which include the heater type (contact,

Ex. 2020-152

radiation), tensioning system, yarn-feed system (apron or roll), and yarn take-up mechanism to name a few of the most important ones. All these factors taken singly or collectively create a complex situation in the production of textured yarns.

In addition, the following factors further complicate the situation when considering the effect of machine variables on the textured yarn quality:

1. simultaneous and sequential draw texturing
2. use of partially drawn polyester yarns
3. type of twisting technique, such as, duo-twist, friction (bush) twisting, fluid-drawn texturing
4. crimp type

There is no one machine that is ideal. To get a better picture of the innovativeness of the various machinery manufacturers, the reader is referred to Table 12.3, in which the most important features of the latest equipment (shown by the manufacturers at ATME-I-1973 at Greenville, S.C., U.S.A.) currently available for yarn texturing are tabulated. A detailed discussion on the subject of machine engineering design is out of the scope of this chapter. However, some novel ideas in texturing shown for the first time at this international machinery exhibit are discussed later.

Nevertheless, it is deemed appropriate to discuss briefly the importance of heater design, since heat setting is perhaps the most critical aspect of the texturing process. In modern texturing machines, the setting time is relatively short; the whole process of twisting, heat setting, and untwisting takes less than 1 sec.

The basic requirements of a heater system include:

1. reliability
2. reproducibility
3. ease of control
4. flexibility
5. economy of operation

The attainment of these requirements would depend to a certain extent on the type of heater employed. According to the mode of heat transfer, the heaters can be grouped in three basic types, that is, radiation, conduction, and convection. A further subdivision can be related to the heating medium, for example, electricity, hot air, oil, steam, Dow-Therm, etc. There is not much information available regarding the influence of the heater type on the quality characteristics of textured yarn. However, there are some studies reported in the literature on the effect of heater temperature and heater length on the bulking and stretch behavior of yarns, and these are discussed in the appropriate sections.

Ex. 2020-153

Table 12.3. Details of Machines Exhibited at the ATME-I, 1973

Manufacturer	Spindles			Magnetic Spindle Drive	Heaters			
					Heater 1		Heater 2	
	No.	Type	RPM		Lgth. (mm)	Type	Lgth. (mm)	Type
ARCT FTF 483	192	Friction or magnetic pin	800,000 600,000	Bi-roll or monoroll	1500	Contact	1000	Radiation and convection
Barmag FK5C	216	Friction or magnetic pin	4 million 400,000 600,000 800,000	Bi-roll	1200-1500	Contact	1000	Convection
Cognetex SFT	192 216	Magnetic pin	800,000	Na	1000	Na	1200	Na
Giudici TG4.V/72	120	Friction	1 million 800,000	Na	990	Contact	–	–
Giudici TG4.F/2	120	Magnetic pin	800,000	Bi-roll	1500	Contact	1000	Radiation
Heberlein FZ 27S	160	Magnetic pin	600,000	Bi-roll	Na	Contact Convect.	Na	Contact convection
Leesona 556	156	Pin	500,000	Direct Drive	1000	Contact	520	Contact
Platt Kosmotex Type 984	132	Friction	40,000	Na	1200	Na	300	Na

Ex. 2020-154

Table 12.3. (continued)

Manufacturer	Spindles			Magnetic Spindle Drive	Heaters			
					Heater 1		Heater 2	
	No.	Type	RPM		Lgth. (mm)	Type	Lgth. (mm)	Type
Scragg Super Draw Set 2	216	Friction or magnetic pin	800,000 600,000	Bi-roll	1000 or 1500	Contact	995	Radiation contact
Sotexa SW30	216	Friction or Magnetic pin	800,000 600,000	Bi-roll	1500	Contact	1200	Convection
Spinner Oy VK-VTS/A	160	Friction	40,000	Na	2000	Contact	2000	Contact
Toshiba J-202	108	Air jet	–	–	420	Convect.	420	Convection

Manufacturer	Temp. Tolerance	Cooling Zone (mm)	Take-Up					
			Speed (m/min)	Type Pkg.	Pkg. Size (mm)	Type Doff.	Yarn Size Range (d tex)	Pkg. Wt. (kg)
ARCT FTF 483	±1°C	1050	400	Straight or bi-con.	250X 250	Semi-auto	20-200	NA
Barmag FK5C	NA	460-910-1700	400 (frict.) (mag. pin) 250	Straight or bi-con	NA	Auto.	15-200	4.5
Cognetex SFT	NA	750	NA	Straight or bi-con.	NA	NA	NA	NA
Giudici TG4.V/72	± 1%		150-200	Straight or bi-con.	185X 220	Manual	15-50	NA
Giudici TG4.F/2	±1°C	1500	300	Straight or bi-con.	290X 300	Manual	17-300	NA
Heberlein FZ 27S	NA	NA	150	Straight or bi-con.	200X 200	Manual	7-300	3.0
Leesona 556	±1°C	430	NA	Straight	139X 270	Manual	8-1388	NA
Platt Kosmotex Type 984	NA	1600	1000	Straight	235X 250	Manual	15-200	NA
Scragg Super Draw Set 2	NA	750 or 900	166-205	Straight or bi-con.	250X 245	Manual	15-250	3.7-4.6

Ex. 2020-156

Table 12.3. (continued)

Manufacturer	Temp. Tolerance	Cooling Zone (mm)	Take-Up: Speed (m/min)	Type Pkg.	Pkg. Size (mm)	Type Doff.	Yarn Size Range (d tex)	Pkg. Wt. (kg)
Sotexa SW30	±0.5%	1800	400	Straight or bi-con	280X 290	Semi-auto.	15-300	NA
Spinner Oy VK-VTS/A	NA	1500 700 mm cooling plate	800	Straight or bi-con.	250X 250	Auto.	15-200	6.0
Toshiba J-202	NA	NA	300	Straight or bi-con.	200X 240	Auto.	15-750	NA

Manufacturer	Supply: Fiber Type	Feeder Yarn Charact.	Type Creel	Type of Texturizing	Method of Texturizing	Thread-up Time (min)	Twist Capabilities	Noise and Fume Controls	Process Monitoring Devices
ARCT FTF 483	Polyester Nylon	Drawn Partially Drawn Undrawn	Over-head	Convent. Simul. Sequen.	FT or FTF	1.5-2.0	S, Z or SZ Combin.	Fume-blower aspirator system	Central location for overall conditions. Indiv. heater monitor
Barmag FK5C	Polyester Nylon	Drawn Partially Drawn Undrawn	Side creel	Convent. Simul. Sequen.	FT or FTF	2.0	S, Z or SZ Combin.	Noise-transparent shield	Indiv. Temp., spdl. sp., Yarn tension at central location

Cognetex SFT	Polyester Nylon	P.O.Y. Undrawn	NA	Simul.	FT or FTF	NA	S, Z or SZ Combin.	NA	NA
Giudici TG4.V/72	Nylon	Drawn	Side creel	Convent.	FT	0.5-1.0	S, Z or SZ Combin.	Fume exhaust	Portable heater monitor. system
Giudici TG4.F/2	Polyester Nylon Acetate	Undrawn P.O.Y	Side creel	Convent. Simul.	FT or FTF	1.0	S, Z or SZ Combin.	Fume exhaust	Indiv. heater monitor.
Heberlein FX 27S	Polyester Nylon	Drawn Undrawn P.O.Y.	Side creel	Convent. Simul. Sequen.	FT of FTF	1.5	NA	Fume removal	Part. monitor for spdl. sp.-cent. loc. monitor available
Leesona 556	Thermo-plastic	Drawn	Side creel	Convent.	FT or FTF	NA	NA	Fume duct. No roller bearings	Central location for overall conditions
Platt Kosmotex Type 984	Polyester Nylon	Undrawn P.O.Y.	Over-head	Sequen.	FTF	NA	NA	Fume exh. top and bottom	Individual heater control monitor
Scragg Super Draw Set 2	Polyester Nylon	Drawn Undrawn P.O.Y.	Side creel	Convent. Simul. Sequen.	FT or FTF	2.0-3.0	NA	Noise-shield Fume-fan	Central individual control module with master temp. setting control
Sotexa SW30	Thermo-plastic	Drawn Undrawn P.O.Y.	Side creel	Convent. Simul. Sequen.	FT or FTF	1.0-1.5	NA	Noise prot. Fume vac.	Central location for temp.
Spinner Oy VK-VTS/A	Thermo-plastic	Drawn Undrawn P.O.Y.	Side creel	Convent. Simul. Sequen.	FT or FTF	NA	NA	Fume-air suction	–
Toshiba J-202	Polyester Nylon	Drawn Undrawn P.O.Y.	Over-head	Convent. Simul. Sequen.	FT or FTF	1.0	NA	Fume-exhaust fan, less noise	Central location for temp.

NA not available.

Ex. 2020-158

PROCESSING VARIABLES

It has been pointed out that the heating and cooling of the yarn is the most critical operation encountered during the process of false-twist texturing. This aspect of the process attains further dimensions when viewed in the light of technological advancements made in the field of increased spindle speeds. However, for effective heat setting, the yarn must be maintained at the setting temperature for a sufficient length of time–an event controlled by yarn speed and heater length–to yield the desired stretch characteristics. To a certain extent, the problem of dwell time has been overcome by incorporating longer heaters (in some modern machines the heater length may go up to 2.0 m).

Heating and Cooling of Yarns

It has been reported by Arthur and Jones (6) that the setting process, in addition to being dependent on the temperature attained by the yarn, is also governed by a rate process that is probably associated with the modifications in the molecular structure at the setting temperature. These authors have reported a detailed study on the heat transfer from hot air to a twisted yarn and the temperature attained by the yarn in a heat zone. They conducted experiments on a model nylon 66 yarn of 15,000 denier (1666 tex) composed of 6 denier per filament. The core temperature of the yarn was measured by a fine thermocouple. They used an analytical expression to calculate the temperature profile in a yarn cross section while it was being transported through a heating medium (air, in this case). The thermal diffusivity of the model nylon 66 yarn was found to vary from 0.95×10^{-3} c.g.s units at 20°C to 0.57×10^{-3} c.g.s. units at 220°C. In the case of highly twisted, low-denier nylon yarns (up to 70 denier) heated in hot air at temperatures between 240 and 500°C, the difference between the surface and yarn axis temperatures in the vicinity of the setting temperature (230-240°C) was essentially found to be negligible. The heat transfer coefficient of highly twisted yarns was approximately constant for a given yarn denier over the temperature range 20-500°C and was independent of yarn speed from 6 to 300 m/min. The values of heat transfer coefficient varied from 3.7×10^{-3} cal/sec cm^2 °C for 30-denier (3.3 tex) yarn to 3.15×10^{-3} cal/sec cm^2 °C for 70 denier (7.7 tex) yarn. The heat-transfer coefficient values were used to calculate the yarn temperature at any time during heating at a particular temperature. These experiments showed that the surface temperature of a 70-denier (7.7 tex) yarn twisted to 75 tpi (2952 tpm) could be raised to 230-240°C (setting temperature) in 0.35 sec, but the yarn produced did not have adequate set. However, a heating time of 0.7 sec, obtained by reducing the processing speed and heating rate, was found to produce a well-set yarn. The investigators conjectured that the poor set obtained at heating times less than 0.35 sec was caused by either (1) incomplete conduction or (2) incomplete molecular rearrangement.

The effect of the process of heating and cooling of false-twist textured yarns has been reported by Morris and Roberts (7). They studied the relation between contact time and yarn temperature and between contact time and the degree of set produced in false-twist 70-denier, 34-filament nylon 66 yarns, by using a Scragg-Shirley Minibulk machine. The degree of set was characterized by the crimp rigidity test devised by the Hosiery and Allied Trades Research Association, England. The procedure consists of suspending of hank of a yarn in water at 20°C tensioned under a load of 0.1 g/den. The relaxed length L_1 is measured after 2 min; the load is then decreased to 0.002 g/den, and the relaxed length L_2 is measured after further lapsed time of 2 min. The crimp rigidity is defined as $100\ (L_1-L_2)/L_1$. The modified C.M.G. heater was used on the bulking machine, and the spindle speed could be varied from about 60,000 to 375,000 rpm. The heater length used was 24 in., assembled in six sections, each of 4 in. length. By using two different types of spindle assemblies in the section heater, the contact time could be varied from 0.15 to 3.5 sec. The relationship between crimp rigidity and spindle speed for nylon 66 yarn is shown in Figure 12.15. The yarns were heat set at 230°C and 80 tpi. On the other hand, Figure 12.16 illustrates the effect of contact time on crimp rigidity These results indicate that the crimp rigidity drops rapidly when the machine speed is increased, whereas the increased contact time increases crimp rigidity exponentially. It must be pointed out that the actual contact time, because of contraction caused by twist (as well as filament linear denisty), is generally higher than would appear from the ratio of heater length and yarn speed. The contact time for 70/34 nylon yarn textured at a nominal twist of 80 tpi and a heater temperature of 240°C has been reported to be 1.45 sec within the spindle speed range of 62,000-250,000 rpm.

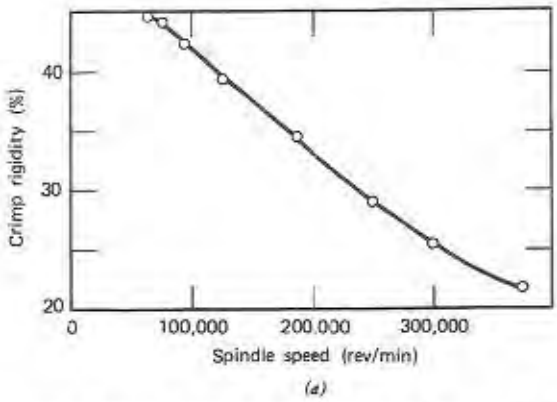
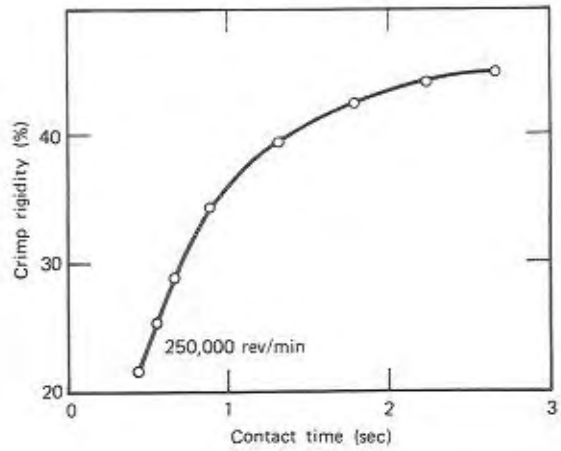


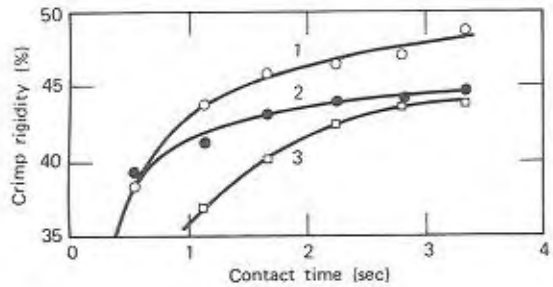
Figure 12.15. Effect of spindle speed on crimp rigidity of twofold 70/34 nylon 66 yarn processed at 230°C (after Morris and Roberts).

Ex. 2020-160

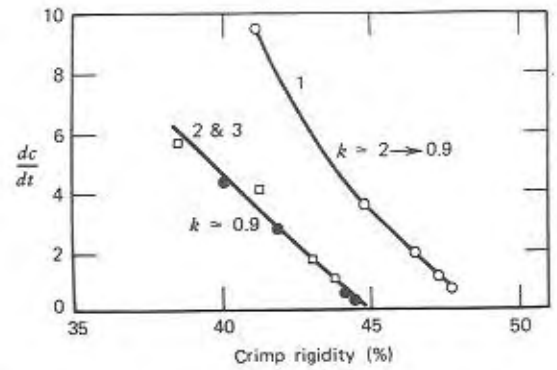


(b)

Figure 12.16. Effect of contact time on crimp rigidity (after Morris and Roberts).



(a)



(b)

Figure 12.17. Variation of crimp rigidity with time for yarn processed at: (1) constant heater temperature (230°C); (2) constant yarn temperature (218°C) after two sections (the results refer to twofold 70/34 nylon 6.6 yarn processed on the multistage heater at a spindle speed of 48,000 rev/min). After Morris and Roberts.

Ex. 2020-161

Studies on the effect of yarn speed and heater temperature have indicated that crimp rigidity is determined not only by the yarn temperature and contact time, but is also significantly dependent on the rate of change of temperature with time. These conclusions are based on the observations that, for a constant heater temperature and yarn speed, the crimp rigidity increases exponentially with time, and there are two distinct regions with different "time constants" in this process. During the first phase, when the yarn temperature is increasing rapidly, the crimp rigidity changes likewise; in the second period, after the yarn has reached the heater temperature, the crimp rigidity continues to increase, but at a much slower rate until a maximum is reached. This is shown in Figure 12.17 (7). This illustration demonstrates that the yarn temperature reaches the heater temperature after about 0.6 sec; however, the crimp rigidity still shows an increasing trend, at a slower rate, and shows no sign of leveling off when the yarn temperature reaches a constant value. This relationship (for temperature rise) has been shown to have the analytical form (8):

$$T_y = T_h (1-e^{-kt}) \tag{12.2}$$

where

T_y = yarn temperature
T_h = heater temperature
k = heat transfer function
and t = heating time

T_y and T_h are temperatures measured above ambient level. (When $kt = 3$, T_y is 95% of T_h) and

$$\frac{dT_y}{dt} = k\ (T_h - T_y) \tag{12.3}$$

(which is identical to the relationship derived by Morris and Roberts (7) for the change in crimp rigidity: $-\frac{dc}{dt} = k\ (Cm-C)$, where C is the crimp rigidity, and Cm is the value of crimp rigidity when the yarn reaches the heater temperature).

