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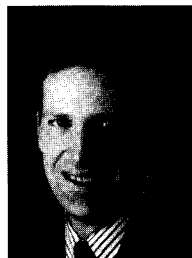
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A Technology Review of Wood-Plastic Composites

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Abstract

Wood has long been used by the plastics industry as inexpensive filler to increase strength and stiffness of thermoplastic or to reduce raw material costs. During the late 1980s, researchers and industries began investigating high filler levels and coupling agents to encourage interaction between the wood and thermoplastic components. An improved sophistication in processing and formulations led to development of wood-plastic composites (WPC) that exhibit synergistic material properties. Wood-plastic composites consist primarily of wood and thermoplastic polymers. Traditionally, the materials have been viewed as a wood fiber or particle reinforcing a continuous thermoplastic matrix. Therefore, WPC development has followed previous work on synthetic fibers and fillers such as glass, carbon, boron, aramid, and mineral fillers. Like their synthetic counterparts, WPC researchers have sought enhanced strength, stiffness, creep, and thermal stability. However, the commercial success of these emerging materials has been primarily by the promise of improved moisture performance, recycled and waste material utilization, and efficiency in product and process design. The goal of this paper is to provide an overview of the technology for producing wood plastic composites. This overview will address

commercialization, material selection, and production methods.

Commercialization of Wood-Plastic Composites

The science regarding wood plastic composites (WPC) is focused primarily on the chemical interaction between the dissimilar material components. Although this issue is of strong importance, the lack of resolution has not limited commercialization of this material class. Instead, the material and product development has progressed on two fronts, property and process improvements.

Property Advantages

Despite the recent success of traditional engineered wood products, their susceptibility to water adsorption, thickness swell, and bio-deterioration has limited use in exposed environments. Methods to overcome the hygroscopic nature of wood range from plastic overlays to chemical treatments aimed at limiting hydrogen-bonding sites. Although these methods have provided some resistance to water adsorption and thickness swell, their effectiveness is limited. Prevention of bio-deterioration has historically been accomplished using impregnated fungicides and insecticides. The addition of thermoplas-

tics to wood composites has a significant influence on the water absorption of the material (Deaner et al. 1996; Laver 1996). However, little research has addressed the ability for material and product design to influence the durability of wood-based materials.

When compared to solid thermoplastics, WPCs exhibit different mechanical and physical properties. Strength and stiffness are generally influenced with increased levels of wood fillers dependent on the materials and processing methods. Higher concentrations of wood filler impart a natural resistance to ultraviolet degradation. Under some conditions, wood fillers can also increase the melt or softening temperature of the thermoplastic, which allows for expanded serviceability.

Processing Advantages

With the exception of molded door skins, traditional wood composite products are flat pressed to produce prismatic elements. Any shaping of the material occurs in secondary manufacturing steps and typically involves machining and assembly steps that are waste and labor intensive. The extrusion processes utilized to produce commercial wood-plastic composites have concentrated on producing highly contoured linear parts (Laver 1996; Puppini 1999). This technique provides definite material cost and process advantages by alleviating many post-manufacturing steps that add costs to the final product.

Wood-thermoplastic composites have many processing advantages when compared with synthetic and mineral-filled thermoplastics. Wood fibers provide a sufficient reinforcement at a much lower cost than synthetic fibers, while the composite product density is much lower than synthetic and mineral filled thermoplastics. When synthetic and mineral fillers are used, machine wear and damage of processing equipment is much higher than with wood fillers. Fiber damage during processing is greatly reduced when wood is utilized, which allows for recycling production waste without compromising quality.

General Disadvantages

Disadvantages can also be found with WPCs when contrasted with solid thermoplastics and synthetic and mineral-filled plastics. Water adsorption and thickness swell is higher with WPCs, which is virtually nonexistent with solid polymers. Interfacial adhesion is very limited with wood and thermoplastics. The polar nature of wood and the non-polar in-

fluence of thermoplastics require coupling agents or surface activating methods to promote adhesion. Dispersing fibers throughout the matrix can be difficult not only with wood filler, but also with many other types of fillers. However, dispersing agents and proper mixing techniques have been found to effectively distribute the filler throughout the matrix.

