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The Pneumatic Tire

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Preface

For many years, tire engineers relied on the monograph, “*Mechanics of Pneumatic Tires*”, edited by S. K. Clark, for detailed information about the principles of tire design and use. Published originally by the National Bureau of Standards, U.S. Department of Commerce in 1971, and in a later (1981) edition by the National Highway Traffic Safety Administration (NHTSA), U.S. Department of Transportation, it has long been out of print. No textbook or monograph of comparable range and depth has appeared since. While many chapters of the two editions contain authoritative reviews that are still relevant today, they were prepared in an era when bias ply and belted-bias tires were in widespread use in the U.S. and thus they did not deal in a comprehensive way with more recent tire technology, notably the radial constructions now adopted nearly universally. In 2002, therefore, Dr. H.K. Brewer and Dr. R. Owings of NHTSA proposed that NHTSA should sponsor and publish electronically a new book on passenger car tires, under our editorship, to meet the needs of a new generation of tire scientists, engineers, designers and users. The present text is the outcome.

Professor Clark agreed to serve as chair of an Editorial Board, composed of leading executives in the tire industry (listed on following page), which gave advice on the choice of authors and subjects and provided detailed reviews of the manuscripts. We are greatly indebted to Professor Clark and the other members of the Editorial Board for their expert guidance and constructive criticisms during the long process of preparing and revising the book. In particular, we would like to acknowledge the careful and thorough reviews provided by Dr. D. R. Dryden and his colleagues at Cooper Tire & Rubber Company. Nevertheless, final decisions about wording and content have been our responsibility.

The chapter authors are recognized authorities in tire science and technology. They have prepared scholarly and up-to-date reviews of the various aspects of passenger car tire design, construction and use, and included test questions in many instances, so that the book can be used for self-study or as a teaching text by engineers and others entering the tire industry.

Conversion of chapter manuscripts, prepared in different typesstyles and formats, into a consistent and attractive book manuscript was carried out by Ms. M. Caprez-Overholt. We are indebted to her and her colleague, Mr. Don Smith, of *Rubber World* for their skillful assistance.

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Tire Cord and Cord-to-Rubber Bonding

by E. T. McDonel

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Chapter 3

Tire Cord and Cord-to-Rubber Bonding

by E. T. McDonel

1. Textile cord

A number of references give detailed and comprehensive information on the chemistry, production, and properties of today's tire textiles (1-5). The chapter by Takeyama, Matsui, and Hijiri in the 1981 edition of the "Mechanics of Pneumatic Tires" provides an in-depth review of tire cord technology that is still current. The other references contain information on all aspects of the chemistry, manufacture, processing and physical properties of industrial cords for tires.

The present discussion will review current use and current trends for industrial textiles in tires as well as the physical attributes of cords now used. Textiles developed for use in tires are a small but exacting part of the huge textile industry. The average tire engineer, unless specializing in this area, is not always familiar with textile vocabulary, the chemical composition of tire textiles, the manufacturing process, the rationale for selecting certain textiles for certain tires, possible deficiencies of textiles in some applications, and the very important need for excellent cord-to-rubber adhesion in all applications. This chapter will provide an overview of these topics.

Tire textile market

The pneumatic tire performs a unique function in the transportation industry due to its deformation and damping characteristics that provide ready vehicle mobility in all terrains and environments. Billions of tires are in use, ranging in technical needs from tires for bicycles and animal-drawn vehicles to space shuttle landing gear. Carcass and belt textiles (along with the bead wire) provide essentially the whole strength of the pneumatic tire.

In 1993, tire textile fibers used in North America were approximately 55% polyester, 43% nylon, and 2% rayon (6). Worldwide, the mix was 57% nylon, 24% polyester and 19% rayon. In 1997 North American steel tire wire cord capacity was reported as 295,000 metric tons and bead wire capacity as 164,000 metric tons (30). Today passenger and light truck tires are over 90% radial, with polyester replacing nylon and rayon in the carcass. Steel cord predominates in the belt. Development of "run-flat" tires in Europe has resulted in renewed interest in rayon. High-speed tires continue to employ a rayon or polyester carcass, while nylon dominates in heavy duty bias-ply tires. In North America it is estimated that tire shipments in 2002 were approximately 303 million passenger, 50 million light truck, and 23 million medium/heavy duty truck units (7). Table 3.1 summarizes tire usage in 2001. Over 99% of US passenger tires were radial with 98% having a polyester and 2% a rayon carcass, and with 97% steel, 2% aramid and 1% nylon (both of the latter used in belt overlays) in the belt. 98% of light truck tires had a polyester carcass and 2% a rayon carcass, with 97.5% steel, 1.5% aramid, and 1% nylon (both used as belt overlays) in the belt. Medium truck tires were 94% replacement radial and 99% OE radial using all-steel or nylon carcass and steel belt. Heavy-duty truck tires were 62% replacement radial and 56% OE radial using all-steel construction or nylon carcass and steel belt. Bias truck tires use a nylon carcass.(8). The total usage of textiles in radial passenger and light tires may be estimated by noting that steel belts comprise 10-12% of the tire weight and carcass cord about 5%, thus a typical passenger tire

would contain about 1 kilogram (2.2 pounds) of steel cord and 0.5 kilograms (1.1 pounds) of polyester cord.

Table 3.1: Textile cord makeup of US tires - 2001

<u>Belt Material</u>	<u>Steel</u>	<u>Aramid</u>	<u>Nylon</u>
Passenger/Light Truck			
OE	97	2	1
Replacement	99	1	0
<u>Carcass Material</u>	<u>Polyester</u>	<u>Rayon</u>	<u>Nylon</u>
Passenger			
OE	98	2	0
Replacement	98	2	0
Light truck (radial)			
OE	100	0	0
Replacement	97	2	1
Light Truck (bias)			
OE	0	0	100
Replacement	22	0	78

Evolution of pneumatic tire fabrics

Tire fabrics have changed in response to the constant demand for better tire performance. Table 3.2 provides an historical summary of this evolution. The early pneumatic tires developed in the 1880s for bicycles by J.B. Dunlop and applied to automobiles in the 1890s used expensive Irish flax. Cotton soon replaced flax and remained the major tire textile until after World War II, but it has been phased out since the mid-1950s. Continuous filament viscose rayon and steel cord (France) were introduced in the late 1930s. Nylon became generally available for tires in the late 1940s and has met the needs of heavy-duty tires in large truck, earthmover, and aircraft tires. However, rayon held sway in passenger tires, particularly for new cars (O.E.), because of poor ride characteristics with nylon due to its lower dimensional stability. Polyester cord was first introduced by Goodyear in the early 1960s to provide better strength than rayon and better dimensional stability than nylon. Polyester has gone through several technical improvements to surmount early shortcomings and has become the dominant textile for passenger and light truck radial carcasses in North America and has increasing use worldwide.

Brass-plated steel cord introduced in North America in 1955 is dominant in radial tire belts. Fiber glass belts introduced in belted-bias tires in 1967 can give good radial belt performance but for a number of reasons fiber glass was not accepted by the market and has been totally phased out. Aramid fiber was introduced in 1974 by DuPont. It has shown slow but steady growth, particularly in radial tire belts, but its high cost is a deterrent.

All of the presently-employed textile materials are continuously improved through modifications in polymerization, drawing, and heat setting during cord manufacture.