The value of factor k is the slope of the plot of dT_y/dt vs. T_y, which is found to be approximately equal to 5 in practice. In other words, the yarn temperature reaches 95% of its final value at $t = 3/5 = 0.6$ sec. From the plot of crimp rigidity against contact time (Figure 12.17), a k value of 2 is obtained. When the yarn temperature is rising and at constant yarn temperature, $k = 1$. This type of analysis would suggest that a time of 1.5 sec is required when $k = 2$, or 3 sec for a value of $k = 1$, for a yarn to attain 95% of its final crimp rigidity value.

The next important step in the processing of textured yarn is the cooling of the yarn before untwisting, because it is during this stage that the setting effect

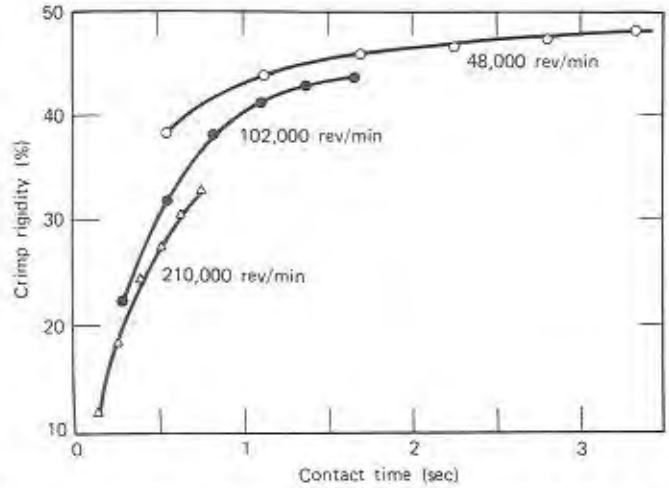


Figure 12.18. Relationship between contact time and crimp rigidity at three spindle speeds. After Morris and Roberts.

takes place. Denton and Morris (8) have considered this aspect of the process. Some idea of what happens to the crimp rigidity when the cooling time is changed can be obtained from the illustration shown in Figure 12.18 (7). These experiments were conducted with a multistage heater, at three different spindle speeds, while the cooling distance was kept constant at 10 in. An examination of the crimp rigidity at each heating time included in all three curves (e.g., 0.7 sec) shows that the crimp rigidity tends to decrease with increasing yarn speed; in other words, crimp rigidity increases with cooling times, which, according to the authors, are as follows:

Spindle Speed	Cooling Time
48,000 rpm	1.6 sec
102,000 rpm	0.8 sec
210,000 rpm	0.4 sec

Further studies on the effects of cooling times covering a much wider range have been reported (8); here the heater length was varied while the heating time was kept constant. The cooling distance above the top of the heater was fixed at 11 in., and the cooling time varied from 0.2 to 1.3 sec. The results of this experiment, shown in the lower curve of Figure 12.19, demonstrate that the crimp rigidity increases as the cooling time increases. This effect is highly pronounced in the initial part of the curve (lower cooling times-representative of times used in some present-day equipment) and tends to level off at higher cooling times.

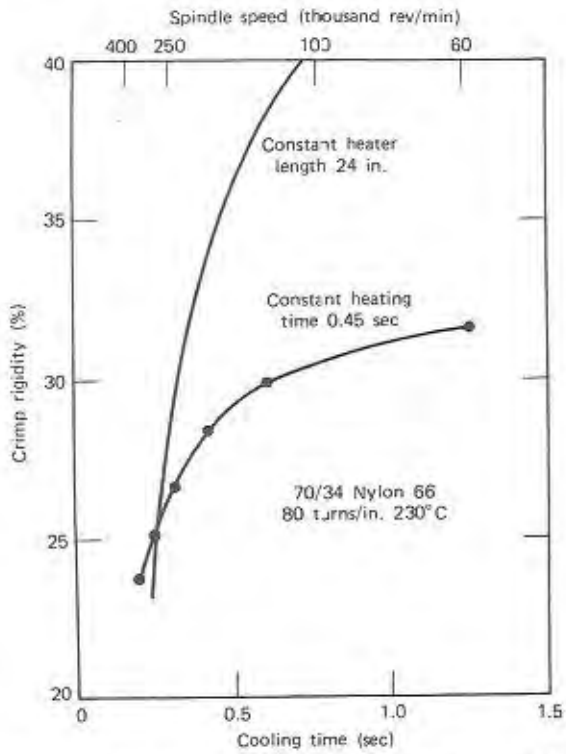


Figure 12.19. Effect of cooling time on crimp rigidity. After Denton and Morris.

The upper curve shows the joint effect of heating and cooling time. It is obvious that the effect of heating time alone is greater; however, the influence of reduced cooling time becomes progressively more important as the spindle speed increases.

The importance of the influence of cooling time has been further discussed by the authors when the process is considered in the light of thread line temperature profile above the heater. This approach is extremely helpful in determining the cooling time required for processing different linear density (denier) yarns. This can be best understood by looking at the value of k in the cooling exponential $T = T_o\, e^{-kt}$ derived from results shown in Figure 12.20. The value of k obtained by substituting the temperature of the yarn as it leaves the heater (230°C) and the temperature after cooling for 0.3 sec (130°C), both taken from Figure 12.20, is found to be 2.3, which is substantially independent of yarn speed. Calculations by Denton and Morris (8) suggest that, for a yarn to cool down to a temperature of 60°C before untwisting, a cooling time of 1 sec would be required, as compared to a time of about 0.25 sec allowed on modern

Ex. 2020-164

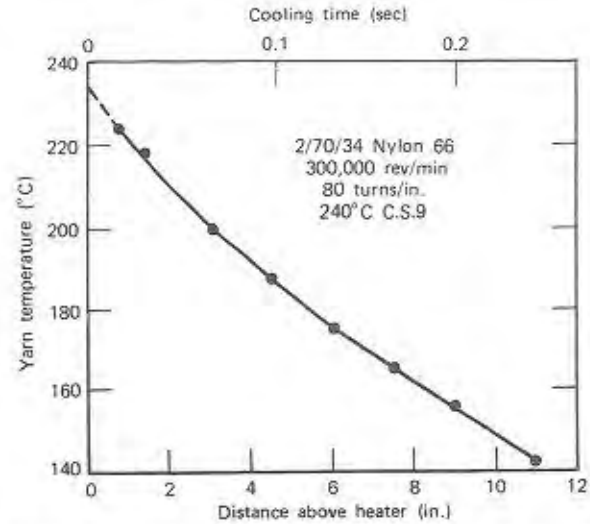


Figure 12.20. Cooling of yarn after leaving the heater. After Denton and Morris.

machines. Figure 12.20 shows that at 0.25 sec the yarn is at a temperature of 140°C. These results relate to a 70-denier yarn. On the other hand, the value of k' would be different for heavy-denier yarns as obtained from equation :

$$k' = \frac{2h}{\rho c r} \tag{12.4}$$

where h is the heat transfer coefficient in air
ρ = yarn density
c = specific heat
and r = radius of the yarn

The specific heat of conditioned nylon (65% r.h., 20°C) is constant at 1.01 ± 0.02 cal/g/°C over the range 60-200°C, at heating rates between 100°C/sec and 1000°C/sec, as reported by Jones and Porter (9).

As the yarn denier is increased from 70 denier to 150 denier, r increases by a factor of 1.4, and the value of k' decreases by 1.4; thus the cooling time for the heavy denier yarn must be increased by the same factor to cool it down to the same temperature. Yarn with lower specific heat will come down more rapidly.

In addition to the crimp rigidity, the tensile characteristics of textured yarns are also influenced by the heater temperature (10). The tensile modulus and breaking tenacity generally show a linear decrease, whereas the extension-at-

Ex. 2020-165

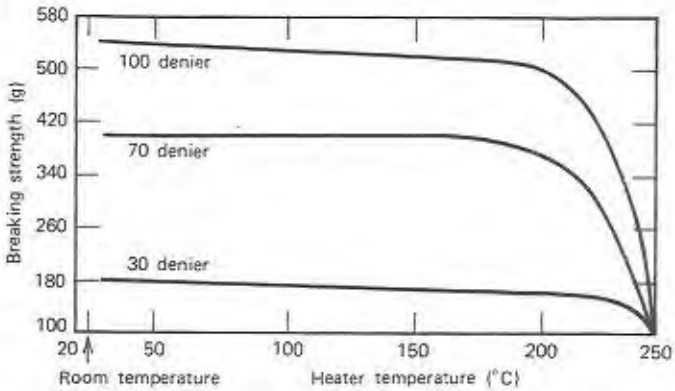


Figure 12.21. Effect of heater temperature on breaking strength. After Burnip and Hearle.

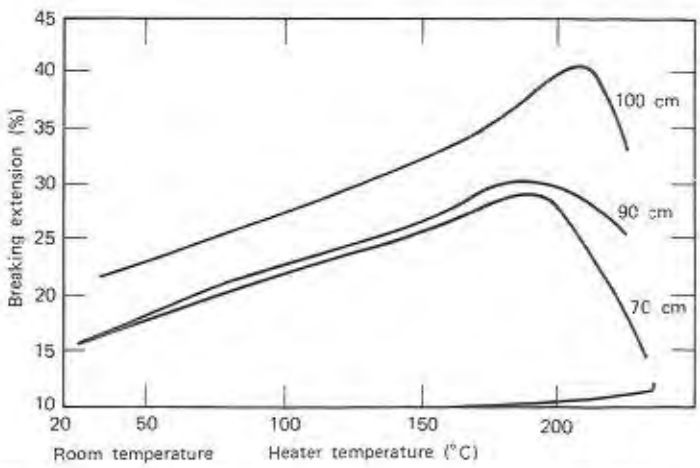


Figure 12.22. Effect of heater temperature on breaking extension. After Burnip and Hearle.

break and the effective stretch (measured at the point of intersection of tangents drawn to the low- and high-modulus regions of the load-extension curve) increase with increasing heater temperature. Figures 12.21 and 12.22 show the kind of relationship observed between heater temperature and breaking load and breaking extension. These changes in the tensile behavior of textured yarns are manifestations of the changes occurring in the morphological structure because of the heat treatment. There are changes in the size and distribution of crystallites brought about by the deformation processes (tension and bending) in the heated state, and these are temperature dependent.

Ex. 2020-166

There is not much information available in the literature on the relative suitability of various heat transfer modes such as conduction, convection, or radiation in the heating of yarn during texturing. But most of the heating systems have inherent capabilities that make them greatly flexible for whatever purpose they are employed.

Yarn Twist

The amount of twist inserted during texturing influences such characteristics as the bulk, crimp, strength, elongation-at-break, and the retractive power of the end product. Twist affects the yarn structure and is manifested in the deformation of individual filaments because of the helical path they follow and the radial disposition (migration) in the yarn cross section. Excessively high twist has a tendency to cause the yarn to have characteristics similar to crepe-spun yarn. On the other hand, low levels of twist cause the yarn to have a "stringy" appearance, probably because of the inability of the insufficiently distorted

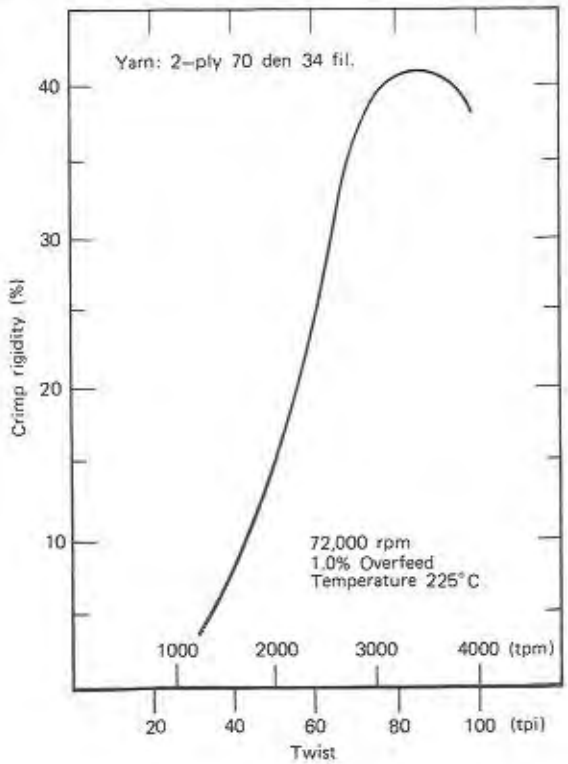


Figure 12.23. Effect of twist on crimp rigidity.

filaments to coil up in loops. The crimp rigidity of false-twist textured yarns in relation to yarn twist is affected in the manner shown in Figure 12.23 (11). The crimp rigidity increases sharply with increasing twist, but at very high levels it tends to either level off or show a downward trend. At excessively high twists, the yarn tends to have tight spots that are detrimental to its bulking and dyeing behavior. Twist also has a profound influence on the tensile properties of textured yarns. The breaking strength and elongation both show a decreasing trend. The basis for the selection of the processing twist is dependent on the consideration that the tenacity of the textured yarn does not fall below a certain desired level. It has been pointed out by Krause (12) that high processing twist levels cause the yarn to develop high torque, which is enough for it to overcome the frictional resistance on the guide pins of the false twist spindle, thus enabling the yarn to roll over the pin, causing slippage and resulting in a reduced amount of absolute twist in the yarn. This type of behavior can also cause reduction in yarn tension. To achieve softness and extra-fine pebble appearance in fabrics, higher twists are employed, whereas low twist levels would produce course and relatively harsh crepe-like handle.

Threadline Tension in the Heat Zone

Low thread line tension conditions during processing can result in the appearance of coiled filaments because of yarn ballooning, loss of twist, or formation of tight spots. On the other hand, high tension may result in reduced bulk, and it may also cause excessive yarn breakage, thus adversely affecting the production efficiency. During the false twisting process, the yarn tension may be controlled in two different ways:

1. constant tension device—used on the earlier Fluflon-type machines, in which the yarn is passed through a gate tensioner before entering the heater so as to impose a predetermined constant tension.
2. constant extension—in which the positive yarn feed system is employed, and the tension is varied by manipulating the relative speeds of delivery and take-up.

The processing tension in the constant-tension type systems is mainly dependent on the initial imposed tension, and the heater temperature has no significant effect (13). However, variation in twist may cause some fluctuations in tension below the heater, but the tension remains essentially unchanged above the heater.

In the constant-extension type machines, the effect of thermal shrinkage, that is, the development of the contractile force, is the dominant factor in determining the threadline tension. The contractile force increases as the temperature is increased up to about the second-order transition of the polymer, and then tends

Ex. 2020-168

to decrease. The other complicating factors include the tangential force on the yarn because of twisting, softening because of heat, and contraction because of twist. This situation can be modified, to a certain extent, by overfeeding the yarn, however, excessive overfeed can nullify the process of torque-crimp. Contractile stresses (including the tension caused by yarn friction) of 1.28 g/tex at 100°C and 1.33 g/tex at 180°C have been reported (13) for 70 denier, 34-filament nylon 66 yarn with 0% overfeed and 0.3 g pretension (without twisting). However, when the same yarn was processed on a false-twist texturing apparatus (45,000 rpm spindle speed), an overfeed of 7% caused instability in the threadline, and 4% underfeed tended to produce frequent yarn breakages above the spindle. There must be, therefore, a compromise in the adjustment of heater temperature and yarn feed rate (under- or overfeed) with some concern for twist and initial tension. Nylon yarns processed at low tensions (because of overfeed) are generally known to have increased dye uptake, presumably because of changes in the morphology of the polymer.

With increasing thread line tension, yarn stretch increases initially, passes through a maximum, and subsequently decreases at very high tensions. Yarn denier and yarn bulk decreases with increasing tension, but the residual shrinkage increases.

Post-Treatment

Textured yarns produced by the false-twisting technique generally have higher stretch and retain some twist liveliness. Before use in knitted or woven structures, the textured yarns are generally stabilized and post-treated by heat treatment to reduce their stretch behavior, to control crimp, to attain increased softness of hand and bulk, and to suppress their torque liveliness. This is accomplished by relaxing or stretching the yarn in a second heated zone. The relaxation may vary up to about 30% of the fully stretched length; thus the yarn develops crimp, and the heating allows the decay of internal torsional and bending stresses.

In recent years, the use of polyester yarns in the United States alone has jumped to approximately 1.3 billion pounds, which accounts for nearly 80% of all the fibers used in texturing, with an expected growth rate of nearly 7% over the next 5 years. Polyester yarns present some special problems during setting; consequently, the post-treatment (including efficient cooling) attains even greater importance in the processing of textured polyester yarns. The post-treatment of yarns can be accomplished by any of the following two methods used in practice. In the early stages of the processing of textured yarns, the most widely used method was that of overfeeding the yarn by a desired amount; the yarn was then soft-wound on the take-up packages. The setting operation was then carried out either in (1) steam under pressure in autoclave or (2) during the dyeing operation. This process is used in making Helenca® SS (smoother sweater) and

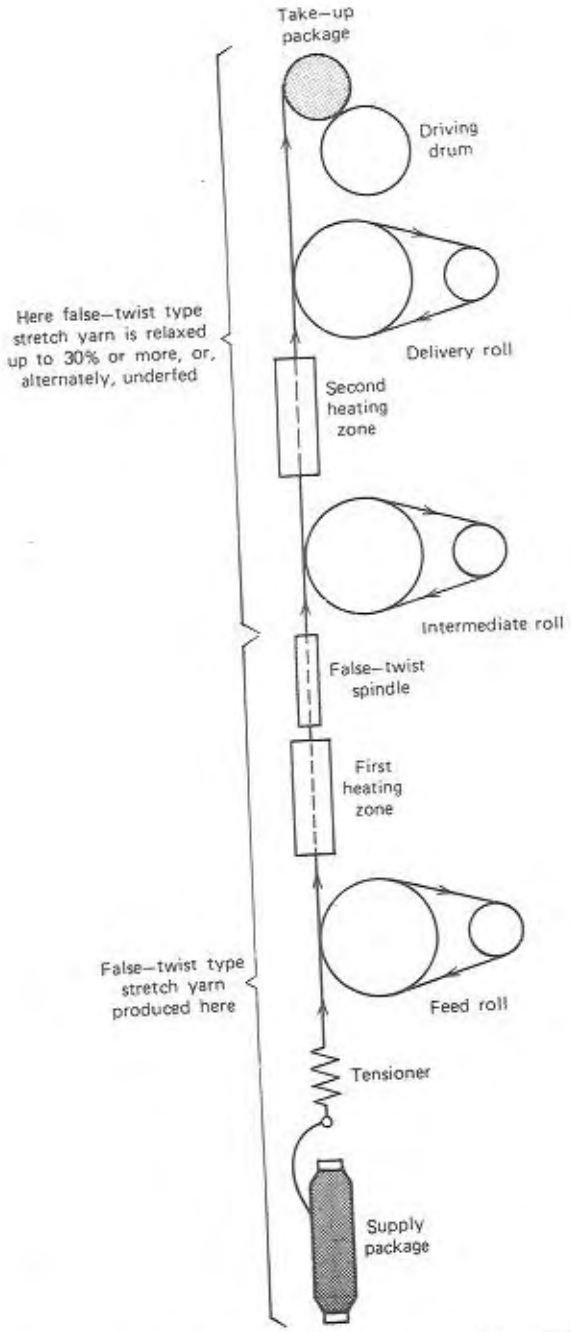


Figure 12.24. Arrangement used for producing post-treated (modified stretch) textured yarns.