Raw Materials

Wood

In the plastics industry, fillers can be classified into two major groups, particulate and fibrous. Particulates are generally classified as fillers or reinforcing fillers if interphase adhesion is high. Particulates have dimensions that are approximately equal in all directions and can be any shape. Fibers are considered reinforcing because they bear a majority of the load applied and their length is much greater than the cross-sectional dimension (Manson and Sperling 1976; Matthews and Rawlings 1994). Fillers or particles can be used to increase mechanical properties; however, they are more commonly used as extenders to lower polymer use. Fibers are explicitly added to increase stiffness and strength of the composite. For WPCs, the wood is generally in the form of a short fiber, particle, or flour. These small sizes integrate well into the processing techniques utilized by the plastics industry. Many species are used in commercial production with pine, maple, and oak being the most common. Currently, the species selection appears to be influenced more by availability than engineering.

Thermoplastics

The two major classes of polymers, thermoplastic, and thermosets, can be differentiated by their response to temperature. Thermosetting polymers polymerize and increase stiffness with an initial increased temperature. In contrast, thermoplastics repeatedly soften or melt with increasing temperature. The structure and morphology of the polymer chains can further differentiate thermoplastics.

Thermoplastic polymers exhibit both amorphous and semi-crystalline morphologies. Amorphous polymers consist of randomly configured molecular chains, such as polystyrene (PS) and polyvinyl chloride (PVC). Other polymers, such as polyethylene (PE) and polypropylene (PP), exhibit varying degrees of crystallinity, which dominate the physical and mechanical properties. A regular order of molecular chains with sufficient intermolecular bonds to

prevent disorder from thermal energy is necessary to form a three-dimensional crystalline lattice (Rosen 1993). Temperature influences crystalline polymers somewhat differently than amorphous polymers. The crystalline region of the polymer undergoes a first order, melt phase transition with increasing temperature (Sperling 1986). Amorphous polymers do not exhibit a true melt phase, but may soften to a point of viscous flow similar to melting.

There are a variety of thermoplastics available for composite manufacturing although only a few can be used for WPCs. The primary selection criteria for a thermoplastic used in WPCs is a melting or softening temperature less than the thermal degradation temperature of wood ($\approx 210^{\circ}\text{C}$). This thermal criterion restricts selection to the class of polymers known as polyolephins. Commonly used thermoplastics having softening or melting temperatures that are suitable for WPC processing include polystyrene (PS), low- and high-density polyethylene (LDPE and HDPE), polypropylene (PP), and polyvinyl chloride (PVC) (Fig. 1). Polyethylene is one of the most commonly used thermoplastics comprising up to 75 percent of total plastic waste (Mustafa and Balatinecz 1996).

For polyolephins, either virgin or recycled plastics are commercially available in the form of pellets, powder, flakes, or films. Recovered products such as milk jugs, battery casing, film stock, and plastic shopping bags can be utilized as raw materials. Although low cost recovered products are often

difficult to control, the source of recycled material is limited sorting technologies (Mustafa and Balatinecz 1996).

Properties of Wood-Plastic Composites

Wood-plastic composites exhibit hybrid properties of wood and plastic. In general, adding wood to a thermoplastic matrix increases the mechanical properties and thermal stability when compared to the solid thermoplastics. Conversely, the thermoplastic component can present moisture barriers to the wood elements, decreasing the water adsorption and swelling characteristics as compared to wood and traditional wood composites.

Mechanical Properties

A number of studies have addressed the influence wood fibers have on the tensile properties of various thermoplastics. The mechanical properties of the virgin polymers differ; Figures 2 and 3 show plots of relative strength and stiffness, respectively. The tensile strength of twin-screw extruded samples of PP, recycled HDPE, and PS gradually decreased with the addition of wood fibers (Fig. 2). In contrast, the tensile modulus increased with fiber addition (Fig. 3). Fiber additions greater than 5 percent are ineffective for a polystyrene matrix (Liang et al. 1994). The behavior of PP was similar to that of PS; however, modulus reached a maximum with a 30 percent wood fiber percentage (Takase and Shiraishi 1989). The addition of wood fiber was more effective for increasing the modulus of recycled HDPE-wood fiber composites over a range of 0 to 60 percent loading (Yam et al. 1990). In contrast to the PP and PS, the addition of wood to HDPE did not appear to reach a maximum at any point.