Table 3.2: Evolution of pneumatic tire fabrics

<u>Cord</u>	<u>Introduced</u>	<u>Comments</u>
Irish flax	1888	- Staple fiber/no adhesive, expensive
Cotton (square woven)	1900	- Staple fiber/ no adhesive, lower cost
Cotton (cord)	1920	- Same as above, lighter weight
Steel cord (Europe)	1937	- Used in first radial tires, copper plated for adhesion
Rayon	1938	- Viscose continuous filament, RFL/NR adhesive cord dip required
Nylon (commercial)	1947	- Continuous filament drawn and heat set for tensile strength, RFL/VP-SBR adhesive employed
Steel cord (USA)	1955	- Brass plating for adhesion
Polyester	1962	- drawn and heat set for tensile strength, 2 step adhesion dip, isocyanate/RFL
Fiberglass	1967	- RFL adhesive on individual filaments
Aramid	1974	- Special RFL/VP-SBR adhesive
Rayon (polynosic)	1975	- High tenacity rayon
Polyester (2nd rev)	1982	- Modified lower shrinkage
Steel cord (open const)	1980s	- Higher rubber penetration adhesion/corrosion resistance
Polyester (3rd gen)	1995	- High modulus/lower shrinkage
Steel cord (3rd gen)	1990s	- High tensile steel. New drawing and twisting (e.g., BETRU™)
Polyethylene naphthalate	1990-2000s	- Potential new tire fabric, not yet commercial

Textile industry nomenclature

The terminology used for defining tire cords comes from the textile industry. Table 3.3 gives the common vocabulary. Tire cords are built up from yarns which in turn come from filaments. Filaments from a production spinnerette are gathered together, slightly twisted, and placed on “beams” for further processing. Figure 3.1 shows a common hemp rope which

Figure 3.1: Hemp rope illustrating cord construction - filament/yarn/cord (rope)

shows this construction, but on a larger scale. The filaments are twisted “Z” into yarns and the yarns are back-twisted “S” to form a cord. The size of a tire filament, yarn, or cord is measured by its weight per unit length - linear density or “denier” (denier is the weight in grams of 9000 meters) or “decitex” (weight in grams of 10,000 meters). Textile cords are identified by their yarn denier and their construction. Thus a 940/2 8x8 nylon cord is formed from 2 - 940 decitex yarns twisted separately at 8 turns per inch and then back-twisted together at 8 turns per inch to form the cord. A 1650/3 10x10 rayon cord would comprise 3-1650 denier yarns twisted at 10 turns per inch separately and back-twisted together at 10 tpi. For a given material, use of higher denier yarns or more yarns per cord result in a higher breaking

Table 3.3: Textile terminology

Fiber	- a material with high strength in the fiber axis direction and with a length at least 100 times greater than its diameter.
Filament	- the smallest continuous element of a tire cord.
Yarn/strand	- an assembly of filaments, usually gathered directly from the spinnerette, twisted lightly (e.g., 0.3 turns per inch), and rolled up on beams for further processing. Ply-twisted yarns are further twisted before assembling into cords.
Cord	- a twisted or formed structure composed of two or more yarns.
Warp	- an assembly of cords that run in a lengthwise direction along the fiber axis.
Pick/filling	- a low strength thread placed at right angles to the warp (1 to 2 per inch) to give handling stability to a sheet of warp cords. These have very low tensile and high elongation to avoid distortion of a calendered sheet during expansion of a green tire.
Denier	- the linear density of a textile item (e.g., a yarn) defined as the weight in grams of a length of 9000 meters. Thus, the larger the denier, the stronger the item. For example, a 2000 denier yarn would be twice as heavy as a 1000 denier yarn and presumably twice as strong.
Decitex	- the linear density in SI units (partially), defined as the weight in grams of a length of 10,000 meters.
Twist	- the number of 360° turns per unit length of a yarn or cord, e.g. 10 twists per inch or 40 twists per 10 cm.
Twist direction	- twist direction is termed “S” if the spiral turns clockwise from top to bottom for a vertically held cord and “Z” for a similar counter clockwise turning.
Twist balance	- if a set of yarns and the resulting cord have same twist it is termed a balanced cord.
Lay	- lay is the inverse of twist. It is the length of cord needed to complete one 360° rotation, e.g., a 12.5 lay would exhibit one rotation in 12.5 mm. Lay is the measurement used for steel cord constructions.
Strength	- the tensile load required to rupture a cord at a given rate of extension, i.e., the breaking load of a given cord. Tire cord strength is reported in Newtons or pounds, rather than MPa, due to the difficulty of determining the true cross-sectional area of a bundle of fibers. Fiber tensile strength is some times reported: Tensile strength (psi) = 12800 (specific gravity)(tenacity in grams per denier).
Tenacity	- Tire cord strengths are frequently reported as tenacity in grams per denier or centinewtons per decitex. This value is essentially strength for equal weight. It can be useful when comparing cords of similar specific gravities, but should be used with caution in tire strength calculations where equal volumes of cord may be used rather than equal weights, for example, when comparing nylon to steel in a radial carcass.

strength of the cord.

Steel cord constructions are defined differently, based on the filament diameter and method of construction. The high specific gravity of steel compared to that of organic textiles distorts comparisons of cord strength when “tenacity” is reported. This makes steel appear to have lower strength. Steel cord nomenclature and physical properties will be described in the section on steel cords.

Table 3.4

<u>Functions of tire cords</u> - Maintain durability against bruise and impact - Support inertial load and contain inflating gas - Provide tire rigidity for acceleration, cornering, braking - Provide dimensional stability for uniformity, ride, handling. <u>Cord Requirements</u> - Large length to diameter ratio , eg, long filaments - High axial orientation for axial stiffness and strength - Good lateral flexibility (low bending stiffness) - Twist to allow filaments to exert axial strength in concert with other filaments in the bundle - Twist and tire design to prevent cord from operating in compression.
--

General function of tire textiles

Table 3.4 summarizes the essential functions of tire cords and their basic requirements.

Tire cords are the strength members of a tire. As such, they must define the tire shape, support the loads, and contain the inflation gas. They must provide the tire with axial and lateral rigidity for acceleration, braking, and cornering and dimensional stability for uniformity, handling, and ride. They must also provide bruise, fatigue, and resistance to separation for durability.

Table 3.5: Ideal cord properties for a tire carcass

Dimensional stability –low shrink during cure, no flat spotting, no long term growth High tensile strength High tensile modulus Low bending modulus High durability – fatigue resistance, low heat generation on flexing, high adhesion to rubber, chemical and oxidation resistance, heat resistance High toughness – impact and abuse resistance Low hysteresis loss at high speeds.

Table 3.6: Ideal cord properties for a radial tire belt

High tensile strength High bending modulus – high stiffness Ultra-high tensile modulus High compression modulus High adhesion to rubber Good resistance to chemical attack
--

Textiles for the carcass and for the radial belt have different requirements. Kovac (4) and Pomies (9) have succinctly summarized the ideal properties for cords in each of these applications:

As with all tire components, choice of a textile cord for a given tire application may require compromises involving cost, intended market segment and end-use application. The tire engineer has a number of choices for a tire textile:

- Chemical composition of textile
- Cost per unit length and weight (cost in tire)
- Denier – filament size and strength
- Cord construction – number of yarn plies
- Cord twist
- Number of cords per unit length in ply
- Number of plies in the tire

These choices will naturally be predicated on the tire specifications for the particular application and market, usually balancing cost against required performance.

Five materials currently make up the major tire textile usage – rayon, nylon, polyester, aramid, and steel. Table 3.7 lists the physical properties of these materials. The high modulus of steel and aramid find their major use in radial belts and in single-ply carcasses for large radial tires. Rayon is used in both carcass and belt of passenger radial tires but lacks strength for durable heavy-duty tires. Modern polyester cord is an excellent carcass textile for use with steel belts in passenger and light truck tires and is becoming dominant worldwide. However, it lacks the toughness and heat resistance required for large tires where nylon is the textile of choice in large bias truck, earthmover and aircraft tires but nylon and polyester do not have the high stiffness necessary for good performance in radial belts. Yarn and textile producers are making continuing improvements in their products, therefore these data are for a general comparison only. In particular, modifications in the last twenty years have resulted in significant improvements in the dimensional stability of polyester and the tensile strength of steel. Also, aramid modifications have improved its compression fatigue properties.

Physical properties of commercially-available tire cords are usually more meaningful to tire engineers. The following table summarizes typical physical properties of some commonly used cord sizes of organic textile fabrics (10). Data are for untreated yarn bundles lightly twisted at 0.2 to 0.3 turns per inch.