Ex. 2020-170

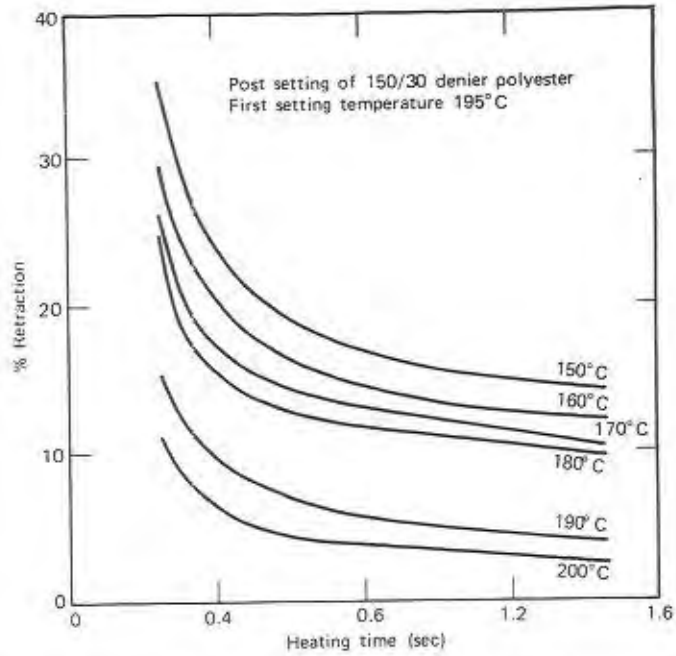


Figure 12.25. Post treatment; yarn retraction versus heating time at various second heater temperature. After Denton and Morris.

"Crimplene"® type yarns The second method, which is continuous in nature is also known as the "dry method," has gained great importance in the industry. In this process the yarn is generally overfed (up to 30% or more) through a second heater situated immediatley after the spindle on the false-twist machine, as shown in Figure 12.24. The relaxation shrinkage of yarns produced by the dry and the autoclave methods generally varies between 8 and 15% and 3 and 5%, respectively, compared to 45 and 70% for regular stretch yarns. The yarns set by the autoclave method are exposed for a very long time, and consequently they are completely set and are essentially free from twist liveliness. On the other hand, heating times in the dry method are relatively short and are of the order of 1 sec; therefore, the efficiency of heating rate, in addition to the time and temperature, are of extreme importance of producing yarns of desired stretch and bulk by this method.

Denton and Morris (8) have reported some preliminary results of their investigation on the effects of time and temperature of dry post-treatment on the properties of a 150-denier postset textured polyester yarn. The temperature of first setting was 195°C. The property measured to characterize the bulking

Ex. 2020-171

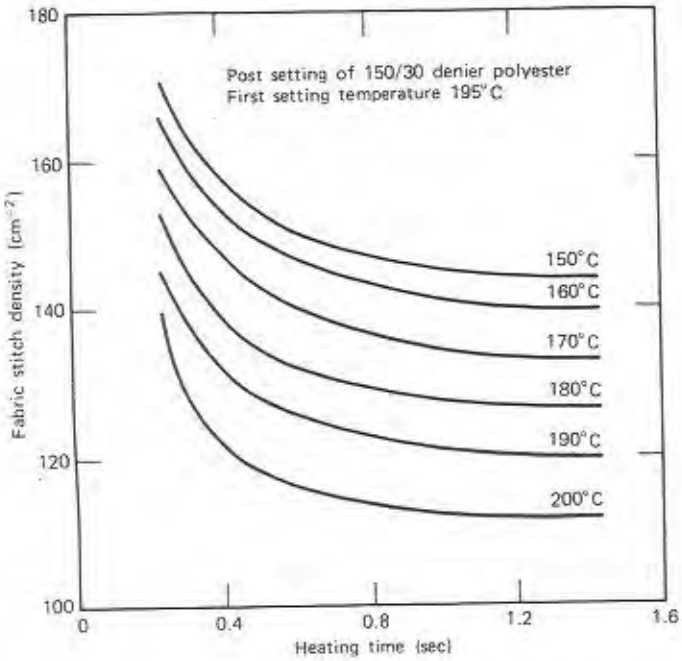


Figure 12.26. Post treatment; fabric stitch density for yarns post set at various times and temperatures. Fabric stitch length 2.9 mm (Denton and Morris).

power of these post-treated yarns was the percent retraction. The bulking power is measured on a hank of yarn after it has been heated for 5 min at 120°C with a load of 0.005 g/d. The results for the influence of heating time on percent retraction are shown in Figure 12.25. It is clear from this illustration that a heating time of approximately 1 sec is required to complete the setting process. Similar times were obtained when the effect of post-treatment parameters on the stitch density of plain knitted structures from these yarns was studied, as shown in Figure 12.26. This higher time of 1 sec suggests that longer heater lengths would be required to produce desirable stretch characteristics. This development is evident from the fact that the length of the second heater used on the most modern false-twisting units approaches 2 m.

Setting and Yarn Properties

Arthur (26) has suggested that the false-twist textured yarns develop the stretch and bulking characteristics because the individual filaments are set in a twisted form. In other words, the yarn behaves as a twist-free bundle of twist-lively fila-

Ex. 2020-172

ments. However, the situation in real false-twist textured yarns is more complicated because the filaments are also set in the twisted yarns in the form of helices. These helices have varying radii because of the migration imposed by the twisting operation. Consequently, the simple model suggested above fails to explain fully the behavior of these yarns. On the basis of the observation of the geometric structure of these yarns, Denton (27) suggests a half-reversed migrating helix model, in which individual filaments are held around the yarn axis in a helix, varying in diameter as they move from the yarn center to the surface and back again. After untwisting, the helical coils show occasional reversal of direction, but the basic geometric shape essentially remains the same. Denton and Morris (8) have carried out a theoretical analysis of such a model and found that this model explains the structure and properties of real yarns. A veiw of the false-twist textured yarn is shown in the diagram (Figure 12.26(*A*)).

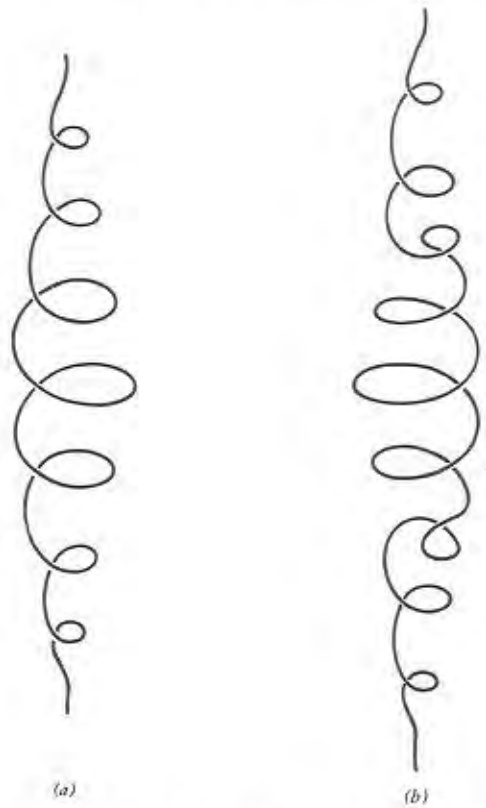


Figure 12.26(*A*). Diagram showing the migrating helix model of a filament in a false-twist textured yarn. (*a*) Setting and before untwisting, (*b*) after twisting, showing reversal. After Denton (27)

Draw Texturing

Until recently, the yarn texturing operation was performed solely by the throwsters. The feed or parent yarn supplied by the fiber manufacturers was fully drawn and oriented. More recently, the fiber manufacturers realized the opportunity of making (by increased take-up speeds) the production of filament yarns more economical and claiming a share of the fast-growing textured yarn market. The production figures reported in the published literature (14) indicate that, by the year 1978, the United States production of producer-textured (fiber manufacturers) yarn would account for nearly 36% of the total domestic shipments, compared to 15% reported in 1973. This growth pattern has been mainly due to the development of draw texturing technology. In addition to the economic considerations mentioned earlier, there are some technological aspects that were also responsible for prompting developments in the draw-texturizing field. These include:

1. Yarn quality, for example, uniformity of dyeing. This is an important aspect, particularly in warp knitting, in which a very large number of yarn ends are used to construct a warp beam. The uneven dyeing can result because of tension variations (a) within a parent yarn (from inside to outside diameter of bobbin), and (b) during the texturing operation. On the other hand, these variations in tensions are practically eliminated because of the nature of the draw texturing process.
2. Yarn processability. The production efficiency of the conventional texturing process is influenced by the spindle speed and the flat yarn quality. The parent yarn generally contains defects that are introduced during the winding operation performed on the draw-twister (ring travelers) and during the packing and unpacking of the bobbins. These defects, when viewed in terms of the machine parameters, such as the high spindle speeds (in excess of 800,000 rpm), pin diameter (1 mm), and the feed rates of 100 m/min, can compound the situation.

Draw texturing is a process in which an undrawn (fully or partially) flat yarn is drawn to the desired size and then textured in a continuous manner. The texturing process pertaining to the false-twisting method has already been discussed in detail. Some important aspects of the feeder yarn qualities are mentioned earlier in the text. However, it is deemed advisable to throw some light on the quality requirements of the feeder yarn meant for processing on draw-texturing equipment. In the conventional method of texturing, the feeder yarn is generally fully drawn, and the method of production of continuous-filament yarns is discussed in Chapter 11. However, it must be pointed out that the fully drawn yarn is produced in two steps, which makes the process expensive. This inspired the use of completely undrawn yarns (during texturing) in order to make the whole

Ex. 2020-174

process more economical. However, the use of undrawn yarn in the draw texturing process caused some technical difficulties, and the processed yarn had some undesirable characteristics. Some of these are:

1. The undrawn yarn has poor shelf life. Particularly, the polyester undrawn yarn has a shelf life of approximately 100 hr.
2. The undrawn yarn packages are generally unstable, which causes variations in tension as well as filament cross-sectional shape.
3. It has low zero tenacity temperature, that is, the temperature at which the filament completely loses its strength.
4. The undrawn yarn is very sensitive to moisture and temperature changes in the environment, and this can result in the production of different effects from the inside to the outside of the bobbin.
5. It presents some difficulties as to the quality of the transfer knots that are essential for continuous uninterrupted operation and reduced down time.

To overcome the aforementioned drawbacks and to satisfy the demand for better-quality feeder yarn, the attention of technologists shifted to the use of partially oriented yarn (POY is the abbreviated term used in the trade). This development was the result of a compromise between increased production and yarn quality. The partially oriented yarn is produced in a single-stage process with take-up speeds of 3500 m/min (increasing productivity by 50-60%), compared to the conventional two-step process in which take-up speeds of 1300

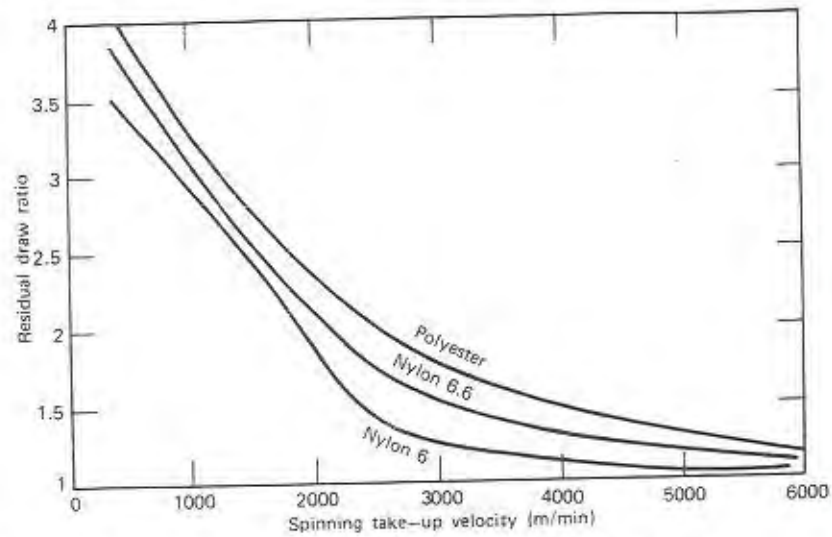


Figure 12.27. Relationship between spinning speed and residual draw ratio.

m/min are common. The partially oriented yarn spun at these speeds is quite satisfactory during storage for several weeks, and, in general, there is little difference between nylon and polyester. The partially drawn yarns meant for textuing generally have a draw ratio varying between 1.5 and 2.2. Figure 12.27 shows the relationship between the spinning take-up speed and the residual draw ratio for polyester and nylon yarns (15). It is clear from the illustration that, at spinning speeds up to 1500 m/min, the draw ratios are higher than 2.5:1. At medium speeds up to 3500 m/min, the draw ratios are less than 2:1. At spinning speeds higher than 4000 m/min and up to 6000 m/min, the curve for production flattens off (draw ratios approach 1:1), and the increase is only about 10-15%. The resultant advantages of partial drawing, which modifies the molecular orientation, are the increase in temperature tolerance and higher zero strength temperature, as shown in Table 12.4 (15). The increased orientation increases the birefringence. The yarn number 9 is a fully drawn yarn. The partially drawn yarns can be processed on almost all types of commercial draw-texturing equipment. A partially drawn yarn denier of 270-300 (residual draw ratio 1.8 to 2.0) is preferred for producing 150-denier textured yarns.

Table 12.4. Zero Strength Temperature of Various Polyester Yarns

Yarn	Birefringence ($n_{\parallel}-n_{\perp}$)	Crystallization Exotherm Centered at	Temp. of Zero Strength
1	0.004	138°C	145°C
2	0.003	135	145
3	0.010	131	143
4	0.008	131	145
5	0.038	107	250
6	0.050	106	240
7	0.056	97	234
8	0.055	98	232
9	0.218	–	251

Draw-Texturing Process

The drawing operation can be combined with any of the existing texturing processes. However, there are two possible ways in which this combination can be achieved.

1. Single-zone or simultaneous or in-draw process, in which the drawing and texturing are carried out simultaneously in one zone between the feed roll and the drawing godet, as shown in Figure 12.28*a*.
2. Two-zone or sequential or out-draw process, in which the drawing is per-

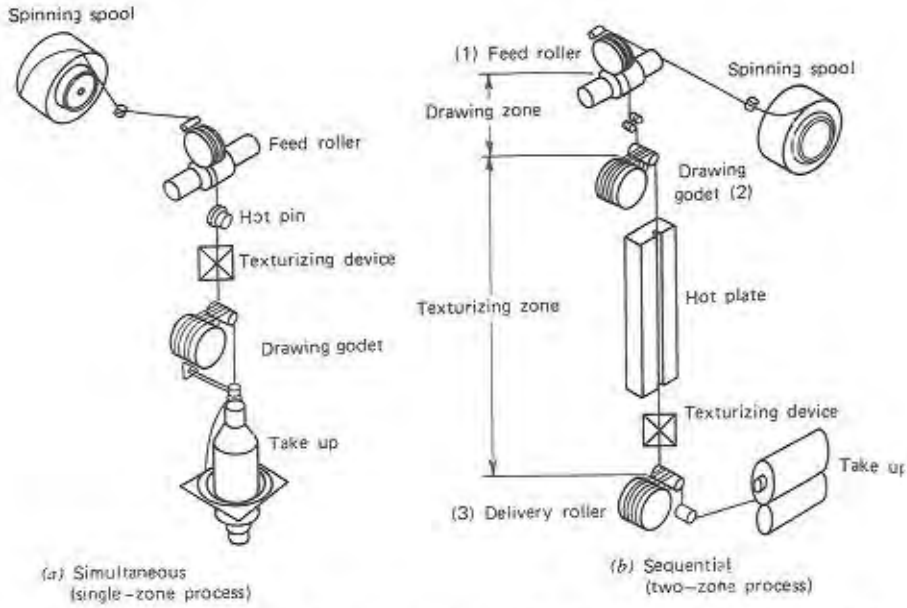


Figure 12.28. Arrangements for draw texturing. (*a*) Simultaneous (single-zone process), (*b*) sequential (two-zone process). (Courtesy: Enka Glanzstoff AG)

formed between feed assembly one and two and the texturing between two and three, as shown in Figure 12.28*b*.

The most important system of texturing combined with drawing is the false-twist process (either spindle or friction twisting). The two-zone method produces yarn with characteristics similar to conventionally textured yarns. However, the sequential system that requires the incorporation of an extra set of feed rolls, and in the case of polyester, temperature-controlled hot pins or plates, suffers from the high cost of the development of drawing-false-twisting machines. Nevertheless, systems of the sequential type have been developed; one such machine has been described by Mattingley (16) and is known as the texDror system. Yarn output speeds of 175 m/min have been claimed for this system. On the other hand, the single-zone or the simultaneous process seems to be more attractive from the point of view of economy. This process is identical to the conventional system, the only difference being in the speed of the input feed roll, which is considerably slower in the draw-texturing process (required to accomplish drawing). Nevertheless, there are some subtle differences in yarn quality between the conventionally produced and the draw-textured (sequential as well as simultaneous) yarns that deserve attention.