Moisture Properties

Adding wood to a thermoplastic matrix will inevitably cause an increase in moisture uptake. The moisture content of the wood filler during processing is generally below 1 percent, therefore any filler exposed on the surface will absorb the surrounding water vapor and obtain an equilibrium moisture content (EMC). Klason et al. (1984) exposed molded PP-wood flour composites to a 50 percent relative humidity (RH) at 23°C for 150 days and observed an equilibrium moisture content (EMC) of 1.6 percent at a filler loading of 60 percent. The EMC dropped as the flour percentage decreased. When the same samples were subjected to a water soak test, an 8 to 10 percent moisture content for flour percentages

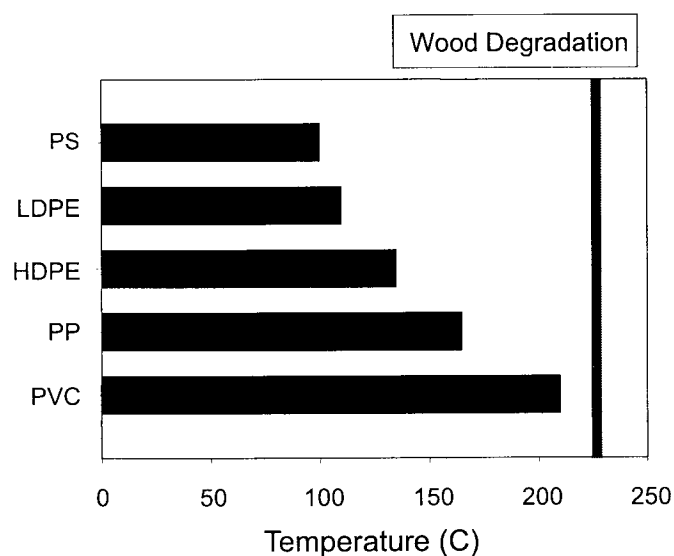


Figure 1.—Processing temperatures for commonly used thermoplastics.

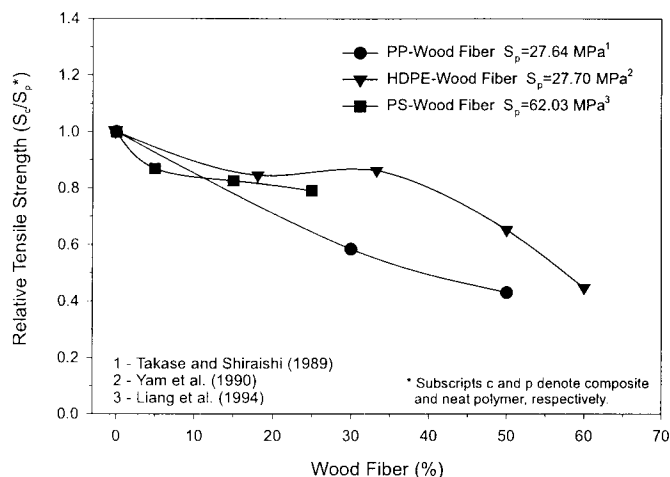


Figure 2.—Relative tensile strength of PP, recycled HDPE, and PS with reinforcing wood fibers.

between 20 to 60 percent, resulted after samples were placed in a 90°C water bath for 7 days.

Liang (1995) flat pressed wood-fiber/polystyrene composites and subjected them to liquid water exposure in an ASTM 1037 test. As might be expected, increasing polystyrene content decreased the water absorption and thickness swell. However, the increased performance was disproportionate to the amount of polystyrene in the formulation. For three different wood-fiber types, the addition of 25 percent polystyrene decreased the water absorption from over 40 percent to less than 10 percent. Liang concluded that the polystyrene addition must result in significant changes in material structure.