Table 3.7: Typical filament properties of major tire textiles

	Rayon	Nylon 6	Nylon 66	Polyester	Aramid	Steel
Tenacity (cN/Tex)	50	80	85	80	190	35
% Elong at break	6	19	16	13	4	2.5
Modulus (cN/Tex)	800	300	500	850	4000	1500
Shrinkage (% at 150C)	<0.1	6.0	5.0	2.0	<0.1	<0.1
Moisture regain (% at RT)	13	4.5	4.5	0.5	<2.0	<0.1
Specific gravity	1.52	1.14	1.14	1.38	1.44	7.85
Melting temperature (C)	>210	225	250	250	>500	--
Glass transition temperature(C)	--	55	55	80	--	--
Heat resistance (C)	150	180	180	180	250	--
Approximate relative cost per unit weight (PET=1.00)	1.33	--	1.13	100	5.00	--

Table 3.8: Physical properties of commercial tire cords

Linear density dtex	# of filaments	Breaking force N	Breaking tenacity mN/tex	Breaking elongation %	EASL* %(xN)	Shrinkage % at 180C
Nylon 66	140	80	840	18	9.6(45N)	5.1
940	280	118	840	19.5	10.4(90N)	5.1
1880						
Polyester	210	94	848	11.2	6.0(60N)	7.6
1100	280	100	686	10.4	5.2(90N)	3.6
1440						
(low shrink)						
Rayon**	1000	96	510	12.8	4.6(45N)	nil
1840	1350	517	12.5	nil		
2440						
Aramid (11)	1000	325	2030	4.8	--	nil
1500						

*Elongation at specified load (inverse modulus measure)
 **Conditioned 75% humidity -- 0.4 TPI

Table 3.9 qualitatively ranks tire cord reinforcements for important tire performance properties. It should be understood that the textile industry is continually upgrading their specific products so that these rankings may change.

Again note that nylon and polyester do not have the requisite bending stiffness to make useful radial tire belts. As discussed below, glass fiber and polyvinyl alcohol are potential belt materials.

Table 3.9: Relative performance of tire cord materials (4,9)

<u>Dimensional stability (carcass)</u>	
Uniformity in curing	Rayon> Advanced Polyester >Nylon
Appearance (sidewall indentations)	Rayon> Advanced Polyester >Nylon
Dynamic stiffness (steering)	Rayon> Advanced Polyester >Nylon
Flat spotting	Rayon> Advanced Polyester >Nylon
<u>Durability (carcass)</u>	
Fatigue resistance/heat generation	Nylon> Advanced Polyester > Rayon
Impact Resistance (Toughness)	Nylon> Advanced Polyester > Rayon
High speed/ run-flat tires	Rayon> Advanced Polyester
Strength	Aramid> Steel> Nylon> Polyester> Rayon
Modulus(stiffness)	Aramid> Steel> Rayon>> Polyester> Nylon
Elongation	Nylon> Polyester> Rayon> Steel = Aramid
Compression fatigue	Nylon> Polyester> Rayon> Steel> Aramid
Chemical resistance	Aramid> Nylon> Rayon> Polyester> Steel

General comments on cord usage in various types of tires

Polyester – Polyester is the condensation polymerization product of ethylene glycol and terephthalic acid. Newer modifications resulting from increased molecular weight and revised processing are called DSP-PET (dimensionally stable PET), with 50% increased modulus and 50% reduced shrinkage, bringing it close to rayon for dimensional stability. It has become relatively inexpensive making it a good choice for passenger and small light

truck tires. Polyester must be used with carefully designed rubber adhesion systems and carcass rubber compounds to prevent cord deterioration in use. Polyester cord is not recommended for use in high-load/high-speed/ high-temperature applications, as in truck, aircraft and racing tires, because of rapid loss in properties at tire temperatures above about 120C.

Rayon (12) - Tire cord strength has been improved 300% since its introduction by improved coagulation and heat treatment. The low- shrink, high-modulus, good-adhesion properties of rayon make it an excellent choice for use in passenger tires. However, rayon has lost market share to polyester due to higher cost and environmental concerns with production facilities. Rayon had historically been used in truck tires but has been displaced by nylon with higher strength and impact resistance. Rayon is used for racing tires and has gained renewed interest in the development of an extended-mobility self-supporting passenger tire.

Nylon- Nylon is a generic term for aliphatic polyamides. Two varieties are used in tires cords Nylon 6 (polycaprolactam) and Nylon 66 (product of adipic acid/hexamethylene diamine condensation). Both materials give similar properties with Nylon 6 being somewhat less expensive, but more sensitive to moisture and subject to loss in tensile strength if moisture is present at tire curing temperatures. Nylon tire cord strength has been improved 25-50% from early versions by processing modifications. Its low modulus and low glass transition temperature make it unacceptable as a belt material or for applications where aesthetics, ride, and handling are important, i.e., in passenger tires. Nylon is preferred in uses requiring carcass toughness, bruise and impact resistance, high strength, and low heat generation, e.g., in tires for medium and heavy-duty trucks, off-road equipment, and aircraft. In these applications nylon can be used in the bias-ply tire carcass or in radial tire carcasses with steel or aramid belts.

Aramid (13) - Aramid is a wholly aromatic polyamide. The most common commercial material is poly(p-phenylene terephthalamide), eg, Kevlar™ or Twaron™. Aramid cords have very high strength, high modulus, and low elongation. The relatively high cost has slowed adoption as a general radial belt material where steel cord is performing well. It is particularly suited where weight is important, such as in the belts of radial aircraft tires or in overlay plies for premium high-speed tires. As with steel cords, aramid can be used as multiple plies in flat belts. However, in carcass applications aramid must be used as a single ply. In a multiply carcass construction, aramid's low elongation will prevent the outer ply from adjusting to the average curvature, thus placing the inner plies into compression. This reduces the contribution of the inner plies to the total strength, but, more seriously, early failures of the inner ply are encountered due to the poor dynamic fatigue resistance of aramid in compression. Work on aramid copolymers to improve elongation and fatigue resistance has been reported.(14).

Other potentially useful fibers for tires

Glass fiber – fiber glass was introduced to the US tire industry in the 1960s with Goodyear's development of a belted-bias tire. This tire was soon replaced by the radial tire, however. Some attempts were made to use fiber glass in the belts of radial tires but in spite of its excellent credentials, fiber glass quickly lost out to steel as the premier belt material. Premature failures were encountered, both in cold weather use and with inappropriate tread designs that put the top belt into compression. However, a review of its properties gives glass fiber an excellent rating as a belt material if proper tread design and latex adhesive dips are used. Its specific stiffness and strength are equal to those of steel, whereas the specific

gravity is only 2.54 compared to 7.85 for steel. The initial modulus is 2150 cN/tex compared to 1500 for steel. Rubber adhesion is excellent with no problems with rusting due to water in the belt. Each filament of fiber glass is coated with a latex dip before the filaments are twisted into a yarn. It has been established that this latex must be formulated from a low glass transition polymer to prevent the premature glass breakage seen in the early glass fiber development.

Polyvinyl alcohol – PVA fibers have properties similar to both rayon and advanced polyester, but with higher tenacity than rayon and lower shrinkage than polyester. Reported properties (15) are – tenacity 14 g/den, elongation 8.7%, $T_g = -90^\circ\text{C}$, $T_m = -265^\circ\text{C}$, Modulus = 180 g/den, specific gravity = 1.3. High molecular weight, high crystallinity fibers are stable in water at 115°C . This textile has been used successfully in the carcass and belts of radial passenger tires. A major drawback has been the lack of suppliers of multiple cord material.

Polyethylene Naphthalate (PEN) - PEN is similar to the standard polyethylene terephthalate (PET) polyester, being a copolymer of ethylene glycol and naphthalic acid. This new textile has been developed by Allied-Signal (presently Honeywell High Performance Fibers) and is being evaluated for tires. Its properties have been reported by Rim (16). It is claimed to surpass DSP-PET for use in the carcass of passenger car tires, having lower shrinkage, higher modulus, and higher T_g (120°C vs. 80°C). It also has potential as a restrictive overlay belt for light truck and high-speed passenger tires, replacing nylon overlays. A disadvantage is the high price, about 2.5 times that of polyester. Table 3.10 compares treated cord properties of PEN with other tire textiles.