Ex. 2020-177

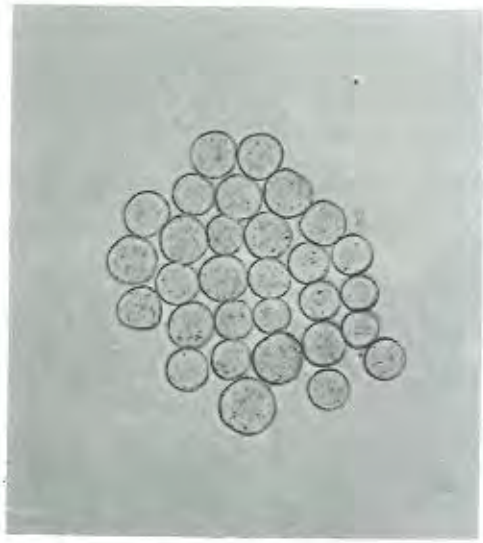


Figure 12.29(*a*). Filaments of a 150 d tex (135 den)/30 fils polyester yarn in different drawing state in the draw-textured zone.

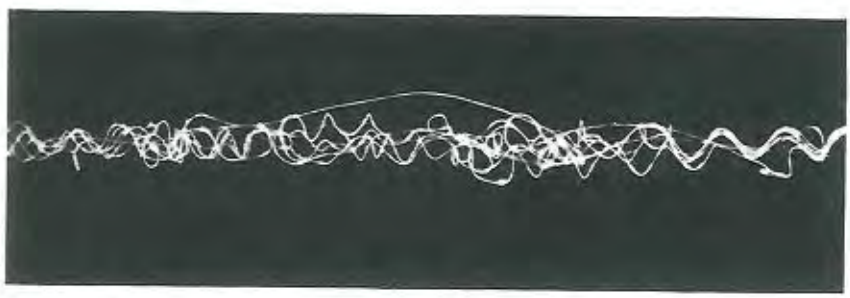


Figure 12.29(*b*). Untextured filaments formed into loops (nylon 66 hosiery yarn, 22 d tex (20 den)/7 fils false-twist textured in the first zone). (Courtesy: Enka Glanzstoff AG)

1. It has been observed (17) that, in draw texturing, broken filaments occur in the yarn. The explanation for this defect lies in the unevenly drawn state of the filaments immediately above the hot plate, as shown in Figure 12.29*a*. These filaments are generally fully drawn before or after the twist spindle. In other words, some of the drawing would occur in the cooling zone, causing some filaments to break. To avoid this, some adjustments in the false-twisting processing parameters are needed. Uneven drawing can also cause some fully drawn filaments to lose their crimp; as a result, some filaments may end up in looped form and protrude out of the filament

bundle, as shown in Figure 12.29*b*.

2. Filaments in draw-texturing processes suffer greater cross-sectional shape deformations than are observed for conventionally textured yarns (Figure 12.30). This modification in the cross-sectional shape imparts certain undesirable glitter to the resultant yarn and fabric.

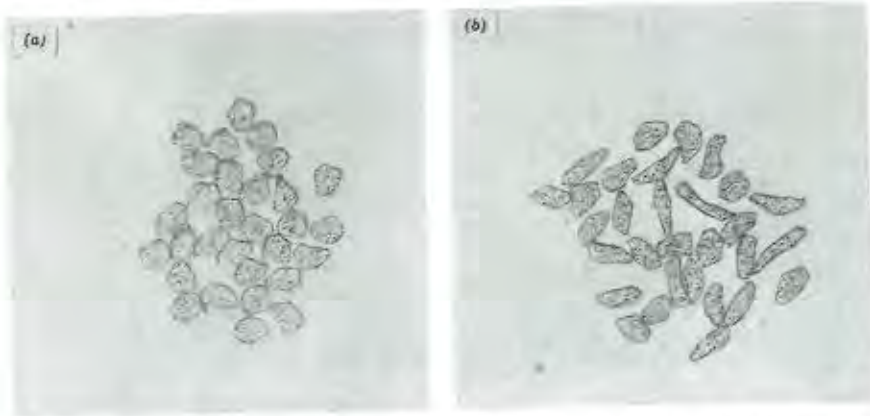


Figure 12.30. Deformed cross section of textured polyester filament yarn–150 d tex (135 den)/30 fils. (*a*) conventional; (*b*) draw-textured (Courtesy: Enka Glanzstoff AG)

3. Surprisingly, the draw-textured yarns, dye deeper than the conventional yarns.
4. The fabrics made from draw-textured yarns generally have a crisper hand than the conventional yarns. This may be attributed to the greater filament cross-sectional deformation, as mentioned earlier.
5. Because of the use of larger supply yarn packages (20-25 vs. 7-10 lb), draw texturing offers reduced processing cost because of less frequent creeling and fewer yarn breakages associated with fewer knots. Higher spindle speeds (600,000 vs. 400,000 rpm for conventional) are another plus for the draw-texturing process.
6. The efficiency of subsequent processes is improved because of the longer yarn length (larger packages) that are knot free.
7. There are essentially no differences in the tensile properties of conventionally and sequentially draw-textured yarns. However, the simultaneous process produces yarns that show lower tenacity but slightly higher elongation-to-break when compared to conventionally textured yarns. This is shown in Table 12.5 (15) for a 150-denier textured polyester yarn. Mey (18) has reported similar effects of draw ratio on the properties of conventionally false-twisted textured nylon yarn.

Table 12.5. Comparison Between Properties of Conventional and Draw-Textured Polyester Yarns

Property	Conventional/Sequential	Simultaneous
Tenacity (g/den)	3.2-4.5	2.7-3.5
Breaking elongation (%)	26-35	27-40
Leesona skein Shrinkage set method (%)	15-25	15-25
Thickness index (FAK Fabrik)	60-70	60-66
Torque (FAK Fabrik)	6-18	4-10
Fiber shrinkage	–	Variable
Fiber cross section (compared to feed yarn)	Similar	Deformed
Luster	Similar	Greater

Recent Advances in False-Twist Texturing

This section is designed to familiarize the reader with the latest developments in the field of conventional and/or draw-false-twist texturing processes. Most of the equipment shown at the last international textile exhibition (ATME-I-1973, Greenville, S.C., USA) indicated that machinery manufacturers placed the accent on lower maintenance cost and better yarn quality (improved heater design), in addition to the most obvious factors, such as productivity and labor-saving devices. The other important observation made by a large section of the texturing trade was that simultaneous draw-finishing coupled with friction spindles would constitute the major thrust in yarn texturing. There was one completely new and revolutionary concept called "fluid texturing" unveiled at the show, and it promised some advantages over the existing texturing devices. Some features of these new developments are discussed. The main features of most texturing equipment shown at the exhibition are summarized in Table 12.3.

The machine marketed by BARMAG (American Barmag Corporation, Charlotte, N.C., USA), called Autocrimper FK 5C, is designed to adapt both to conventional texturing and to sequential and simultaneous draw texturing (Figure 12.31). An important feature of the machine is the new Dow-Therm Vapor Condensation primary heating system, in which the temperature of the heater plate is controlled accurately throughout the entire surface within close tolerances. The cooling zone can be adjusted between 18 and 30 in. The machine can be supplied with either friction (the equivalent of 4 million rpm) or

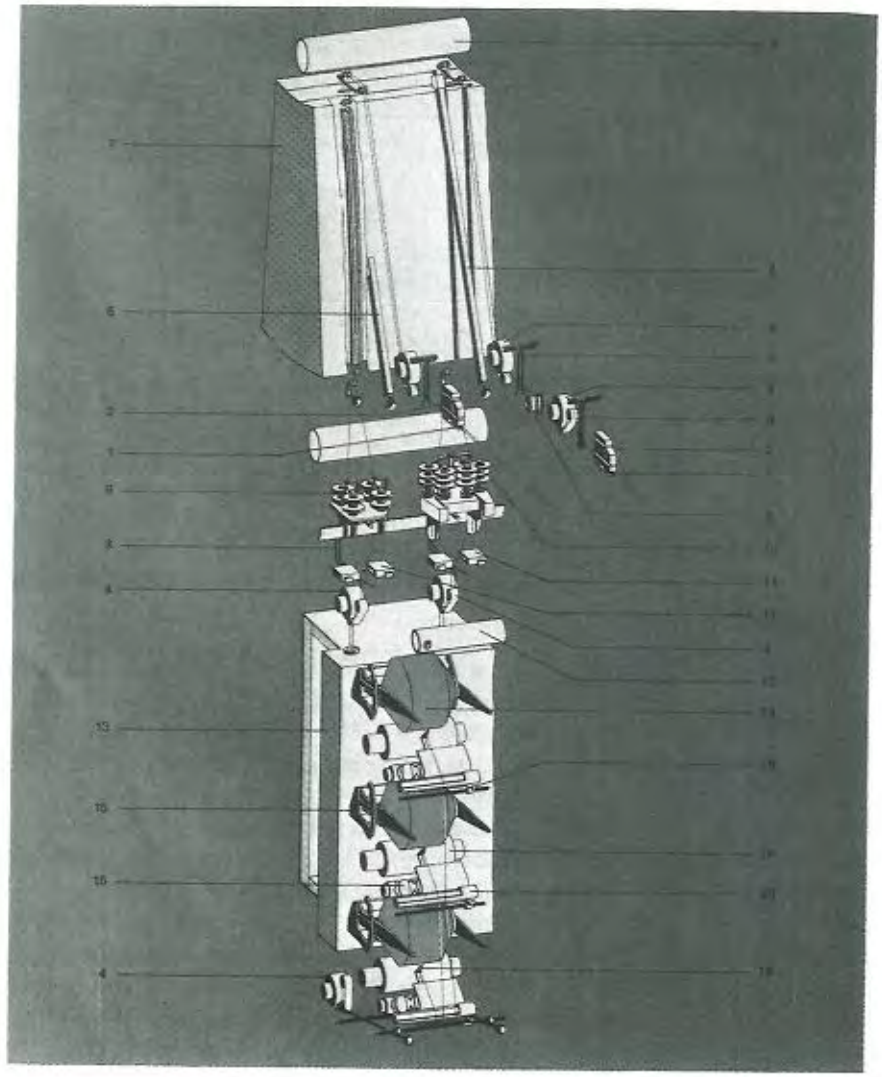


Figure 12.31(*a*). Line diagram showing set up of Barmag's Autocrimper FK 5C. (Courtesy Barmag Corporation) (1) Creel. (2) Yarn tensioners. (3) Yarn cutter. (4) Threadguide fork. (5) Apron feed system. (6) Threading device. (7) Primary heating. (8) Fume extraction. (9) Magnetic unit. (10) Friction unit. (11) Yarn break sensor (12) Yarn aspirator. (13) Setting equipment. (14) Take-up unit. (15) Swivel mounted tube holder. (16) Traverse motion. (17) Drive rolls. (18) Traversing thread guide. (19) Guide. (20) Yarn oiler.

Ex. 2020-181

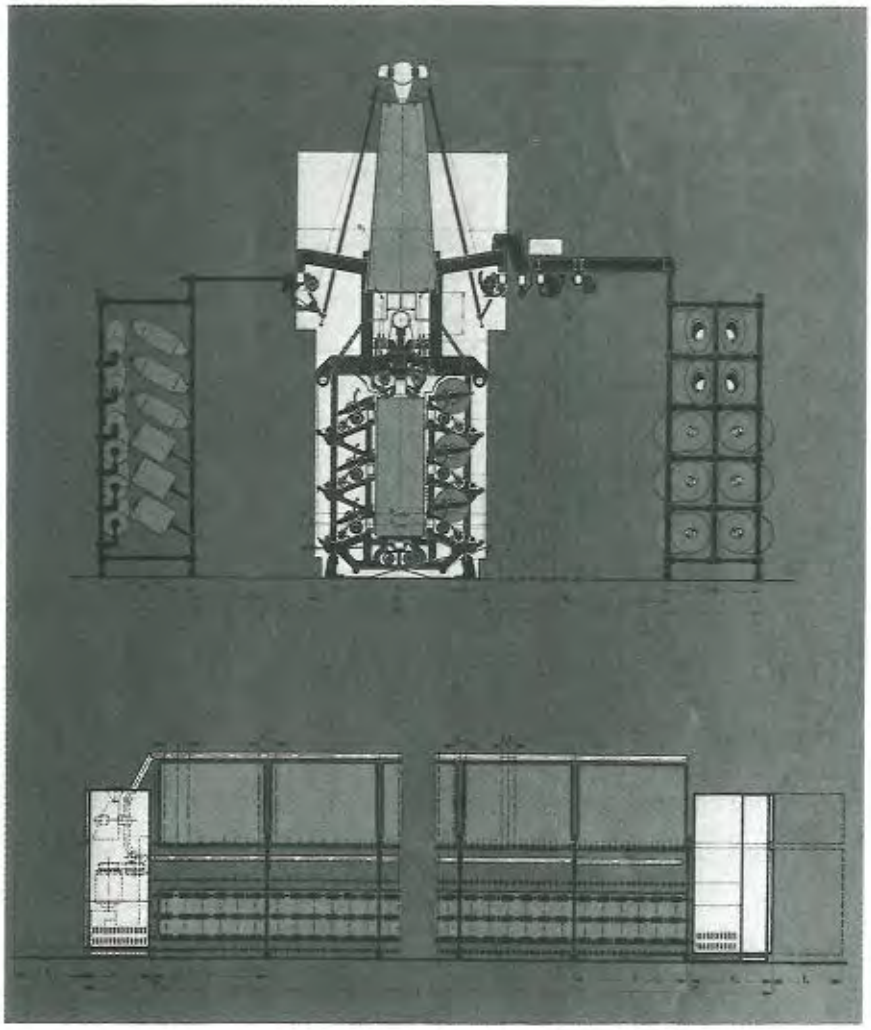


Figure 12.31(*b*). Side view of Autocrimper FK 5C.

magnetic pin spindle (800,000 rpm). It incorporates a relatively new tape-feed system that practically assures slip-free yarn transport even at high yarn tensions.

Spinner OY of Finland, a pioneer in the use of the friction-twist principle and the first company to combine drawing and texturing into one process, showed their latest frictional-spindle false-twisting machine, called 32VK-VTS/A. This machine has two heaters and is capable of processing both high-elasticity and set

Ex. 2020-182

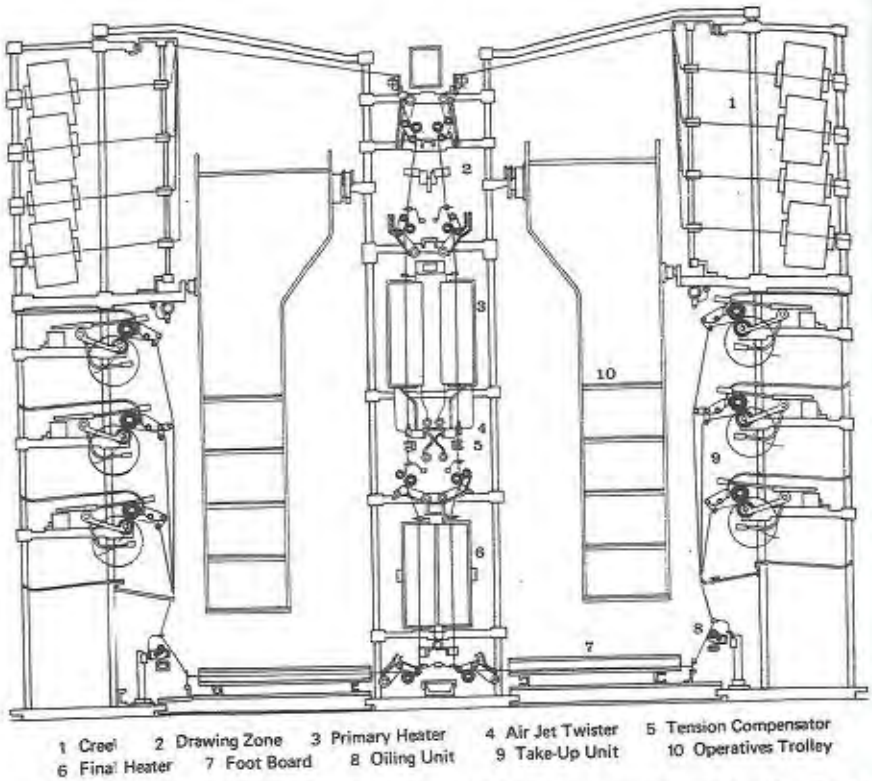
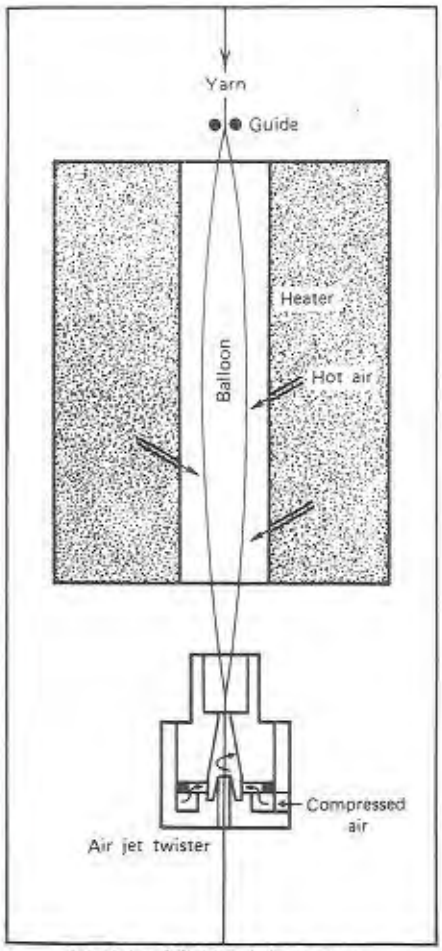


Figure 12.32. Fluid draw-texturing set up model J-202 (Courtesy: Toshiba Machine Co. of Japan).

yarns over a large denier range (15-200 denier). A 245-denier, 34-filament polyester feed yarn can be processed into a nominal 150-denier yarn at 500 m/min.