Wood Particle Type and Content

Törmälä et al. (1985) compared the influence of different wood particle types on composite properties. Plywood grindings were mixed with LDPE and processed with a single-screw extruder. The fibrous grindings increased the ductility of the composite when compared to materials produced with particulate wood flour. However, the improved extensional characteristics were accompanied by a decreased tensile strength of 20 to 30 percent from an unfilled polymer. A cross-sectional sample of a tensile test displayed prominent fiber pullout with the plywood grindings indicating poor interfacial adhesion between the grindings and LDPE. Maiti and Singh (1986) examined different sizes of wood flours compounded with HDPE without coupling agents. The extruded samples displayed an increasing modulus with decreasing particle sizes (180 to 425 μm). Al-

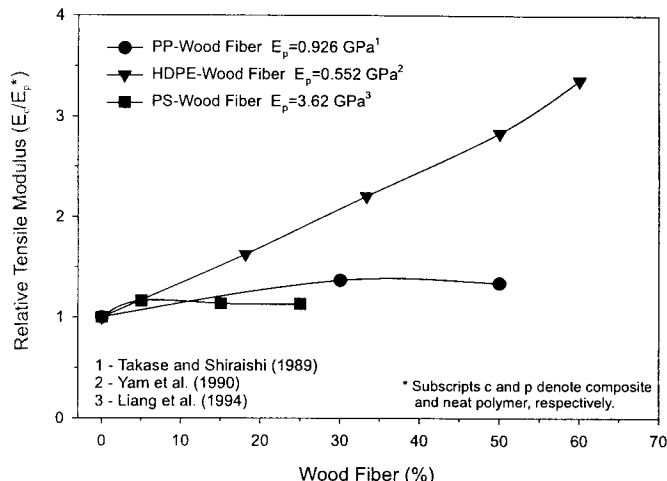


Figure 3.—Relative tensile modulus of PP, recycled HDPE, and PS with reinforcing wood fibers.

though yield strength increased with decreasing filler size, all of the composites displayed lower yield strengths than the unfilled polymer. Maiti and Singh (1986) surmised that the decreased properties with increased particle size resulted from poor adhesion between the filler and thermoplastic since no coupling or dispersing agents were used in either study.

Comparing fibers, particles, and flour, the strength reduction appears similar as the filler loading increases (Tabs. 1 and 2). Without dispersing or coupling agents, the greatest modulus increases are realized using wood flours. Both strength and stiffness increases can be realized with increasing fiber length if adhesion between the wood and thermoplastics is good. However, when using wood fibers without effective dispersion or coupling agents, the benefits for mechanical properties are negated.

The wood content influences the mechanical properties of extruded WPCs. Yam et al. (1990) used a co-rotating twin-screw extruder to produce an HDPE/wood fiber composite. Both flexure and tensile modulus increased with increased fiber loading for heat-treated, acetylate treated, and untreated fibers. However, a reduced tensile and impact strength was found in all composites as the fiber content increased from 0.0 to 60 percent by weight. Takase and Shiraishi (1989) found similar results with composites produced by hot pressing polypropylene and wood pulp; however, the addition of coupling agents caused an increase in the tensile strength with increased fiber content.

A decrease in composite strength properties with increased fiber content is also found with fiber rein-

Table 1.—Tensile properties of WPC using wood fiber as filler for PP, PS, HDPE, and LLDPE.