Textile Cord Manufacture (3, 5)

The organic textile materials used today are all man-made. Natural fibers such as cotton do

Table 3.10: PEN properties vs. other cord reinforcements

	Nylon 66	Rayon	DSP PET	PEN	Aramid
Tenacity (cN/dtex)	7	4.5	6.2	7	14
Modulus (cN/dtex)	25	50	60	130	300
% Shrinkage at 177°C	7	0.5	2	2	nil

not have sufficient filament length to provide the high strength needed. Manufacture of steel cord is quite different from that for organic textiles and will be covered in a later section. The processes for producing continuous textile filaments are melt spinning (nylon and polyester) and solution spinning (rayon and aramid).

Melt spinning

In the melt spinning process molten polymer is filtered and pumped through a spinnerette containing a large number of very fine holes. A positive displacement pump is used to give an extremely accurate and constant flow through the spinnerette. The extruded semi-molten polymer is stretched to about 25 times its original length while solidifying in a cool air stream. The solidified bundle is then treated with a spin finish to lubricate the filaments and cold-drawn over a series of take-up rolls ("godets"). The drawing process elongates the filaments by several hundred percent while the polymer is still above its glass transition temperature. This procedure increases the strength and modulus, and reduces the breaking elongation, by increasing the polymer crystallinity and molecular orientation. The final

structure of drawn, crystalline thermoplastic polymers contains crystalline fibrils, highly aligned polymer molecules and unoriented molecules.

Controlled feed rates and draw speeds are necessary to ensure filament uniformity and close control of the linear density (denier). Finally, the filament bundles are gathered, lightly twisted, and stored on “beams” to be transferred for further processing and cord manufacture. Compared to standard textile products, tire cord polymer melts are of higher molecular weight (at least 2 times higher) and after drawing have 2 to 4 times the tensile modulus values, with breaking elongations in the 10-20% range.

Solution spinning

Rayon (regenerated cellulose) and aramids have no defined melting temperature and must be dissolved for extrusion as continuous filaments. A concentrated solution or slurry is pumped through the spinnerette into a coagulating bath of non-solvent (wet spinning) or air-dried to evaporate the solvent (dry spinning). Filaments are air-dried under tension and not extensively drawn since crystallinity and orientation are already highly developed. Spin finish is applied, as with melt-spun textiles, and the filament bundles are “beamed” for downstream processing. Aramids emerge with their high-strength properties intact. Rayon tenacities have been increased over three-fold by refinements in coagulation, modified finishing procedures, and heat treatments to alter crystal size.

Cord assembly

In a conventional cord production, producer yarns (lightly twisted bundles of 0.2 to 2 turns per inch) are removed from beams and ply twisted to a specified level, 6 to 12 turns per inch (tpi), usually in the “Z” direction. Cords are formed by cable twisting when two or more yarn plies are back twisted in the “S” direction to form a greige (untreated) cord. Tire cords are usually balanced with equal twist levels in yarns and cords. Figure 3.2 shows a cord construction with “Z” and “S” twists.

Tire cords can be constructed in a wide range of sizes and strengths. Yarn producers generally offer standard denier sizes, for example, nylon might be offered as 840, 1260, and 1680 denier yarns, going from lightest to strongest. Cord constructions would be identified as, for example, 840/2 or 1680/3 with the heaviest cords having the highest strength.

Twist effects

Twist levels are important for tire cord performance. Higher twists allow a cord to behave like a spring which will not open up under compression, while lower twists allow a cord to behave as a rod, maximizing the strength. Table 3.11 lists changes in general performance with increasing twist level. As twist increases the tenacity decreases, fatigue in compression improves (the main reason for higher twists), the cord cost per tire increases (because cords become shorter as they are twisted), and shrinkage during processing and cure increases.

Tenacity and fatigue resistance are sometimes reduced with increasing twist. In a tire the construction should be such that no cord will open up, chafe, or fret in a compression mode. Cord fatigue in compression is a critical factor in tire sidewalls where bending stresses and strains are high. In bias tires sidewall compressive stresses are more likely to occur and typical twists are 12x12 tpi (turns per inch), while in radial tires carcass cord twists are typically 6x6 tpi.

Figure 3.2: An example of cord construction using “S” and “Z” twists

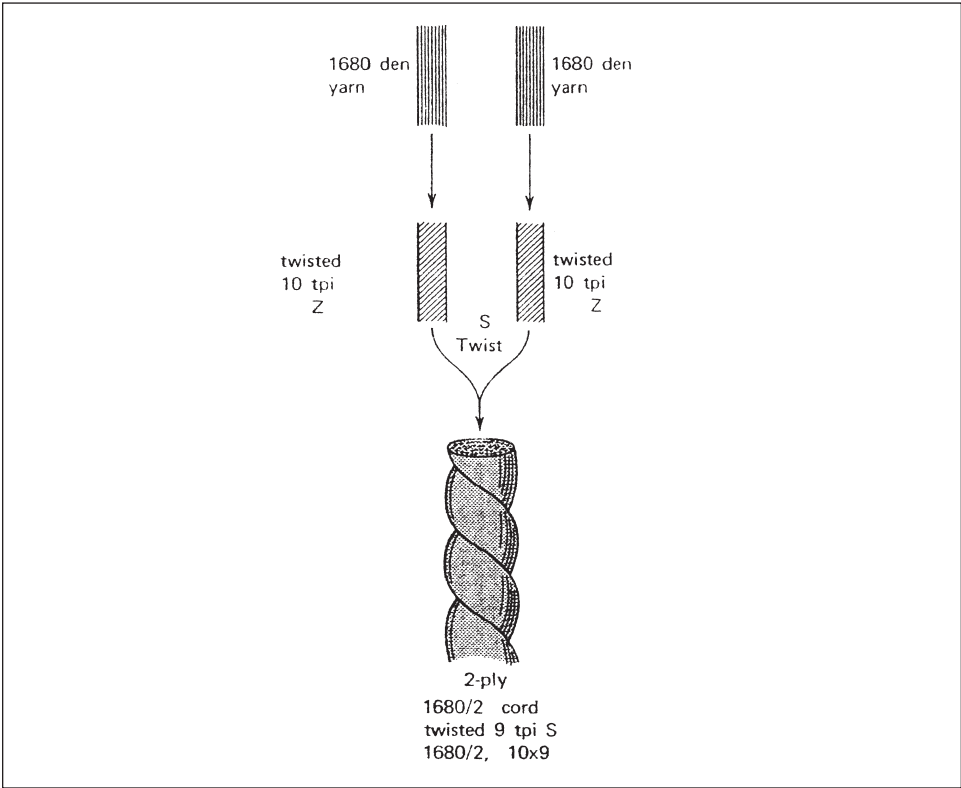


Table 3.11: Cord property changes with increasing twist levels

Reduction in strength
Reduction in initial modulus
Reduction in cyclic tension fatigue resistance
Increase in elongation to break
Increase in rupture energy
Increase in cyclic compression fatigue resistance
Increase in cord cost per tire

Twist multiplier

The amount of twist relates to both tenacity and compression fatigue resistance. To obtain equivalent fatigue performance in a product when changing cord size, cords must be twisted to the same helix angle using a “twist multiplier” relationship:

For the same material:

$$\text{Cord A tpi} \times \sqrt{\text{Cord A denier}} = \text{Cord B tpi} \times \sqrt{\text{Cord B denier}}.$$

[For example: Cord A of 2000/2 construction at 8 tpi would be equal to Cord B of 1000/2 at 11.3 tpi.]

For different materials specific gravity must also be considered:

$$\text{Cord A tpi} \times \sqrt{\text{Cord A denier}} / \sqrt{\text{Cord A SpGr}} = \text{Cord B tpi} \times \sqrt{\text{Cord B denier}} / \sqrt{\text{Cord B SpGr}}$$

[For example, an 840/2 nylon (1.14 SpGr) at 11.0 tpi would have the same helix angle as a 1100/2 aramid (1.44 SpGr) at 11.3 tpi.]