The concept of fluid texturing, originally developed and patented by Uniroyal Corporation in the United States, has been exclusively licensed and perfected by Toshiba Machine Company of Japan. A schematic of the model J-202 Fluid Draw-Texturer is shown in Figure 12.32. This concept can be applied to single- or double-heater false twisters, with or without continuous predrawing, to process textured yarns at practically double the present production rates. This is achieved mainly by the complete elimination of the conventional false-twist spindle or friction devices and using a compressed-air jet, as shown in Figure 12.33. The use of an air jet ensures rapid, smooth, and quiet (very low noise level) operation at low yarn tensions. The machine can process 150 denier textured polyester yarn from a 260-denier, partially drawn yarn at an output speed of 240 m/min. The air comsumption at standard 100 psi pressure is

Ex. 2020-183



Principle of fluid twisting system

Figure 12.33. Principle of fluid-twisting system.

extremely low (10 l/min/position). The special type of heater is of the non-contact type, and the use of hot blown air into the path of the yarn makes the thermal setting more effective.

The Kosmotex yarn-texturing machine manufactured by Platt International Company of England is of the sequential type (separate draw, texturing, setting, and take-up zones). This machine is capable of processing 150-denier (167-decitex) set polyester yarn at 600 m/min. A friction spindle of the bush type is used for twisting. The successful operation of friction twisting as applied to the process of draw texturizing depends on the following factors:

Ex. 2020-184

1. Frictional characteristics of the bush surface must provide stable twist conditions
2. the application of spin finish is critical to optimum fiber-to-fiber friction
3. fiber-to-fiber surface friction must be optimized by applying a desired amount of spin finish to feeder yarn
4. stability to the threadline demands careful adjustment of processing conditions, for example, there should be no tension variations with twist variations (twist bleed or surging).

The developments in false-twist texturing described above and those apparent from the machine details given in Table 12.3 should not be accepted as a limit to the technological development in the sophisticated area of texturing. The area that needs most urgent attention is the conservation of power. In texturing, a large part of the heat input to yarn heaters is used to make up losses rather than to heat the yarn. Higher output rates may be considered to make more efficient use of power. Noise level is another important factor for which most countries are setting mandatory limits to protect workers. The use of friction aggregates with individual motor drive at each position, and air support bearings, or the use of the air-jet twisting principle, offer inherently low noise levels.

Edge-Crimped Yarns

Stretch and modified stretch yarns can also be produced by a process known as "edge crimping." Edge-crimping processes have been developed and licensed by Deering Milliken Research Corporation (USA) and ICI Fibers Ltd. (U.K.). The yarns produced by the edge-crimping process are marked Agilon®. The commercial use of the edge-crimping process has grown slowly and steadily, mostly using 15-denier monofilament and 15-denier/3-filament yarns for use in the ladies stretch hosiery area. Since its introduction, the use of edge-crimped yarns has been extended to heavy-denier yarns for use in such diversified areas as carpets (1000 denier and heavier), knitted outerwear, men's hosiery, etc.

Thermoplastic yarns are edge crimped by a continuous process in which a yarn is tensioned, stretched, heated, bent, and drawn around an edge, followed by shrinking and cooling steps. The basic principle of edge-crimping is illustrated in Figure 12.34. The crimp development in a filament is caused by the bilateral compressional and extensional strain deformations induced in the heated filament as it is being pulled over a blunt knife edge. The part of the filament touching the knife edge is under compression, whereas that on the outside experiences extension. Consequently, the region pressed against the knife edge is deformed into a flat, and the filament cross section appears as shown in Figure 12.35*a*. The final crimp development is thus a function of temperature, bending curvature, and the dwell time on the edge. The bending curvature is determined by the filament or yarn diameter, threadline tension, the angle of inclination of

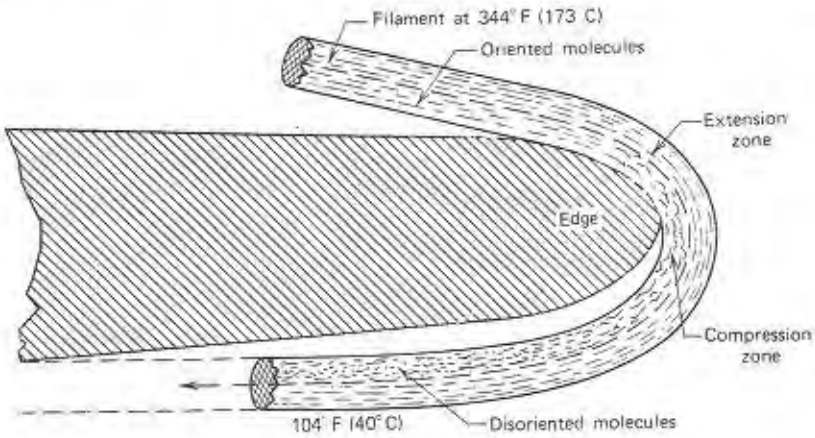


Figure 12.34. Principle of edge crimping.

the yarn as it bends around the knife edge, and to a certain extent on the geometry of the edge itself. The dwell time on the bend is influenced by the speed at which the yarn or filament is withdrawn. When a filament or a yarn is heated above its second-order transition (which varies with the polymer type), the polymer material in the compression zone undergoes morphological changes such as rupture of crystallites and disruption of molecular orientation. On the other hand, the region farthest from the edge is stretched, with the intermediate segments being compressed or stretched in direct proportion to their distance from the edge. To develop crimp in the filament, the strains thus induced are relaxed by subsequently relaxing and heating the yarn under controlled conditions.

Relaxation is carried out either in steam or in dry heat. The release of the strains causes the unstable compressed region to shrink, whereas the stretched zone is relatively unaffected. In this process the filaments tend to form coils in almost perfect helical configuration reversing at more or less regular intervals, as illustrated in Figure 12.35*b*. This inherent rotational process of helical reversal produces a yarn that is balanced or torque-free and does not require any further plying operation to modify its torque-livelinesss characteristics.

Mechanism of Edge Crimping

Consider a filament that is being deformed by a tensile strain on one side and a compressive strain on the other. Analysis of such a model (19) predicts that the filament will take up a helical form, and it is possible to calculate the number of helical turns per unit extended length of the filament by the following expression:

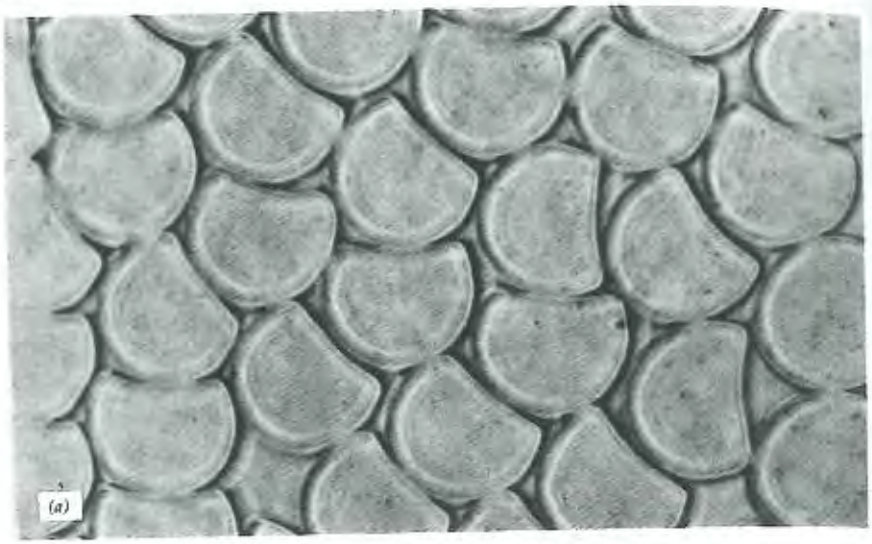


Figure 12.35(*a*). Nylon 66 edge-crimped yarn showing flattened filament cross sections.

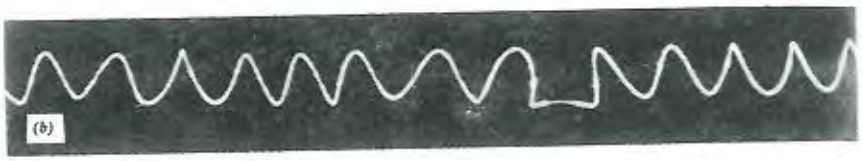


Figure 12.35(*b*). Edge-crimped monofilament. (Courtesy: Deering Milliken Research Corporation)

$$C_f = k\ C_p\ \Delta\sigma/h \tag{12.5}$$

where C_f = frequency or number of crimps per unit extended length of filament
k = constant
$\Delta\sigma$ = strain differential
h = fiber thickness
and C_p = a measure of strain asymmetry.

However, in the above expression, C_p also denotes crimp potential function and is a measure of the original texturizing stress, which is a function of the relative depth of penetration of the compressive forces into the fiber.

In edge crimping, the compressive forces vary along the yarn cross section, being maximum at the contact point and gradually decreasing as the distance increases from this reference point. The application of the above analysis can be applied to the edge-crimped yarn in which the bilateral symmetry is set by the sharp bend of the filament around the edge. The crimp potential function C_p for

Ex. 2020-187

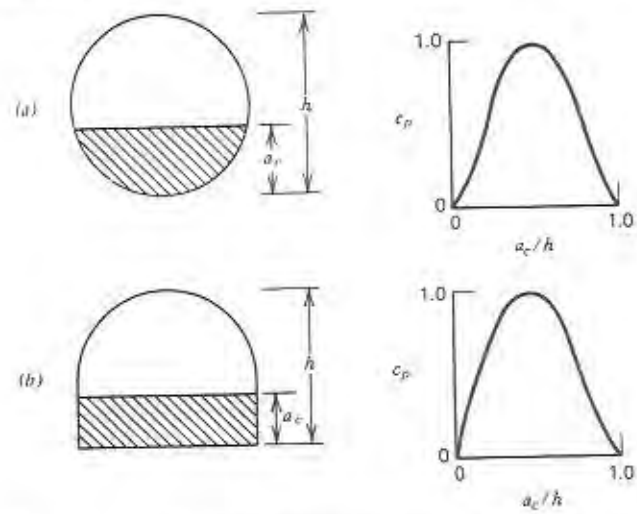


Figure 12.36. Edge-crimping model showing the relationship between crimp potential function and the compressive forces.

such a yarn is a function of the depth of penetration A_c of the compressive forces, and for a circular cross-sectional model, it is shown in Figure 12.36. For this model the crimp potential is at a maximum when the penetration depth is equal to the radius of the filament. The other model (Figure 12.36*b*) is a representation of the edge-crimped yarn. Here the edge deformation, which is flattened, shifts the optimum penetration of the compressive forces toward the deformed edge. Thus the depth of penetration of compression is determined by the temperature of the filament and to a lesser extent by the threadline tension. The maximum strain differential $\Delta\sigma$ between the compressive and tensile components is determined by the geometry of the edge and the angle that the filament makes with the edge. Obviously $\Delta\sigma$ will be highest for the smallest edge angle. Consequently, the highest crimp will be obtained using the smallest angle; however, the angle of 10° is considered to be the practical lower limit. The crimp frequency is inversely proportional to the filament diameter (thickness) and for a circular cross section to the one-half power of denier. In other words, for a given crimp potential, the crimp frequency will be higher for finer denier filaments.

It was determined earlier that the development of crimp is determined by shrinkage and recrystallization during relaxation in the compressive zone. If the longitudinal restraint during relaxation is extremely high, it prevents the formation of coils during crimp development. There is generally some restraint present in practice, and this causes the formation of an open coil helix.

Ex. 2020-188

Modified or stabilized Agilon® yarn with lower stretch and high bulk can be produced on the same machine by adding a bulk-development section. When a stretch yarn is overfed to the development heater, the crimp in the yarn is developed, and it stabilizes in an open bulked configuration. Yarns varying from 0 to 50% shrinkage may be produced by this process. Fabrics made from stabilized Agilon® yarns have a soft, full hand, good surface texture, very good dye uniformity, moderate stretch, and excellent recovery from stretch.

Stuffer-Box Crimping

The process of texturing by the stuffer-box method is based on the principle of heat setting filaments held in a confined space in compressed state and then withdrawing them in their crimped form. The chamber in which the filaments are stuffed is known as the "stuffer box." There are essentially three commercial stuffer-box texturing processes:

1. Pinlon®
2. Spunize®
3. Textralized® yarn

The Pinlon® process can be applied to a single or multi-ends, and the texturing is carried out on a Pinlon machine (KMG Machinery, Ltd., England) that is capable of processing 800-3500 denier and above at an ultrahigh speed of 600 m/min. The types of yarns produced by this process can have a wide variety of crimp configurations.

The Spunize® (Spunize Company of America, Inc.) process imparts three-dimensional crimp at very high speed and heat sets the yarns at the same time. The feed generally consists of multiple ends, and denier varies from 30 to 5000 and heavier. These yarns are generally used for carpet and upholstery materials.

The third commercial process, known by the Ban-Lon® and Textralized® trademarks, is a bulking process exclusively owned and controlled by Joseph Bancroft and Sons Company, Wilmington, Delaware, USA. Ban-Lon® is the trademark identifying garments and fabrics produced from stuffer-box bulked yarns called Textralized® yarns, which are required to meet the standards set by the licensing company. The crimping unit used in producing Textralized® yarns is shown in Figure 12.37. The process itself is carried out on special models of Foster cone winders. The thermoplastic feed yarn is positively fed by two feed rollers into the heated tube-stuffer box. On the output side, the yarn is passed through a weighted hollow tube or slug that impedes the progress of the crimped yarn traveling up the tube, thereby causing the yarn to back up inside the stuffer-box tube. The feed rolls at the same time keep delivering fresh yarn against the backed-up aggregate in the tube. This operation causes the filaments of the yarn to stack up in bent or crimped form. The crimp resembles the

Ex. 2020-189

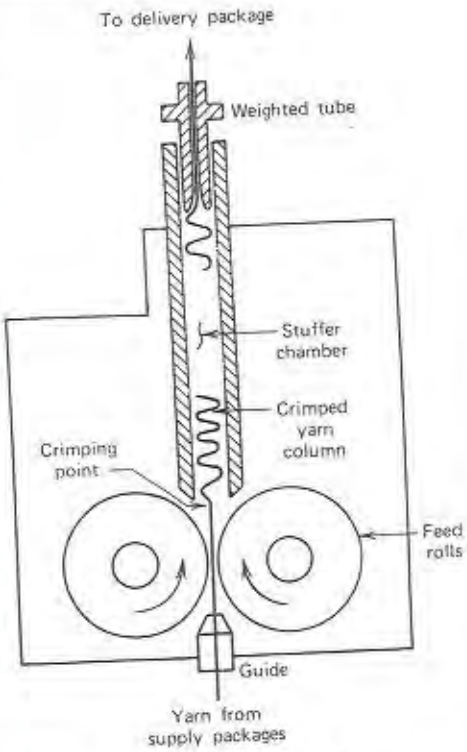


Figure 12.37. Stuffer-box principle used for producing Textured yarns. (Courtesy: Joseph Bancrost & Sons Co.)

saw-tooth configuration. While the feed yarn is being delivered to the stuffer-box, the crimped yarn is removed at a predetermined rate and wound onto the take-up package, and the aggregate in the tube moves up and is heat set at a required temperature in the stuffer box, which is jacketed by heaters. The yarn is oiled as it emerges from the weighted tube, it is then coned.

The ratio of feed to take-up speed and the weight of the tube determine the crimp amplitude and frequency. The temperature of setting and the feed yarn characteristics (filament denier and total yarn denier) are additional factors that determine the crimp quality of the bulked yarn. The tension applied during the heating and cooling cycle undoubtedly affect the degree of stretch and the recovery characteristics that the resultant yarn possesses.

The hot stuffer-box yarns generally have a wiry appearance, a soft feel, and high cover and bulk characteristics. Of course, the amount of relaxation would modify the bulk, as shown in Figure 12.38. These yarns also have good moisture absorption properties because of the minute spaces (interstices) created between the filaments (because of crimp) that can hold moisture. In general, the Textralized® yarns that possess wavy, random, and zigzag crimpness impart the following characteristics to fabrics made from them:

Ex. 2020-190

Figure 12.38. Textralized 2-ply 70 den-34 filament yarn.

1. soft and bulky hand
2. increased volume in the range of 200-300%
3. sufficient elasticity to provide a snug comfortable fit in garment form
4. high moisture sorption, which is good for comfort

Yarn deniers ranging from 15 to 4000 and above are processed by this method. The retractive (uncrimping) power of stuffer-box crimped yarn is governed by the geometry of the crimp (planar in this case), the sharpness of crimp, and the crimp frequency and can be roughly expressed by the following relationship:

$$P = KC_f D^2/N \tag{12.6}$$

where

P = retractive (uncrimping) power
K = constant
C_f = crimp frequency
D = total yarn denier
N = number of filaments in a yarn.

Note that the uncrimping power is proportional to the first power of C_f, whereas in the case of yarns having helical crimp (false twist and edge crimp), it varies as the square of crimp frequency. Thus much of the stretch in stuffer-box crimped yarns can be removed by a relatively small pretension. However, their bulking power is generally excellent.