Weaving

After twisting yarns into cords, 1000 to 1500 cords are woven into a coherent sheet using a very light “pick” fabric as the weft at a very low fill count of one to two picks per inch. Rolls of this fabric (which is about 1.5 to 1.75 meters wide - the practical width of rubber-cord calenders) are transferred for further operations. The function of the pick is to maintain a uniform warp cord spacing during the downstream operations, such as, shipping, adhesive dipping and heat treating, calendering, tire building and lifting. Uniform cord distribution in the finished tire is essential for tire uniformity and performance. In bias-ply tires the pick fabric is usually a weak cotton yarn which breaks readily during tire shaping. In radial tires it consists of a highly extensible filament (undrawn nylon or polyester) in a cotton sheath. The core ensures uniform cord distribution as the tire is shaped and the sheath holds the cord spacing during adhesive treatment and calendering but breaks readily during tire lifting and shaping.

Tire cord processing (17, 18)

Downstream cord processing of tire cords can profoundly influence tire performance. Consistent control of the dimensional stability of the cords through the various environments - dipping, adhesive baking, heat stretching, relaxation, and tire vulcanization- is necessary to control and predict variations in such factors as tire size, tire uniformity, cord-to-cord uniformity, flat spotting, side-wall indentations, and creep during operation. Steel, aramid and rayon are minimally affected during cord processing while the thermoplastic fibers, nylon and polyester, must be very carefully controlled. The radial tire with its high-modulus restrictive belt has greatly alleviated many of the cord growth problems previously seen in bias tires, leading for example to tread groove cracking. A goal of process engineers concerned with dimensional stability when working with the thermoplastic cords is to maximize tensile modulus (often characterized by EASL - elongation at specified load) while minimizing thermal shrinkage. Care must be taken to optimize tensile strength and fatigue properties in these procedures.

Rayon and aramid cord processing

The processing of these cords is relatively simple since they are thermally stable and do not change significantly in downstream operations. Rayon must be carefully protected from moisture regain at all processing stages, especially at roll ends to avoid uneven shrinkage across a fabric roll.

An optimum treatment for processing rayon has been reported (19). Rayon cord made with a higher than specification twist is dipped in cord adhesive under relaxed conditions to open the twist for good dip penetration and to completely wet the cord with the aqueous adhesive. The cord is then tensioned to achieve the specification twist and dried at 130-150C before being baked under tension at 155-175C to cure the adhesive.

Heat treatment for aramid 230-260C is generally at low tension (8.8cN/tex) and with very low stretch to standardize modulus. As with polyester, adhesive application is a two step procedure.

Nylon and polyester cord processing

Thermoplastic fibers, such as nylon and polyester, are considered to be composed of a mixture of crystallites, extended (aligned) non-crystalline molecules, and amorphous “tie” molecules. Crystallization occurs principally during fiber drawing. Cord processing, carried out below the crystal melting temperature, modifies the non-crystalline portion. Skolnik (20) has reported typical changes in nylon orientation during cord processing:

Chawla (17) has summarized a number of studies. In the process of applying and baking a cord adhesive the amorphous portion of a thermoplastic cord will tend to become less oriented, resulting in shrinkage which will, in turn, adversely affect tire uniformity. Shrinkage is partially controlled by stretching the fabric in the heat-setting zone and relaxing it under controlled tension in a second zone. In general, higher relaxation results in lower shrinkage. Net stretch (the difference between stretch in the first zone and relaxation in the second) is often used as a measure of shrinkage and growth potential. This can be deceptive, however, for a number of reasons:

1. Additional crystallinity can occur that will lower shrinkage and/or growth potential,
2. Equilibrium orientation is seldom reached in allotted treatment times, especially with heavy cords,
3. High treatment temperatures can cause polymer flow and molecular weight degradation.

Heat treating conditions vary across the tire industry, serving different needs. Heat treatment of nylon, for example, varies in temperature between 177°C and 246°C, between 7% and 16% stretch, and between 20 and 60 seconds residence time. Chawla also reports studies on polyester cord by Aitken *et al* (21) who recommended a treatment temperature of 246°C, 4% stretch in the first zone and 3% relaxation in the second zone, with 90 seconds residence time in both zones for optimum fatigue resistance. Nylon is generally used at 3-7% net stretch, and polyester at 0 - 4%.

Table 3.12: Changes in % crystallinity and amorphous orientation of nylon

Treatment:	Greige	Heat set	Relax	In mold	Out of mold	Post cure inflation
Temperature C	25	225	205	180	180	180 to 60
Crystallinity (%)	60	63	70	70	70	70
Orientation	High	Very high	Moderate	Low	Low	High

Postcure inflation

On release from the tire curing press, viscoelastic cords in the hot tire are almost completely free to shrink. Postcure inflation (PCI) is therefore employed to stabilize tire size and uniformity. All-steel or all-rayon tires do not require a postcure treatment. Because the postcure inflating equipment is expensive to install and maintain, some companies have minimized or eliminated PCI for their radial tires by predictive mold sizing, control of cord properties, and controlled cooling. The use of PCI entails the following:

Passenger and light truck tires are automatically ejected from the press after the usual 12 to 24 minute cure time, depending on size, and then immediately loaded onto a postcure inflator which re-inflates the tire to 200 to 400 kPa (30 - 60 psi). This loads and stretches the hot cords. Post inflating controls the size, shape, uniformity, and growth of the finished tire. However, the results depend on the time, temperature and load applied to the cords during the

inflation process. Moreover, the cords should be cooled evenly to below their glass transition temperature before release from the inflator. Lim (22) has reported on studies that simulate PCI and non-PCI conditions by measuring EASL (elongation at specified load - the inverse of modulus). For rayon the modulus is constant for cords heated to 177C under 0.06N/tex and cooled to RT with or without tension. No modulus change took place. Under the same conditions nylon showed a 20% increase in modulus and PET a 30% increase. Equilibrium times for the cords were 30 minutes. A practical cooling time for factory tires is usually about two cure cycles. Also, it should be noted that uneven cooling, e.g., from one side to the other, can result in tire distortion, so that tires may be rotated during the PCI treatment.

Skolnik (23) has reported a “coefficient of retraction” for loaded cords in a simulated postcure inflation study. Cords were loaded to 0.9 g/den., heated to 165C, and cooled to various temperatures where the load was released. The coefficient of retraction (CR) is the percent length change per degree C.

1680/2 Nylon 6,6	CR above Tg	Tg (C)	CR below Tg
1680/2 Polyester	0.050	50	0.022
(standard)	0.050	85	0.011

Cord-rubber adhesion

The adhesion of rayon, nylon, polyester, and aramids has been reviewed extensively. Takeyama and Matsui (24) reviewed adhesives for rayon, nylon, and polyester. Solomon (25) updated this work in 1985 to include aramid adhesion and the effects of environmental exposure on degradation of adhesion. Chawla (17) summarized both cord processing and adhesive dip treatments. Dipping and baking of the adhesive is intimately tied in with cord stretching and relaxation procedures.

There are many variations in cord dipping procedures, e.g., one-step vs two-step dipping, dipping in the tire-plant vs in the cord-plant, surface activation of the cord, etc. We consider here only the goal of using adhesives, general operating procedures, and potential problem areas.

The prime goal of the cord adhesive is to avoid separation at the cord-adhesive interface, at the rubber-adhesive interface, or within the adhesive itself. This objective is achieved by using proper dipping procedures. Tire carcass failures that were initially attributed to failure at the adhesive interface were often shown on microscopic examination to be due either to fatigue failure of rubber close to the cord, caused by high stresses resulting from improper construction or irregular cord spacing, or to cord fatigue from excessive compressive stresses.

Mechanism of cord-rubber adhesion

It is generally accepted that the adhesive provides both chemical bonding between the rubber and the cord surface and by mechanical interlocking as the rubber penetrates within the cord interstices. The adhesive must also accommodate the large differences in the two materials:

- high-polarity polymers in cords vs. low polarity of rubber
- high modulus of cords vs. low modulus of rubber.
- Good adhesive durability is achieved by minimizing the abrupt change in modulus at the cord-rubber interface by introducing an adhesive layer of intermediate modulus.