Air-Textured Yarns

The air-jet texturing process for producing bulk yarns was developed by E. I. du Pont de Nemours & Co., Inc., USA. Bulk in continuous-filament yarns can be produced by blowing a stream of air into a twisted yarn while it is being delivered at a higher rate than it is being taken up by the winding process. The air stream creates a turbulance that causes the formation of random loops in overfed individual filaments. In this process, the yarn contracts in length, and as it emerges, the loops are locked in place to impart bulk to the yarn. The yarn thus produced has an appearance like a staple yarn but possesses higher bulk, greater covering power, reduced opacity, and a warmer hand compared to flat

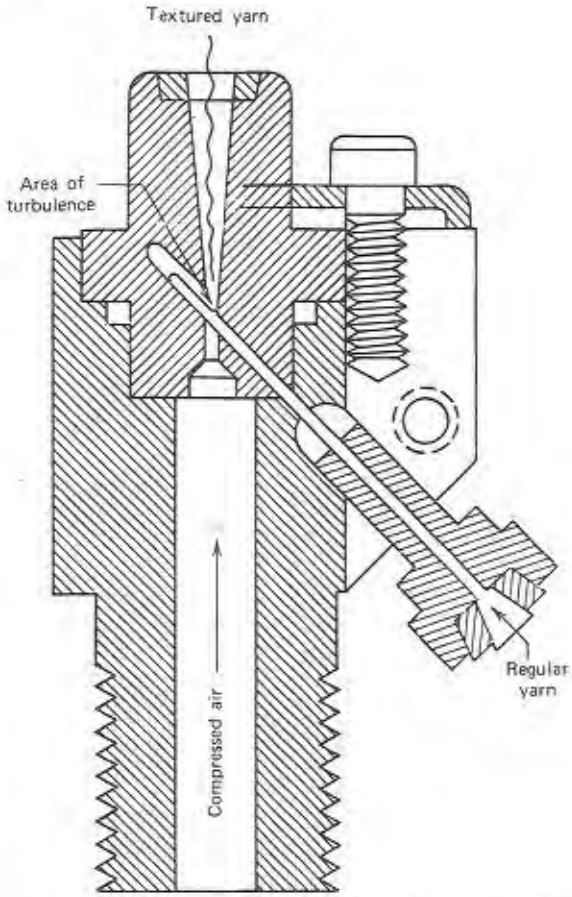


Figure 12.39. Cross section showing air-jet assembly used for producing Taslan-type yarns. (Courtesy, E. I. duPont de Nemours & Co.)

continuous-filament yarn. The textured yarn produced by this process (commercially owned by E. I. du Pont) is designated by the trademark Taslan®.

The air-jet assembly used in the production of Taslan® yarns is shown in Figure 12.39. This assembly can be fitted onto conventional throwing machines; however, there are specially designed machines (Figure 12.40) available on the market that can process yarns at higher speeds and that employ larger take-up packages (Garfield Machine Works, Inc., USA). A schematic illustration of the structure of Taslan® yarn is shown in Figure 12.41; Figure 12.42 shows the actual loop formation and the appearance of a nylon textured yarn. The feed yarn used in air texturing is generally twisted and steam set for the reason that will become obvious from the following discussion.

Ex. 2020-192

Figure 12.40. Garfield Model TT410 Taslan texturing machine (Courtesy, Garfield Machines Works, Inc.)

Ex. 2020-193

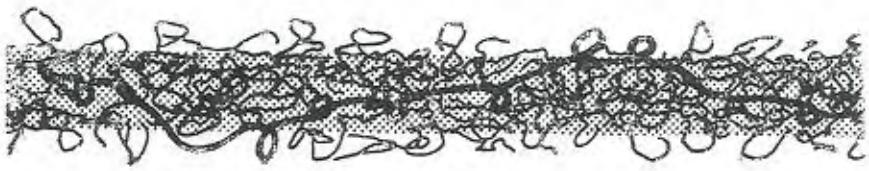


Figure 12.41. Structure of an air-textured yarn (courtesy E. I. Du Pont de Nemours & Company, Inc.).

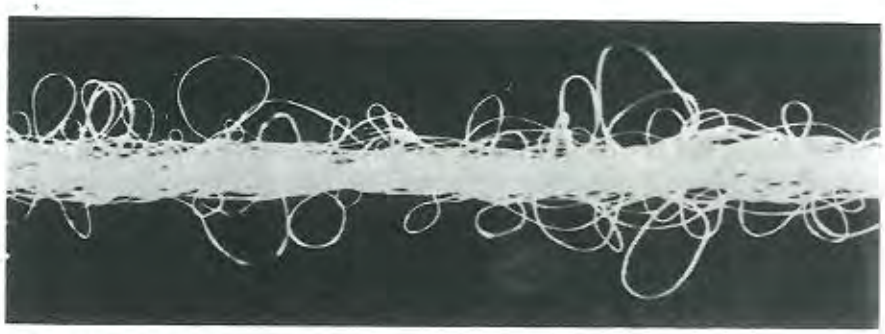


Figure 12.42(*a*). Photomicrograph of an air-textured yarn.

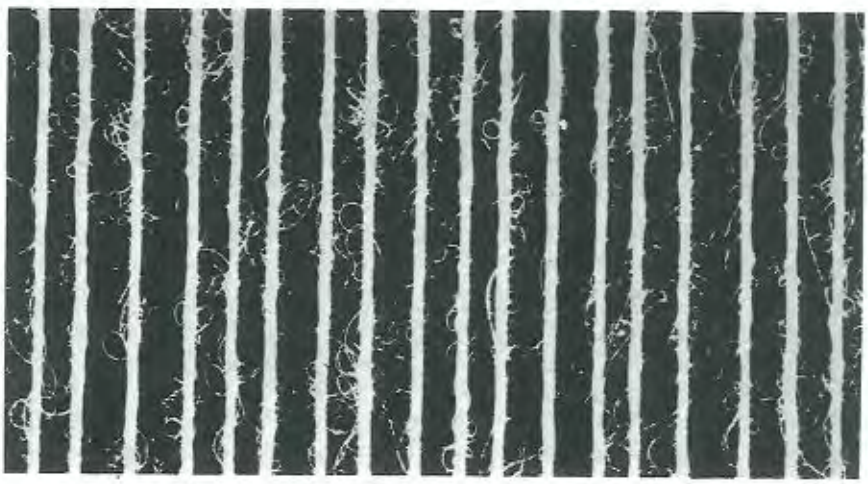


Figure 12.42(*b*). Photomicrograph showing fine-denier, multifilament Taslan textured nylon yarns. (courtesy E. I. Du Pont de Nemours & Company, Inc.).

Ex. 2020-194

An analysis of these questions requires that we must first define the processes involved during air texturing. There are two essential features of this process:

1. the yarn overfeed, which makes available an excess yarn length so that the individual filaments can form loops
2. the turbulant air flow, essential to disrupt and rearrange the looped filaments so that they are interlocked with sufficient interfiber friction to render the yarn stable.

The yarns used in air texturing generally have some initial twist. It has been reported that, if the pretwist in the feed yarn is low, to produce a stable textured yarn, the process needs either higher air pressures to generate greater filament entanglement or, alternatively, additional twist to secure stability. Wray (20) hypothesizes that, if the feed yarns are twisted before entering the jet, the effect of twist will be a contribution to the entanglement after the opening of the filament structure by the air turbulence. He further conjectures that this phenomenon may be explained as follows: First, the turbulence in the air stream helps to open up the twisted bundle, thereby allowing loops to be formed, partially because of the deviation of individual filaments by the air forces, and partially because of the snarling of the twist-lively filaments slackened by the overfeed. Second, interlocking is achieved because of the redistribution of twist in the yarn bundle as it is withdrawn abruptly at right angles to the air stream after leaving the air jet.

Wray further elaborates on the displacement of individual filaments in the "turbulent wake" caused by the obstruction of the feed needle in the path of the air stream and suggests that the tendency to form loops would be increased by

(i) higher twist, and thus greater spirality to effect looping of the tousled coil owing to the snarling of the filaments;

(ii) higher rate of overfeed, since this presents more slack yarn to promote loop formation;

(iii) higher air pressure, since this causes the turbulent action to be more intense and thus expands the yarn structure to allow the combined effect of (i) and (ii) to take place, and may actually assist in forming convolutions in the filaments by deflection and entanglement.

The filament displacement, the looping mechanism, and the interfiber friction further influence rearrangement of filaments caused by tension variations. The filaments that are in the turbulent wake in the Venturi throat become slack and subsequently looped; this action results in the preceding and succeeding sections of the filaments in the immediate vicinity of the loop becoming taut. These

tensioned portions of the filaments tend to move toward the core, replacing the neighboring slackened filaments. This sequence of events continues as fresh overfed yarn is delivered to the needle point, resulting in the formation of loops from slackened filaments.

The next major event, interlocking of the loops, occurs as the yarn is being pulled out of the tube at right angles under a slight threadline tension. Wray suggests that this action may have two effects in affecting interlocking:

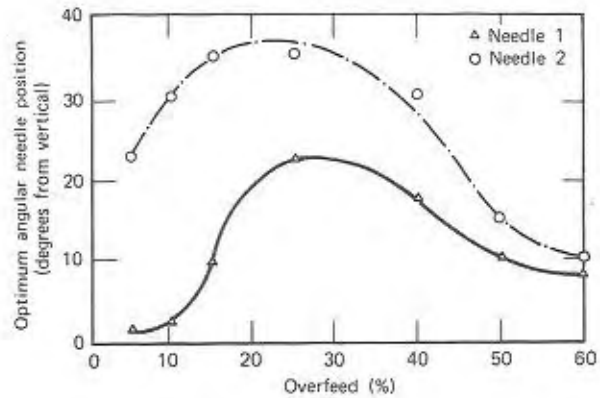
1. The rapid removal of the filaments from the vertical exit stream may help the slack filaments that are in the compression zone inside the bend to be blown through the gaps between the highly tensioned filaments (by virture of being on the outside of the bend).
2. The withdrawal tension may cause straightening of the structure. However, this is very unlikely because the entanglement caused by coiled loops, interfiber friction, and air turbulence would hinder it. The tension would probably affect the compacting of the structure, however, because of the interlocking of those loops and convolutions that are directed inward (toward the yarn axis) at the time they happen to be in the jet. The reason for the occurrence of the inward-directed loops could be attributed to the twist liveliness of the filaments and the "uncontrolled rotation of the filaments," since they are free of axial constraints.

Wray has reported the results of an experimental investigation on a 70-den/34-filament nylon 66 yarn bulked by air texturing to confirm some aspects of the postulated hypothesis. He used a specially constructed transparent air-bulking unit with overfeeds

$$\left(\text{overfeed } \% = \frac{\text{input speed} - \text{output speed}}{\text{output speed}} \times 100\right)$$

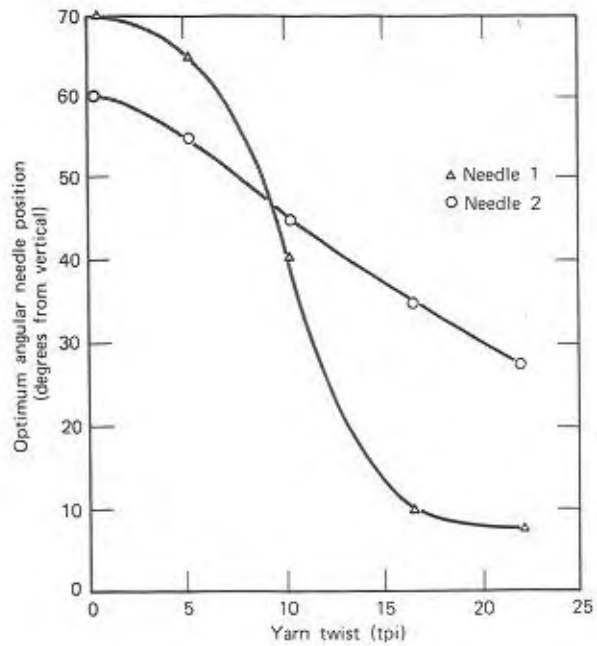
varying from 0 to 60%, yarn pretwist from 0 to 20 turns per inch, and air pressure from 10 to 80 lb/in^2 (gauge). While investigating the effect of a particular processing condition, the other parameters were maintained at constant levels of 15% overfeed and 15 tpi pretwist at 50 lb/in.^{2} (gauge) air pressure. He observed that the angular position of the needle (step on the feed needle) and the relative position of the yarn at the exit end relative to the air jet are quite critical in producing optimum bulk. The angular position of the needle is measured in degrees from the vertical position that occurs when the open end of the needle is facing the exit end of the Venturi. The interactions of angular position of the needle for essentially two identical needles with various processing parameters are shown in Figure 12.43*a* and *b*. It is clear from Figure 12.43*a* that for up to 25% overfeed a more oblique positioning of the needle produces a better

Ex. 2020-196



(a)

Figure 12.43(*a*). The difference in optimum angular needle settings caused by interchanging "identical" needles (for varying overfeed).



(b).

Figure 12.43(*b*). The difference in optimum angular needle settings caused by interchanging two "identical" needles (for varying input-yarn twist). (after Wray)

Ex. 2020-197

yarn. On the other hand, at overfeeds beyond 25%, satisfactory results are obtained if the needle position is moved toward the vertical. The explanation of this behavior lies in the argument that the total yarn volume (or surface area) exposed to the air stream is lower in the former case, whereas it is much higher in the latter condition, which can cause irregular movement of the yarn out of the needle.

When initial twist is increased (Figure 12.43*b*), the angle of the needle point must be reduced to obtain satisfactory bulking. For twistless yarns (in which the filaments are parallel), a steeper angle of 60-70° is required, whereas at higher pretwist (20 turns/in), when the filaments follow a helical path, the reduced angle of inclination ensures maximum exposure to the air stream. Air pressure in the region of 50 lb/in.^{2} requires the needle to be in the horizontal position; any deviations, either toward lower or higher air pressures, would require steeper inclinations.

Furthermore, by using both high speed cine photography and flash-still photography, Wray observed that there was some sliding of the filaments during bulking. The tracer fiber technique used in the study of loop formation confirmed that part of the hypothesis that states that the formation of a loop in a filament is followed by some tensioning of the part immediately following it. This effect, in cooperation with interfiber friction, generates U-shaped waves in the adjoining filaments, and, with the assistance of the bending of the yarn and the overfeed, the residual torsional energy in the filaments form stable loops. The stability of the yarn is strongly affected by the amount of pretwist. Lower pretwist yields yarn with poor bulk, and higher twist helps in the formation of a locked structure (because of the temporary removal of twist by the false-twisting action caused by the turbulent wake producing rotating eddies, and the reassertion of this twist before the yarn leaves the jet). An additional factor accounting for the stability of the textured yarn structure is the "filament slippage" effect mentioned earlier.

Factors Affecting Air-Textured Yarn Properties

When filament yarns are textured by the air-jet process, the most apparent change that occurs in the structure is the formation of a large number of small fiber loops distributed along the length of the yarn. This yarn has a well-defined core, as shown in Figure 12.44. There is a marked increase in overall yarn diameter, and the yarn has increased bulk. The bulked yarn structure is affected both by the feed yarn parameters and by processing variables. The yarn parameters include:

1. filament denier
2. number of filaments and total yarn denier
3. yarn twist

$$\text{Loop size} = \frac{\text{overall diameter} - \text{core diameter}}{2}$$

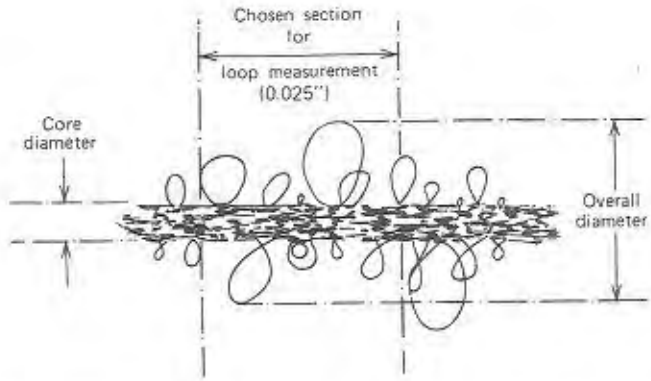


Figure 12.44. Definitions of overall diameter, core diameter, and loop size. (after Wray)

The processing factors include:

1. the amount of overfeed
2. texturing speed
3. the air pressure
4. the angular position of the needle

The effects of the various factors on the properties of air-bulked yarns have been reported in two major studies (21, 22). Some observations made in these studies are discussed below.

Textured Yarn Linear Denisty

When the filament yarns are air textured, the resultant yarn changes in linear density because of bulking. Generally, variation in pretwist and air pressure do not have a significant effect on the linear density of air-textured yarns. However, an increase in overfeed produces a proportional change in linear density. Wray (22) has reported a linear relationship between the overfeed and percent change in bulk yarn linear density.