Basic requirements for a good cord adhesive are listed in table 3.13.

Table 3.13: Requirements for cord-to-rubber adhesives

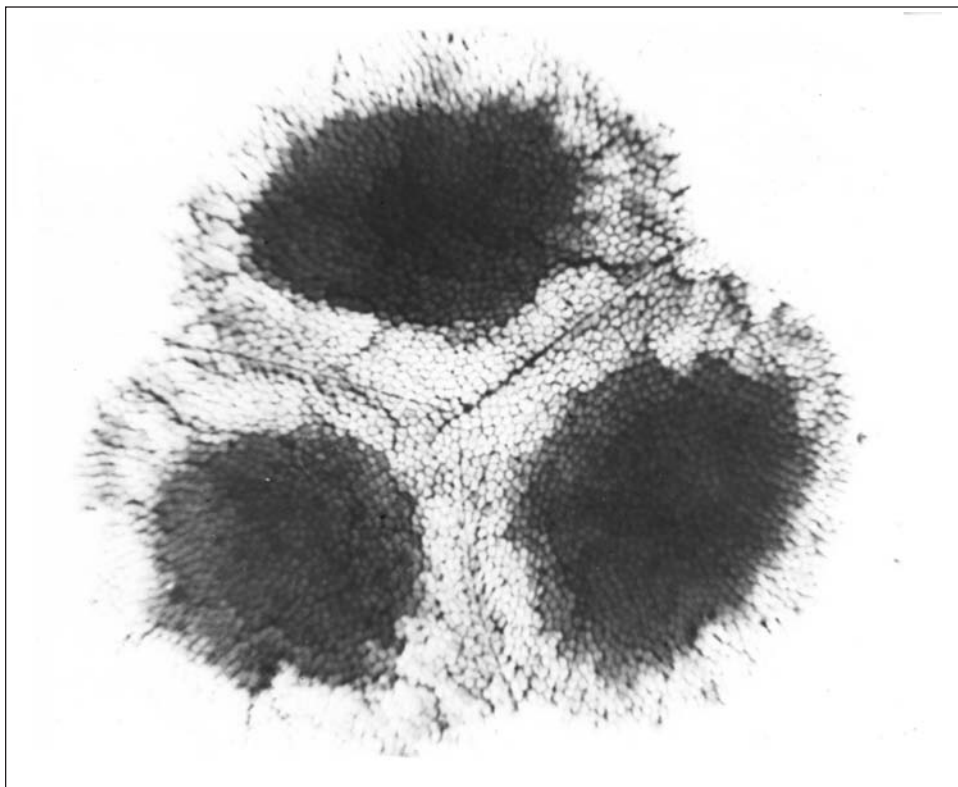
Good bonding to both cord and rubber Intermediate modulus between cord and rubber Rapid rate of bond formation High fatigue resistance in the cured adhesive No chemical deterioration of cord by the adhesive Compatibility with a range of rubber compounds No brittleness or flaking in processing
--

The resorcinol-formaldehyde-rubber latex system (RFL) developed in the 1940s for use with nylon and rayon is still used throughout the tire industry. A synthetic 2-vinyl pyridine-butadiene-styrene copolymer latex, developed for nylon, has replaced the natural rubber latex originally used for rayon, in all modern dips. Resorcinol and formaldehyde react in the dip to give a strong polar polymer with good adhesion to the polar tire cord, while the rubber component of the latex provides good bonding to the rubber. Specific recipes are given in the referenced literature for all textile cords and for both single and double dip treatments.

RFL is used for rayon and nylon exclusively and as the outer dip for polyester and aramid cords. Typically, resorcinol and formaldehyde are mixed and “matured” for up to 24 hours. The latex is blended and the cord is dipped before tensioning. Dip formulations contain 2 - 5% total solids and dip pickup is controlled to about 6 - 8%. The cord is then tensioned and baked. Complete total wetting of the cord is necessary to prevent spotty adhesion. Good dip penetration is important for good adhesion and cord compaction. Dip penetration of 2 - 3 filament layers is optimal. Figure 3.3 shows a cross section of a 1680/3 rayon cord with high penetration of the adhesive into the filaments, with resulting good adhesion and cord compaction.

Polyester and aramid polymers are much less reactive to standard RFL and must be pretreated to obtain good adhesion. A common practice is to employ a multistage dipping process. The cord is first dipped in an aqueous solution of a reactive chemical, such as an epoxide, e.g., the diglycidyl ether of glycerol or a blocked isocyanate, e.g., phenol-blocked polyisocyanate [“Hylene MP”], along with a small amount of wetting agent to give uniform dip pickup. After tensioning and baking the cord is again dipped in a standard RFL for final baking and relaxation. Processing times through each of the steps is generally 30-60 seconds. A general review of cord treatment temperatures is given in table 3.14.

The dip formulation, amount of dip pickup and the curing conditions can all affect adhesion and must be optimized. Strict quality control must be implemented once optimum conditions are established. Problems that must be avoided are: inadequate wetting of the cord, inadequate dip pickup, excessive dip pickup (which can result in flaking off of the adhesive), or overbaking during heat treatment. Any of these conditions can reduce adhesion. The finished cord must be protected from nitrous oxides (if gas or oil heating ovens are used) and from exposure to sunlight, humidity, or ozone if the cords are stored or shipped before being calendered with rubber. The treated cords are generally protected by storing them in polypropylene cloth liners and sealing them in black polyethylene film.

Figure 3.3: Cross-section of a rayon cord showing excellent dip penetration**Table 3.14: Drying, baking and heat setting temperatures for textile cords (°C)**

	Dry	Baking	Heat set/relax
Rayon	120-175	175-260	150-175
Nylon	120-175	225-240	180-245
Polyester	120-175	240-250	210-245
Aramid	120-175	240-250	230-260

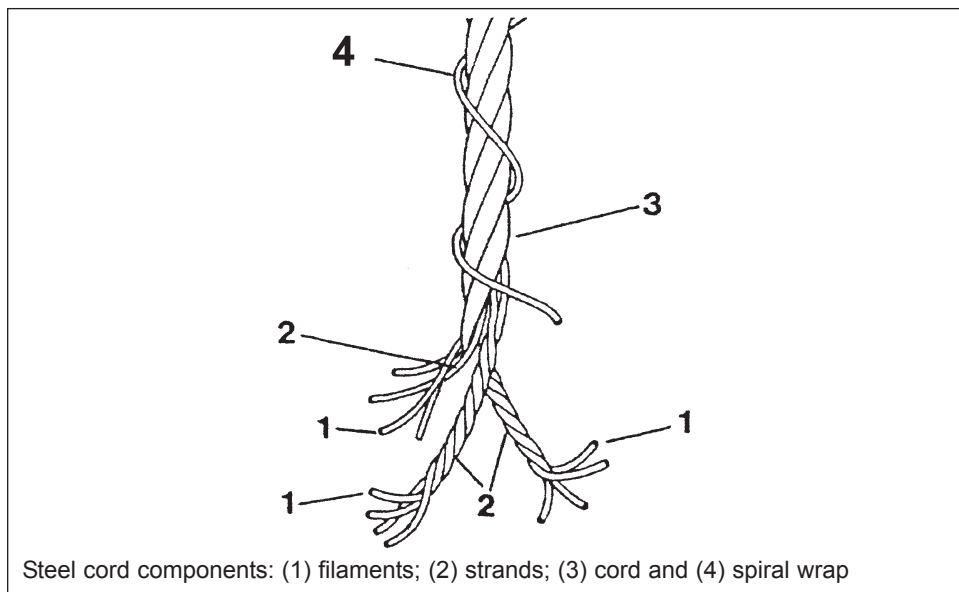
2. Steel cord (26, 27)

Introduction

Steel cord was adopted in Europe with the advent of the radial tire in the 1940s and 1950s. Steel cord, made by cabling fine steel filaments, met the requirements for a stiff, high modulus/high strength belt material at an acceptable cost, giving high strength and compression stiffness with acceptable bending stiffness, good resistance to fretting fatigue, and good adhesion to rubber. The stiffer steel belt provided the radial tire with quicker handling response and longer tread life compared to the bias tire.