Yarn Bulk

The bulk of an air-textured yarn is a function of the frequency and the size of the loops protruding from the yarn core. The du Pont method (23) used for assessing the bulkiness involves comparison of the package densities of the yarn

Ex. 2020-199

before and after texturing. A package is made from parent yarn weighing 3 oz (85 g), and a volumetrically similar package of textured yarn is then wound at the same tension. The ratio between their weights then gives a measure of bulk:

$$\text{percentage bulk} = \frac{\text{net weight of feed or parent-yarn package}}{\text{net weight of textured-yarn package}} \times 100$$

The overall diameter, core diameter, loop size, and loop frequency characteristics are measured by microscopical and graphical techniques (Figure 12.44). The loop size is defined by:

$$\text{loop size} = \frac{\text{overall diameter} - \text{core diameter}}{2}.$$

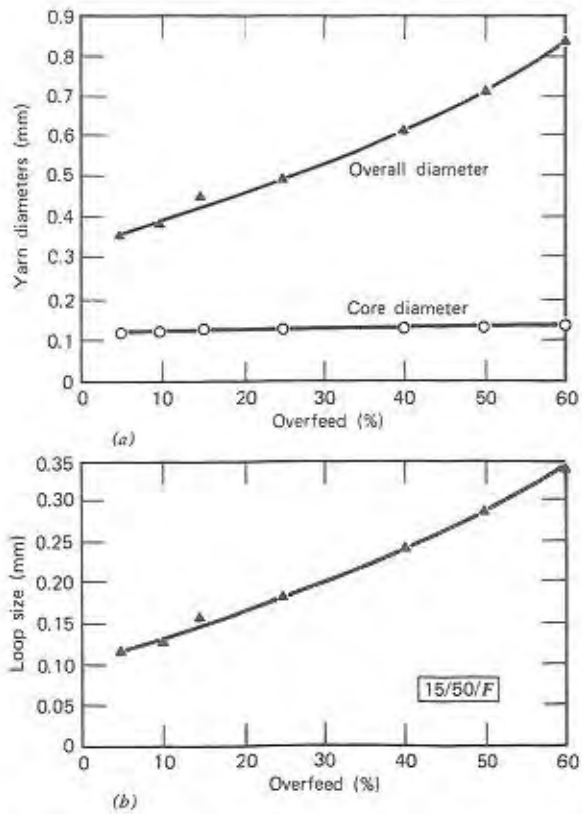


Figure 12.45. The effect of overfeed on overall and core diameters and on loop size. (after Wray)

Ex. 2020-200

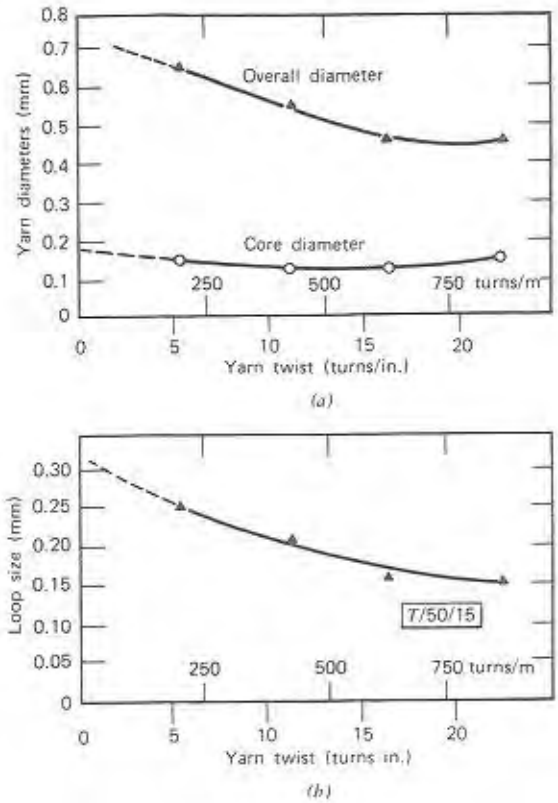


Figure 12.46. The effect of twist on overall and core diameters and on loop size. (after Wray)

The overall diameter and loop size increase with increasing levels of overfeed, as shown in Figure 12.45*a* and *b*. Yarn twist, on the other hand, retards the process of loop formation. As the yarn twist increases, the overall diameter as well as the loop size decrease, as shown in Figure 12.46*a* and *b*. Wray has derived analytical expressions for making theoretical predictions of the frequency and the size of loops based on the considerations of the amount of yarn twist and overfeed. He has observed that there is generally a good agreement between the theoretically predicted trends in loop dimensions for the various processing conditions and the experimentally measured values. A comparison of the theoretically calculated average loop size and number of loops with those obtained experimentally as reported by Wray for nylon 66 (70 den/34 fil twist set at 88°C for 45 min before air bulking) are shown in Figure 12.47*a*, *b*, and *c*. The theoretical loop size has been calculated from the analytical expression $h =$

Ex. 2020-201

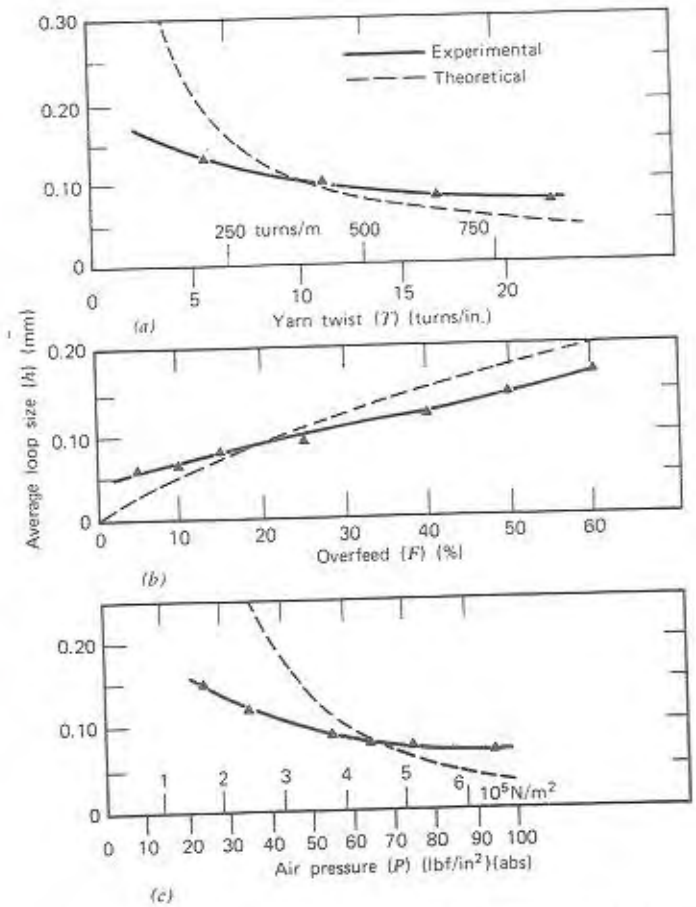


Figure 12.47. Theoretical and experimental values of loop size for varying processing conditions. (after Wray)

$\frac{0.540\,F}{100+F}$ mm, where h = loop diameter and F = % overfeed. The number of loops per centimeter is given by:

$$\text{loops/cm of yarn} = nT\,\frac{(100+F)}{100}\cdot\frac{1}{2.54}$$

where n = effective number of filaments, assumed to be 15/2 in a 34-fil yarn, T = turns per inch, and F = percent overfeed. It is clear from these relationships that there is a good agreement between the theoretically predicted trend for

Ex. 2020-202

loop size and loop frequency with varying yarn twist and percent overfeed with those obtained experimentally by Wray.

Yarn Stability

The usefulness of an air-textured yarn depends a great deal on the stability of the loops formed during the bulking process. In some air-textured yarns, such as those made at high overfeed, even a small amount of hand tension can remove some loops. Once these loops are removed, there is no built-in mechanism for their reformation, as occurs in stretch bulked yarns. The loss of loops during subsequent processing, such as weaving, can be detrimental to fabric quality. The yarn stability is highly affected by the amount of pretwist. At low pretwists, the bulked yarn is generally stringy, loose, and easily extensible because of the low degree of entanglement of long floats of looped filaments. Yarns produced from parent yarns with 10-15 turns/in. (which is within the commercial limit) are most stable. Higher pretwist also tends to yield yarns that are less stable because of the formation of a large number of small loops and lower number of tensioned filaments in a given cross section. (The tensioned filaments are the ones that take up the strains during yarn extension.) Increasing overfeed and air pressure both tend to produce less-stable yarns.

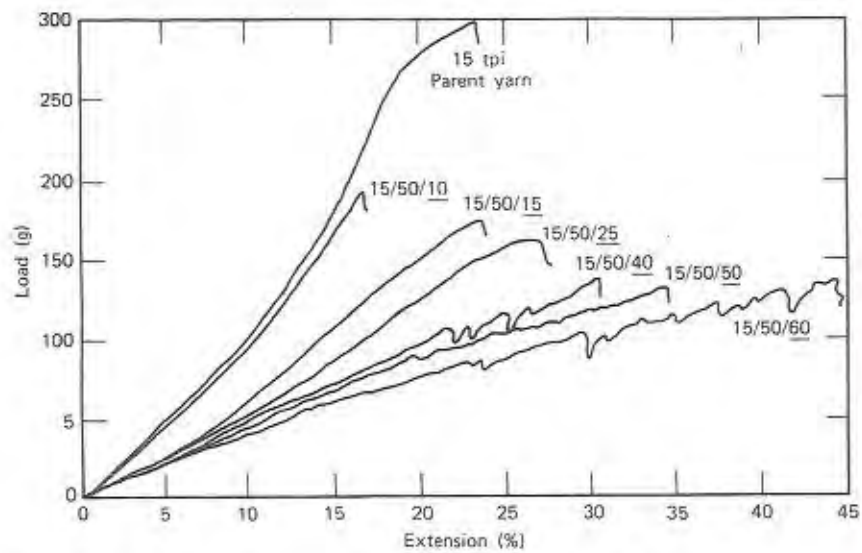


Figure 12.48. Typical load-extension curves (on Instron Tensile Tester) at various overfeeds (Yarn designation–first figure refers to twist per inch; second to % overfeed; and the third to the air pressure lb/in.^{2}). (after Wray)

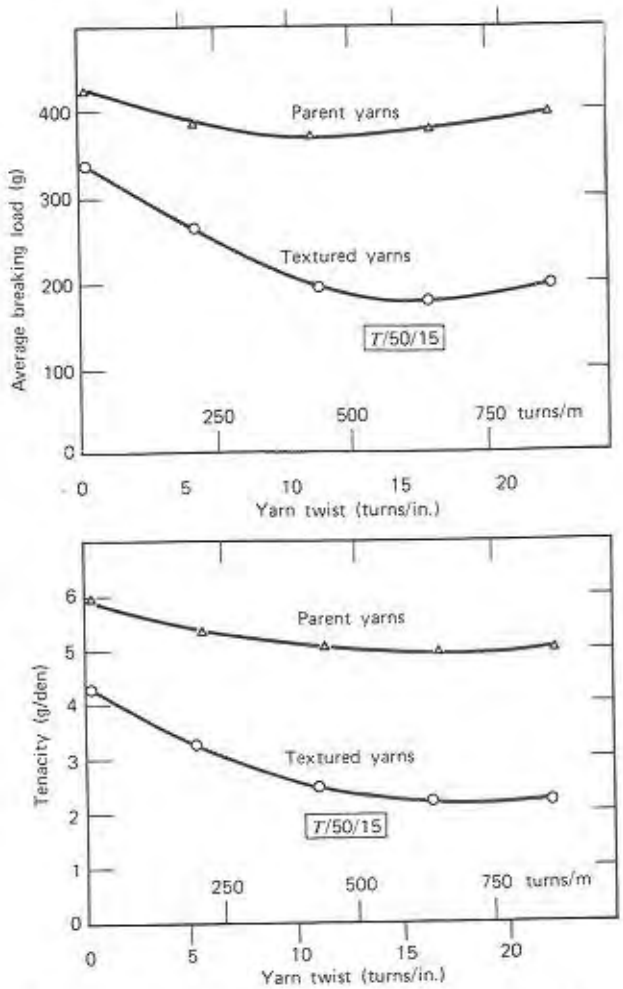


Figure 12.49(*a*). The effect of twist on breaking load and tenacity (determined on Uster Automatic Single-thread Tester). (after Wray)

Tensile Properties

Air-textured yarns generally exhibit lower tenacity and elongation-to-break than that of the parent continuous-filament yarn before texturing. Processing conditions such as twist, overfeed, and air pressure significantly modify the tensile behavior of air-textured yarns, as shown in Figures 12.48 and 12.49.

Tenacity tends to decrease with increasing twist, overfeed, and air pressure. On the other hand, elongation-at-break decreases with increasing yarn twist and

Ex. 2020-204

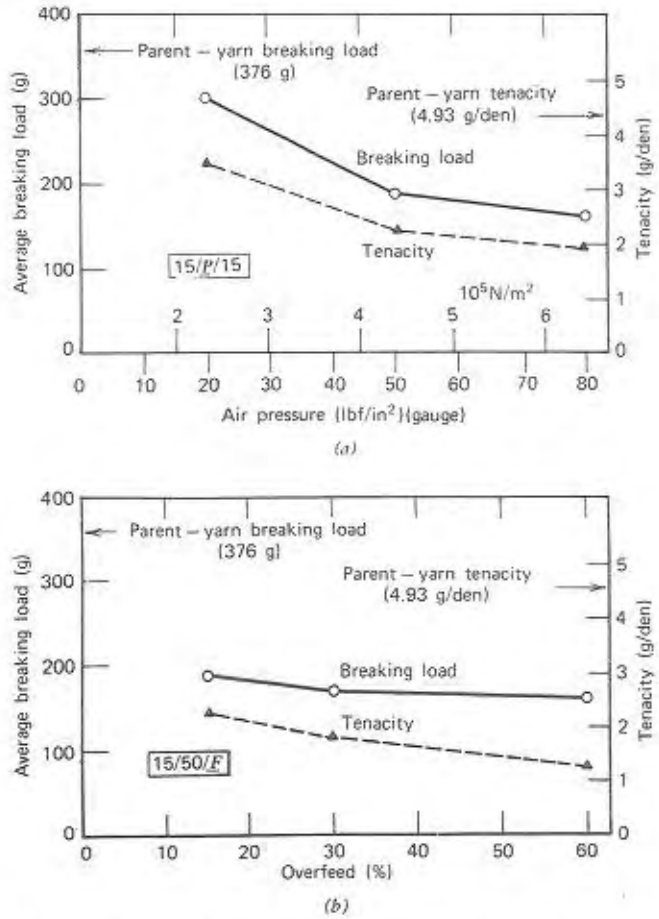


Figure 12.49(*b*). The effect of air pressure and overfeed on breaking load and tenacity. (after Wray)

increases with increased overfeed and air pressure. It must be remembered that the elongation of air-textured yarns is the result of the extension contribution due to the opening of the overfed loops in addition to the normal elastic extension of the straight filaments.

Air-textured yarns are used in a number of end-use applications, such as apparel, furnishings, and some industrial fabrics.

Mechanically Produced Air-Textured Yarns

A very significant development, which resulted from the observation made by

Ex. 2020-205

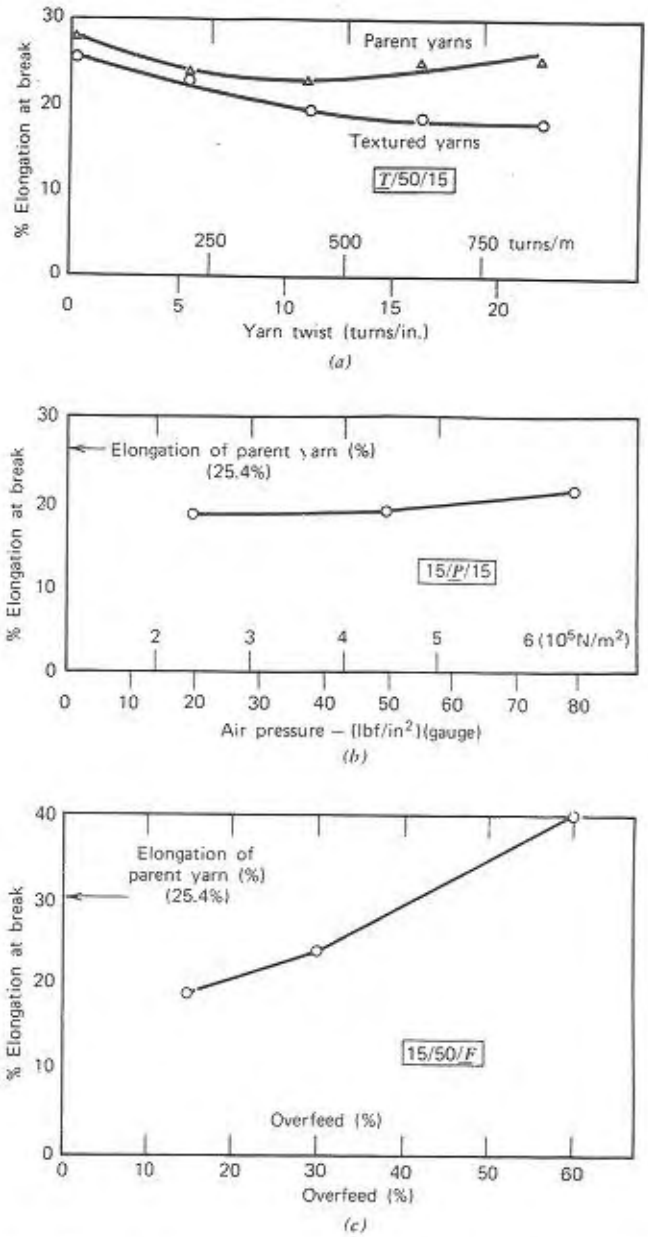


Figure 12.49(*c*). The elongation at break of textured yarns for varying processing conditions. (after Wray)

Ex. 2020-206

Wray (22) concerning the nature of the turbulent wake in the Taslan® jet, was the modification of the design of the jet so that it could operate at lower air pressures. The effect of the design modifications of a Taslan® jet on its overall performance regarding air consumption and bulking efficiency have been discussed by Wray and Entwistle (24). The major change in the design of the jet is the blocking of the otherwise ineffective secondary air stream (depending on the tilt of the needle) by a plug lodged in the needle on the upstream side. Such a change resulted in savings of as much as 65% in air consumption, with little or no effect on the bulk characteristics of air-textured yarns. It was also observed that, with the use of the modified jet, the feed-needle angle was far less critical for satisfactory texturing performance when compared to the original jet design.

The basis of the improved design of the jet and the observations made of the mechanism of air bulking prompted the development of a new method called the mechanical-bulking method, reported by Sen and Wray (25). This method can be used to produce textured yarns with characteristics similar to the air-jet bulked yarns. A line diagram of the mechanical bulking system is shown in Figure 12.50. The system utilizes purely mechanical means for the untwisting process in

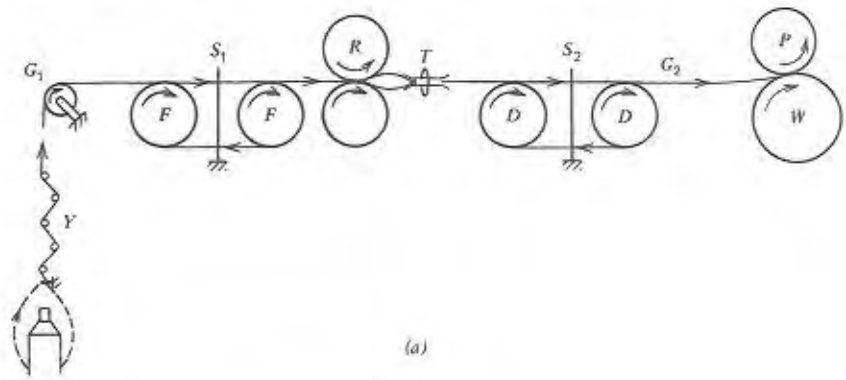


Figure 12.50(*a*). Mechanical builking apparatus.

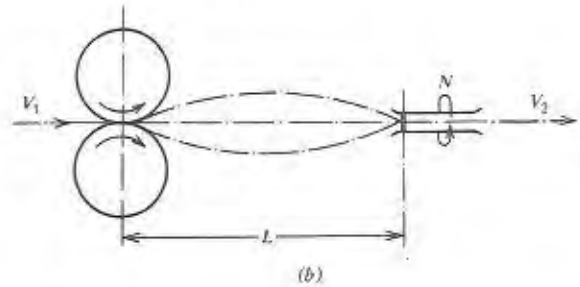


Figure 12.50(*b*). Bulking zone.