Terminology (nomenclature) of steel cord

The terms used for steel cord are similar to those for the textile industry but with important

Figure 3.4: Steel cord components – filament/ strand/ cord/ wrap

differences. Steel filaments are much larger in diameter and the specific gravity is much higher, so that “tenacity” is not particularly meaningful. Individual filament strength is therefore reported in megaPascals (Mpa). Steel cords are described based on the way they are constructed rather than in terms of denier and number of strands, as is the case with textile cords. The generic steel cord, as depicted in figure 3.4, consists of filaments, strands, cord, and wrap, as defined below (26):

Filament – the basic element of a steel cord is a single fine metallic wire, typically 0.15 to 0.38 mm in diameter.

Strand – two or more filaments are combined together.

Cord – a strand when it is used as the final product or, more usually, the result of cabling strands or strands and filaments.

Wrap (Transfil) – a single filament usually 0.15 mm in diameter wrapped around a cord package to maintain compactness.

The significant cord properties, in addition to the number and diameter of the filaments, are listed in Table 3.15. The breaking load is the key property for the tire engineer.

Steel filament manufacture (27)

Filaments are produced by drawing high carbon steel rods through tungsten carbide dies. Currently, four types of steel filament are produced, rated by their carbon content and tensile strength. Table 3.16 lists typical tensile strengths (which also depend somewhat on filament diameter). Advances in drawing and heat treating techniques have made it possible to produce higher tensile strengths at lower carbon levels. Although more costly, the higher strength filaments allow stronger belts or lighter belts of equal strength and thus may lower the overall cost in a tire.

Manufacture of continuous filaments begins with the drawing of a 5-6 mm rod that has been treated with borax for lubrication through tungsten carbide dies to reduce the diameter

Table 3.15: Property definitions of steel cords

- Cord diameter – arithmetic average of the measured minimum and maximum diameters of a cord (mm).
- Linear density – mass of cord per unit length (g/m).
- Breaking load – force required to break a cord (N).
- Tensile strength – force per unit area to break a filament (MPa).
- Length of lay – the axial distance (mm) for a complete 360° revolution of any strand or cord element. The typical range is 2.5 to 25.0 mm. Inverse of twist.
- Direction of lay – Z and S directions are defined as in the textile industry (see Table 3.3)
- Bending stiffness – Resistance to bending under specified load conditions. Bending stiffness depends on filament diameter and cord construction.

Table 3.16: Typical tensile strengths of steel filaments

Filament	% Carbon	Tensile strength (Mpa)	
		0.20 mm diameter	0.35 mm diameter
Regular tensile (RT)	ca. 0.7	3000	2600
High tensile (HT)	ca.0.8	3400	3000
Super high tensile (SHT)	ca.0.9	3650	3400
Ultra high tensile (UHT)	ca.0.96	4000	3650

to about 1-3 mm. The wire is then heat-treated (“austentized/patented”) to maximize the tensile strength by relieving internal strains and modifying the iron carbide structure. It is then electroplated, first with copper and then with zinc, and heat treated to cause metallic interdiffusion yielding a brass coating containing 63/70 Cu and 37/30 Zn. Brass plating facilitates the multiple drawings needed to achieve the final diameters of 0.15-0.40 mm and is a critical factor in cord – rubber adhesion. The brass plating thickness is ultimately about 0.1 to 0.7 μm . Drawing dies must have no burrs that would scratch the brass layer, or corrosion problems might later arise from galvanic action between the iron and copper when in contact with moisture or rubber chemicals.

Steel cord construction

Literally hundreds of steel cord constructions could be employed in tires. However, standardized constructions are usually made to accommodate a range of applications. Steel type, filament diameter, and number of filaments will determine strength, stiffness, and compression fatigue resistance. High-strength steels may be more costly but give a lower tire cost because less material is required.

Cord construction and complexity determine the relative performance. For example cords in heavy duty carcasses require specific constructions for maximum resistance to fretting and fatigue, whereas steel plies that give resistance to cutting and impact damage require a different type of construction with a high breaking elongation.

Characterization of steel cords

Identification of the Construction

Steel cords are identified by the number and diameter of the filaments in each strand, the number of strands, and the way the strands lie around a central axis. A tire cord is defined by

the structure of the cord, the length and direction of lay, and the product type. In defining the structure the basic rule is that the description follows the manufacturing sequence, starting with the innermost strand. A full description of the cord is given by the formula:

Strand 1{(NxF)xD} + Strand 2{(NxF)xD} + Strand 3{(NxF)xD} + ...

where N = number of strands

F = number of filaments

D = diameter of filaments (mm)

A simplified form is when N or F =1, then the 1 is not stated, and if D is the same for several strands it is stated only at the end of the sequence. The wrap is always stated separately. Examples of constructions of some commonly used cords are illustrated below and in Figure 3.5.

$(1 \times 3) \times 0.22 + (1 \times 9) \times 0.22 + (1 \times 15) \times 0.22 + (1 \times 1) \times 0.15$
or $3 + 9 + 15 \times 0.22 + 0.15$

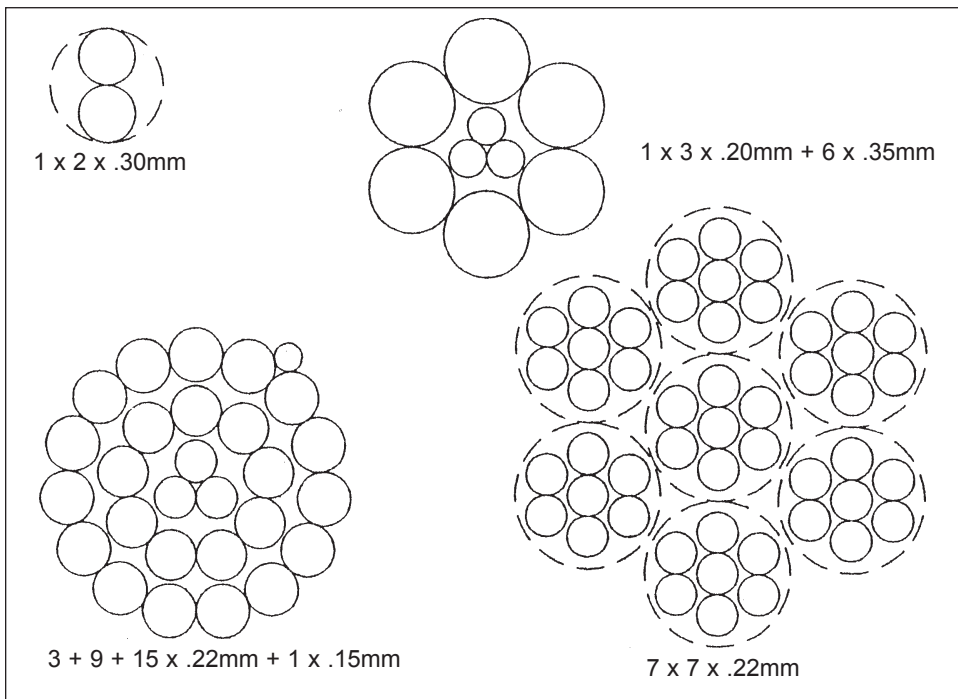
$3 \times 0.20 + 6 \times 0.35$
 $2 + 2 \times 0.28$

$7 \times 7 \times 0.22$

Length and direction of lay

The sequence in both the length and direction follows the manufacturing sequence. For

Figure 3.5: Cross-sections of typical steel cords



example:

3 + 9 + 15x0.22 + 0.15 5/10/16/3.5 SSZS
5S: lay length and direction of strand 3x0.22
10S: lay length and direction of strand 9x0.22
16Z: lay length and direction of strand 15x0.22
3.5S lay length and direction of wrap.

Product type

Several types of cord products are available based on variations in the manufacturing and twisting procedures.

Regular cord – standard cord production in which the lay direction in the strands is opposite to the lay direction in closing the cord. This product is easy to produce, cost effective, and processes well in the tire factory.

Lang's lay cord (LL) – cord in which the lay direction of the strands is the same as the lay direction in closing the cord. High elongation cord (HE) is a Lang's lay cord in which the strands are loosely associated and moveable with respect to each other. This allows the cord to be stretched substantially and gives useful cut protection when used in the top belt of radial truck tires and impact resistance in the rock penetration zone of earth mover and mine tires.

Open cord (OC) - A cord in which the filaments are loosely associated and moveable relative to each other. This permits rubber to penetrate into the cord to maximize adhesion to the filaments and to prevent moisture wicking along the cord that could result in steel corrosion. This cord is difficult to process with standard calendering equipment as excessive tension during processing can close the cord resulting in void formation along the cord. Open construction cord has been the subject of numerous patents for various production techniques and cord designs. Bekaert offers a BETRU™ cord which is less sensitive to calender tensions and cord wicking (28).

Compact cord (CC) – cords are produced in a single compact bundle in which the filaments have mainly linear contact with each other. This construction is useful in applications such as for the carcasses of heavy-duty radial tires where severe fretting fatigue can occur at crossover points in a standard cord.

Physical properties of cords

Arkins and Peterson (28) have reviewed constructions and physical properties of present and future steel cords for various tire applications. They predict the adoption of smaller diameter lighter HT and ST filaments, greater use of compact cords (CC) in large tire carcasses for improved fretting resistance, and more complete rubber coverage of all the filaments using newer twisting processes to give effectively open cords, such as the Bekaert BETRU™ cord. Table 3.17 lists representative constructions and properties of some steel cords used in various radial tires.

Basaran (29) has described the improved fretting resistance of compact cords in radial tire carcasses. He also discussed the improved rubber penetration and coverage of filaments for cords made by the BETRU™ process. BETRU™ cords showed no pressure drop in air wicking tests indicating complete rubber coverage which will protect against moisture penetration and wicking along the cords, for a range of calendering tensions. Open-construction cords, which are designed to give high rubber coverage of the filaments, may close up if excessive wire tensions are imposed at the calendar. In certain constructions this

Table 3.17: Constructions and physical properties of steel radial tire cords

Construction	Lay Length (mm)	Lay direction	Breaking load (N)	Cord diameter (mm)	Linear density (g/m)
Passenger tire belt					
2+1x0.28 HT	-16	-S	555	0.70	1.47
2+2x0.25 HT	-14/14	-SS	605	0.65	1.55
LT carcass					
3x0.20+9x0.175(CC)	10	S	855	0.75	2.49
2+7x0.20 HT	5.6/11.2	SS	915	0.76	2.26
LT belt					
2+2x0.35 HT	16/16	-SS	1060	0.84	3.03
MT carcass					
3+9x0.22+0.15	6.3/12.5/3.5	SSZ	1290	1.17	3.85
0.20+18x0.175 (CC)	12.5	Z	1300	0.90	3.71
MT belt					
3x0.20+6x0.35	10/18	SZ	1660	1.13	5.34
HDT carcass					
3+9+15x0.175	5/10/18	SSZ	1770	1.07	5.20
0.25+18x0.22 (CC)	16	Z	2050	1.13	5.85
HDT belt					
3+9+15x0.22+0.15	6.3/12.5/18/3.5	SSZS	2750	1.62	8.50
(protector belt – 6.5% elongation)					
3+7x0.22 (HE)	4.5/8	SS	1820	1.52	6.95

could cause a capillary channel to form down the cord where moisture may propagate and cause corrosion. Such cords have shortcomings similar to those with standard twist constructions, for example: 1x4x0.25.

Bead wire (30)

Steel bead wire is not considered a cord since it is not constructed from twisted filaments. In terms of steel cord nomenclature, a bead wire would be considered a filament. Tire beads are made from single steel wires of larger diameter. They are manufactured by several processes, including tape-wound beads, single-wire wrapped beads, or cable beads. Each type has certain performance or cost advantages. A similar wire is used in all of these constructions. The wire diameter, number of wires (or turns), and type of steel will depend on the size and load carrying requirements of the tire. Beads are designed with an over-pressure blow-off safety factor, load distortion resistance, rim slippage resistance, and resistance to bead breakage during mounting. Wires for beads are supplied as regular or high strength steel, in various diameters, and bronze or brass coated for adhesion. Table 3.18 lists typical properties of some standard bead wires.

Steel cord adhesion

For maximum long-term durability the steel cord used in radial tires must have a high level of rubber-to-brass adhesion and a high degree of resistance to corrosion caused by water

Table 3.18: Properties of typical commercial bead wires

Diameter mm.	Breaking strength N	Breaking elongation %	Plating metal	
			Bronze	Brass
0.96 NT	1350	5	0.3/0.65	0.3/0.6
1.42 NT	2880	5	0.15/0.45	0.3/0.6
2.00 NT	5260	5	0.1/0.3	0.2/0.4
0.96 HT	1525	-	-	-
1.295 HT	2795	-	-	-
2.00 HT	6125	-	-	-
0.86 ST	1350	-	-	-

NT- normal tensile, HT-high tensile. ST- super high tensile
Bronze: 3% Sn max. Brass: 72% +/- 5 Cu

entering the tire through road cuts and penetrating to the belt cord. Poor performance in either area can result in reduced tire service life. Thus, prevention of loss in adhesion in steel-belted radial tires is a prime consideration for tire engineers.

The exact mechanism of brass-to-rubber adhesion has been the subject of much study and conjecture, but lies beyond the scope of this chapter. Van Ooij (31,32) has reviewed the subject in detail. Basically, it is conjectured that a bond is formed between the polar metals and the non-polar rubber during vulcanization with sulfur by formation of a Cu-S- Rubber bond, as idealized in figure 3.6. However, this bond can readily be converted to CuS with loss of adhesion under some circumstances. There are also indications that optimum bonding involves interfacial layers of oxides and sulfides of both copper and zinc.

Bond durability is tested by measuring bond strength after various aging times and under various conditions: Dry heat aging, steam aging, aging in high humidity, and salt bath immersion. The rubber coverage of the wire after testing is regarded as equally important as the retained bond strength of the rubber compound.

Corrosion (rust) of steel can destroy both the adhesive bond and the wire itself. Figure 3. shows an idealized view of moisture attack on wire through galvanic action if the brass coating is damaged or if water can wick into the cord interstices.

Cord construction, brass composition, brass plating thickness, rubber compound composition, tire curing and storage conditions can all affect wire adhesion. Table 3.19 summarizes the best choice of these parameters.

Each tire manufacturer adopts specific belt coat compounds. Many generic versions may be found in the literature.

Table 3.19: Parameters that maximize cord adhesion

- Brass composition: 65% Cu, 35% Zn , plus/minus 2.5%
- Brass plating thickness: 0.3 - 0.6 μm
- Cord construction: open construction – or BETRU™
- Lower temperature – slower cure, eg., 150 - 160°C
- Radial belt compound variables:
 - High sulfur level –5 to 8 parts per 100 rubber
 - High sulfur to accelerator ratio
 - Delayed action accelerator- slow cure
 - Cobalt salt – improve and corrosion stability
 - Lead oxide – improve high temperature cure stability
 - Silica/Resorcinol/Methylene donor – improve moisture sensitivity

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4. Review Questions

What are the main functions of cords in tires?

What three elements make up the tire cord construction?

What physical properties are needed in tire cord filaments?

How does a carcass cord differ in physical properties from a belt cord?

Name the presently used high volume tire cord materials.

What are the preferred cord materials for passenger tires? Why?

What are the two processes for producing textile cord filaments? How does steel filament production differ from these?

What important compromises are involved in the level of cord twist?

How does the processing of a thermoplastic textile cord differ from that of non-thermoplastic textiles?

What chemical materials are required as adhesives for good polyester or aramid adhesion to rubber? How are these usually applied?

What steel treatment is needed to achieve steel-to-rubber adhesion?

What steel cord constructions are useful to maximize resistance to fretting and resistance to corrosion?