Ex. 2020-207

place of the air jet. The concept of manufacturing air-jet-type textured yarns by mechanical means stems from the observation of the mechanism of bulking during the passage of the yarn through the air jet. The mechanism of the air bulking process as proposed by Wray and later confirmed by Wray and Entwistle is discussed in an earlier section of this chapter. However, the most important aspect of the mechanism of bulking is the temporary untwisting of the pretwisted yarn caused by the rotational nature of the turbulent air stream (resulting in a false-twisting type action) when it is passing through the air jet. When this is combined with the yarn-slackening effect caused by overfeed, it results in the snarling of twist-lively filaments into the loops and coils that are characteristic of air-textured yarns. In the mechanical bulking process, the temporary untwisting of the pretwisted yarn is achieved by mechanical means (false-twist spindle) under conditions of overfeed; consequently, the filaments snarl into loops, and after they have passed through the false-twisting unit, the initial twist reasserts itself, thereby locking the already snarled loops.

In addition to such factors as (1) initial feed-yarn twist, (2) total yarn linear density and number of filaments, and (3) overfeed, the bulking characteristics of the mechanically bulked yarns are also affected by the following parameters: (1) feed-in speed, (2) false-twist spindle speed, and (3) bulking zone length.

The authors suggest that, for the yarn to bulk properly, it must be untwisted to a greater extent than the theoretically required value to bring it to the zero

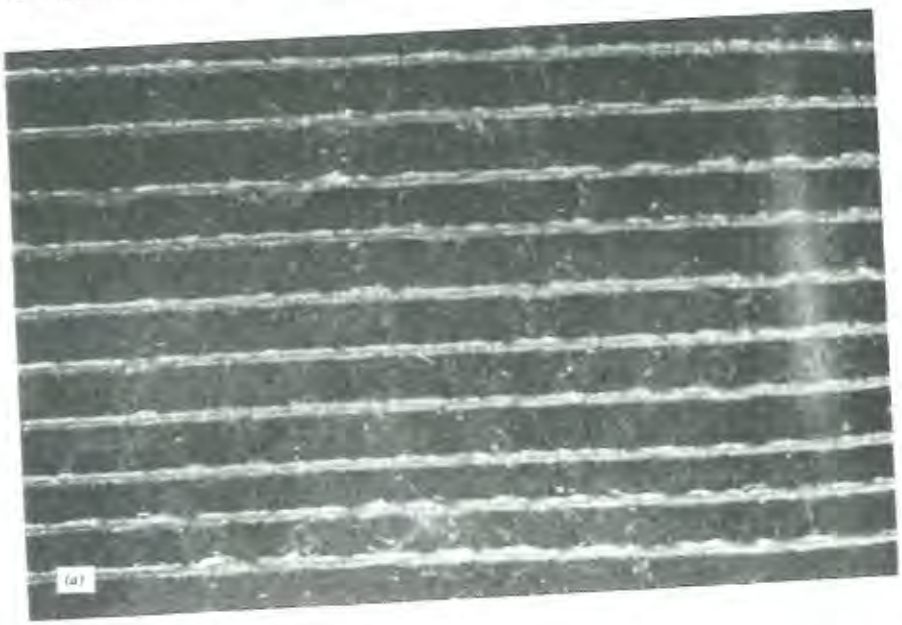


Figure 12.51(*a*). Air-textured yarn.

Ex. 2020-208

Figure 12.51(*b*). Mechanically bulked yarn. (Courtesy, Dr. Gordon Wray)

twist state. This is required to prevent the filaments from reverting to the helical configuration instead of the required snarled and looped entangled state. They suggest that approximately 20-25% extra twist is required to produce bulking. Some typical values of processing variables suggested by Sen and Wray (25) for a nylon 66, 110-den (11·1 tex), 34-filament yarn are:

initial twist in supply yarn	15 tpi
overfeed	10%
feed-in speed	60 in./sec
false-twist spindle speed	1125 rev./sec
bulking zone length, L	1 in.

Some typical mechanically textured and air-textured yarns are shown in Figure 12.51; the former clearly resemble air-textured yarns in physical appearance. The physical bulk, tensile properties, and the percent instability* characteristics of a mechanically bulked yarn are essentially similar to those of a Taslan® yarn manufactured from the same parent yarn. The two most important factors that

*As defined by Wray (22), percent instability = $e_b - e_p$, where e_b = percentage extension of bulked yarn and e_p percentage extension of parent yarn, both measured at 3 gf/tex (0.33 g/d).

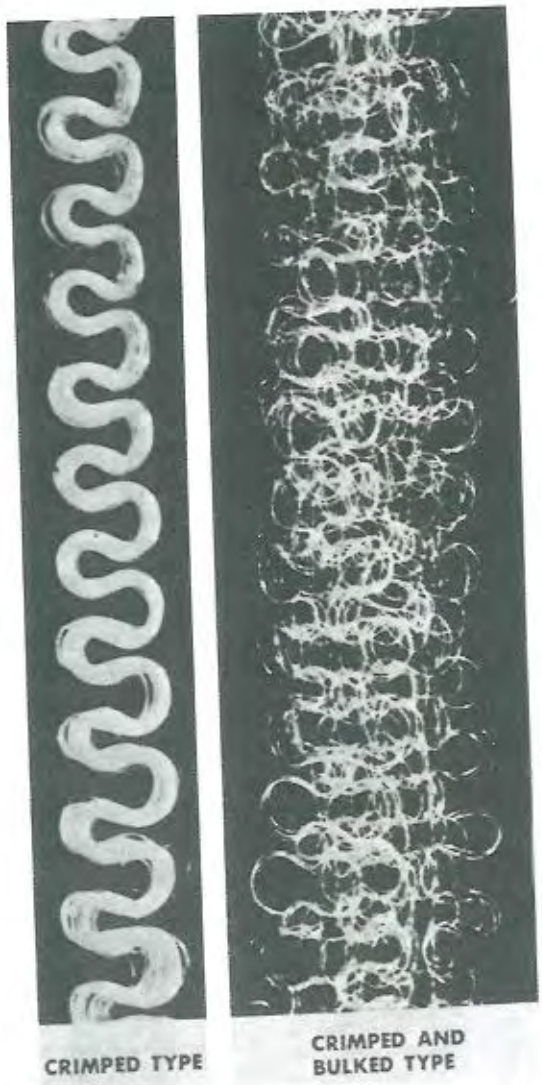


Figure 12.52. Photomicrographs showing 70 den. -34-fil. knit-de-knit Blue "C" nylon crinkle yarns made via the C-B-Tex process.

Ex. 2020-210

affect the bulked yarn characteristics are (1) the overfeed and (2) initial feed yarn twist, and, to a certain textent, (3) the linear density of individual filaments of the feed yarn. Exerting less influence are (1) the bulking zone length, (2) the percentage extra untwisting, and (3) total linear density of the yarn.

Some Additional Methods for Producing Bulked Yarns

Crinkle-Type Textured Yarns

These yarns can be produced by two basically different methods:

Knit-de-knit Method

In this method, the flat yarn is first knit, then heat set and unraveled to produce a crinkle-type structure as shown in Figure 12.52. There are various knitting machines available in the market that can be utilized to manufacture such yarns. The crimp frequency and shape can be varied by varying the needle gauge on the machine and the fabric structure (plain jersey, rib, double jersey, interlock, etc.). The fabrics produced from knit-de-knit crinkle yarns have a pronounced sparkling boucle texture, excellent stretch and recovery from stretch, and full hand. These yarns are torque free and therefore do not require any subsequent heat setting. Knit-de-knit yarns can also be produced by a continuous process called the C-B Tex Crimping process developed by the Textile Machine Works, Reading, Pa., USA. For details the reader is referred to reference 11.

Figure 12.53. Miralon gear-crimped yarn.

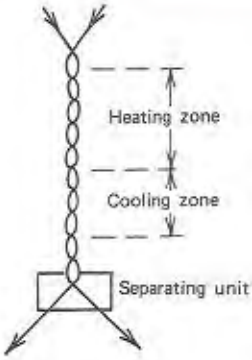


Figure 12.54. Principle of twist texturing.

Ex. 2020-211

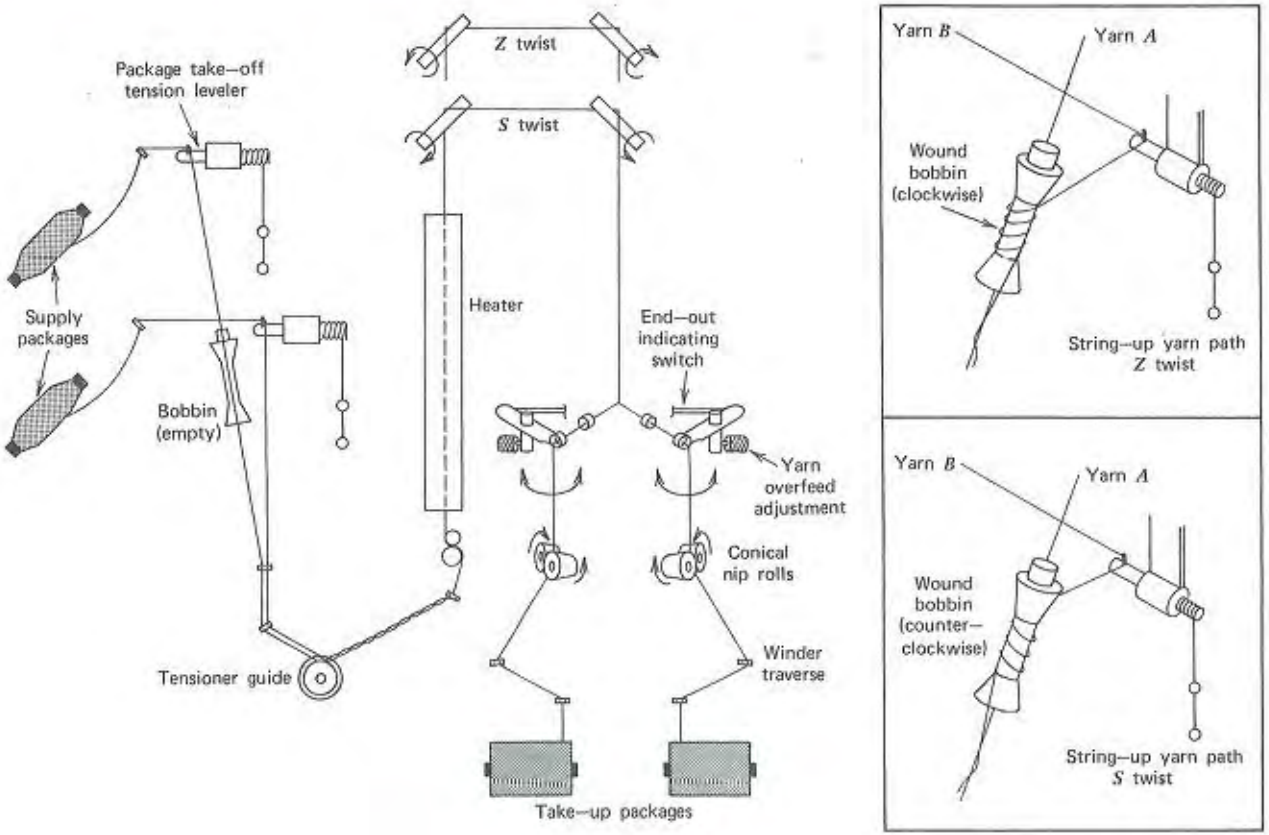


Figure 12.55. Diagram showing yarn path through the Turbo Duotwist machine. Insert shows thread-up bobbin winding detail. (Courtesy, Turbo Machine Co.)

Ex. 2020-212

Gear Crimping

Bulk can also be produced in a continuous-filament yarn when it is passed through closely meshed gears. The gear head is heated so that the crinkle produced in the yarn is permanent. The frequency and the amplitude of the crinkle or crimp can be varied over a wide range, depending on the type of gears used. One such gear crimping process called Miralon® has been developed by John Heathcoat and Sons, Ltd., England. A gear-crimped yarn has the appearance shown in Figure 12.53. These yarns are used in a variety of end-use applications, such as ladies' and children's knitted outerwear, sweaters, and ladies' blouses.

Twist-Textured Yarns

If two ends of yarn are twisted together around a common axis, rather than each yarn being twisted around its own axis, and the configuration is then heat set in the twisted state and finally untwisted, the yarn thus produced possess excellent bulk. The principle of twist-textured yarns is shown in Figure 12.54. This is a very simple and revolutionary concept of introducing texture into thermoplastic continuous-filament yarns. This is because this method enables the texturing of fine-denier yarns in the range of 15-70 denier at very high rates of

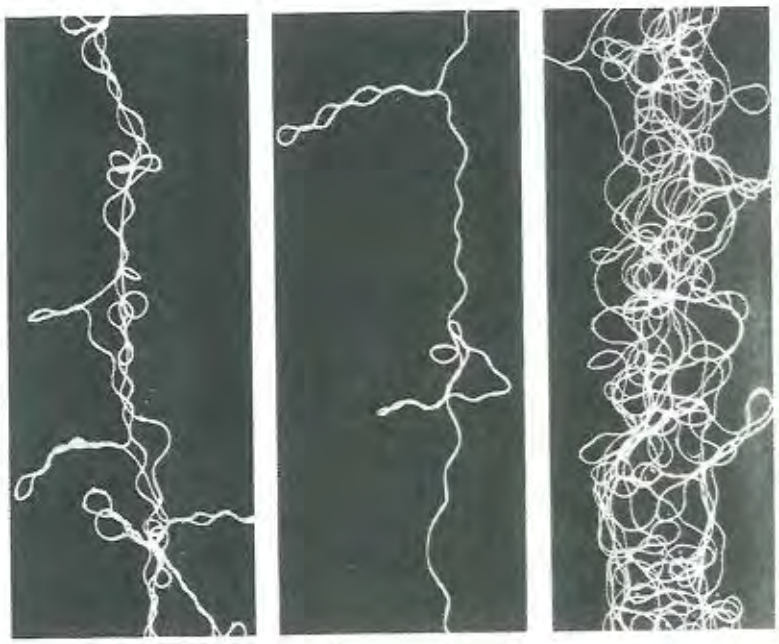


Figure 12.56. Nylon yarns textured on Turbo Duotwist.

production. Moreover, the yarns textured by this method have excellent dyeing uniformity, high cover, and extremely soft, smooth hand. Twist-textured yarns find uses in tricot fabrics, hosiery, and all types of knitted outerwear structures.

Twist-textured yarns are produced on the Turbo Duotwist Machine (Turbo Machine Co., Lansdale, Pa., USA) in addition to various others available commercially. A line diagram of the Turbo Duotwist Machine is shown in Figure 12.55. The twist in the yarn is first introduced and sustained throughout the operation because the yarn is wound around a bobbin (shown in the diagram). The twisted yarn is then passed through a heater (ranging in temperature from 110 to 240°C, depending on yarn denier and processing speed) and then separated before being wound onto separate packages. The yarns can be given either S or Z twist. Yarns produced by this method have the appearance shown in Figure 12.56. Typical yarn processing speeds used in twist texturing range up to 350 m/min, depending on the type of yarn and the heating efficiency.

REFERENCES

1. Finnie, T. A., papers presented at the Fall Technical Conference, November 9, 1973, Textured Yarns Association of America, Inc.
2. *Knitting Times*, November 1971.
3. Arthur, D. F. and A. F. Weller, "The Principles of Friction Twisting," *J. Text. Inst.*, 1960, 51, T66.
4. Thwaites, J. J., *J. Text. Inst.*, 1970, 61, T116.
5. El-Behery, H. M., *Clemson University Review of Industrial Management and Textile Science*, 1971, 13.
6. Arthur, D. F. and C. R. Jones, *J. Text. Inst.*, 1962, 53, T217.
7. Morris, W. J. and A. S. Roberts, Bulk Stretch and Texture, Proc. Annual Conference of Text. Inst., 1966, 54.
8. Denton, M. J. and W. J. Morris, *The Setting of Fibres and Fabrics*, edited by J. W. S. Hearle and L. W. C. Miles, Merrow Technical Library, 1971.
9. Jones, C. R. and J. Porter, *J. Text. Inst.*, 1965, 56, T498.
10. Burnip, M. S. and J. W. S. Hearle, *Man-Made Textiles*, 1960, 37, 54-57.
11. *Textured Yarn Technology*, vol. I, Monsanto Co., 1967.
12. Krause, H. W., Bulk Stretch and Texture, Proc. Annual Conference of Text. Inst., 1966, 54, 147.
13. Burnip, M. S., J. W. S. Hearle, and G. R. Wray, *J. Text. Inst.*, 1961, 52, P343.
14. Mebane, G. Allen, papers presented at the Fall Technical Conference, Nov. 9, 1973, Textured Yarn Association of America, Inc.
15. Maufetti, J., *Knitting Times*, 1974, 53, 58.
16. Mattingley, D. A. E., *Textile Month*, 48, March 1974.
17. Klein, W. and A. Trummer, *Text Mfr.*, 16, January 1973.
18. Mey, W., Bulk Stretch and Texture, Proc. Annual Conference of the Textile Institute, 1966, 77.

19. Fitzgerald, W. E. and G. B. Hughey, *Am. Dyestuff Reporter,* 37, 1966.
20. Wray, G. R., Bulk Stretch and Texture, Proc. Annual Conference of the Text. Inst. 1966, 18.
21. Rozimarynowska, M. K. and J. Godek, Bulk, Stretch and Texture, Proc. Annual Conference of the Textile Institute, 1966, 29.
22. Wray, G. R., *J. Text. Inst.,* 1969, 60, T102.
23. E. I. du Pont Technical Bulletin X-154, October 1961.
24. Wray, G. R. and J. H. Entwistle, *J. Text. Inst.,* 1968, 59, T122.
25. Sen, H. and G. R. Wray, *J. Text. Inst.,* 1970, 61, T77.
26. Arthur, D. F., in *Modern Yarn Production from Man-Made Fibers,* G. R. Wray (Ed.), Columbine Press, London, 1960, 100.
27. Denton, M. J., *Textile Month,* 1969.

Ex. 2020-215