Property	Polymer	Wood fiber content (% weight)					
		0	10 to 15	20 to 25	30 to 35	40	50
Modulus (MPa)	PP ^{2,5,7}	0.9 to 1.0	1.13	1.17	1.2 to 1.4	--	1.24
	PS ¹	1.9	1.9	2.0	2.2	--	--
	HDPE ^{4,6,8}	1.0 to 1.2	1.1	1.1	1.1 to 1.3	1.3	1.55
	LDPE ³	0.33	0.43	0.63	0.72	0.77	--
Strength (MPa)	PP ^{2,5,7}	27 to 34	23.5	23 to 25	16 to 21	20	11.9
	PS ¹	42	36	35	33.8	--	--
	HDPE ^{4,6,8}	25 to 29	24	19	18 to 27	17 to 20	19
	LDPE ³	10.8	13.1	12.2	11.2	10.7	--

¹ Maldas and Kokta (1990)² Raj et al. (1989a)³ Raj et al. (1989b)⁴ Raj et al. (1990b)⁵ Sain and Kokta (1994)⁶ Sleke and Childress (1993)⁷ Takase and Shiriashi (1989)⁸ Yam et al. (1990)**Table 2.**—Tensile properties of WPC using wood flours or particulates for fillers for PP, PS, and HDPE.

Property	Polymer	Wood fiber content (% weight)					
		0	10	20	30	40	50
Modulus (MPa)	PP ^{1,2}	1.1	1.22	1.55	2.0	2.4	2.85
	PS ^{1,3}	1.5 to 1.7	1.7 to 2.0	1.8 to 2.5	1.9 to 2.9	2.0 to 3.3	3.95
	HDPE ^{1,4}	0.81	0.8 to 1.1	1.3 to 1.5	1.4 to 1.8	1.6 to 1.8	2.5
Strength (MPa)	PP ²	--	--	--	--	--	26.6
	PS ^{1,3}	40.3	35.7	36.4	34.3	29.9	--
	HDPE ^{1,4}	--	26.5	25	19	15	--

¹ Klason et al. (1984)² Meyer et al. (1991)³ Maldas et al. (1988)⁴ Raj et al. (1990a)

forcing materials other than wood. Chiu et al. (1991) extruded glass fiber reinforced PP and found decreased yield strength and increased modulus with increasing fiber content. As with wood, adding glass fibers to the polymer matrix will increase the strength only when a strong interfacial bond exists.

Woodhams et al. (1984, 1993) found the influence of fiber dispersion in a PP matrix played an important role in the strength properties of the composite (Fig. 4). Working with chemical dispersing agents blended with PP and wood fiber, Woodhams et al.

(1984) observed higher tensile strength properties as fiber loading increased. Woodhams et al. (1993) blended thermomechanical pulp with PP using an intensive shear mixer. As the fiber loading increased, a positive correlation with modulus and strength was observed for both tensile and flexural properties. Impact energy decreased with increased fiber content for unnotched samples. Park and Balatinecz (1997) found similar results when they compared two high shear mixers. Mixing sawdust and linear low density PE with a ring roller and grinding mill

showed higher flexural strengths, but lower tensile strengths, when 30 percent sawdust was added. Karmaker and Youngquist (1996) also used a high shear mixer and observed an increase in tensile strength with composites made with jute and PP.

With traditional synthetic fiber-reinforced thermoplastics, the concentration or loading of fibers is often limited to less than 50 percent by weight (Woodhams et al. 1984). This limit results from both viscosity increases and increased fiber damage during processing. Wood fibers, being more compliant and ductile than most synthetics, will bend rather than fracture in the blending shear fields (Czarnecki and White 1980). Under some mixing conditions, it is possible to extrude wood-fiber composites containing up to 75 percent by weight filler, which becomes an important factor when optimizing mechanical properties at the lowest costs (Pabedinskas et al. 1993).

Production Methods

Adding fibers or particles to thermoplastics has been shown to provide a variety of mechanical and processing advantages. However, the dispersion of the polymer melt throughout the wood particles can be a major processing challenge. The quality of the finished product for most melt processes depends on the quality of mixing (Gramann and Osswald 1993). In preparing short fiber reinforced composites, it is necessary to optimize the degree of compounding or mixing. Inadequate compounding causes poor dispersion of the plastic and poor wetting of the fibers, while excessive compounding causes severe fiber damage. Both scenarios result in a reduction of mechanical properties when compared to the optimal condition (Yam et al. 1990).

The thermoplastic industry has utilized many different extruding techniques to produce a variety of products. These products include solid or hollow bodied sections, coverings, film or flat sheets, monofilament fibers, netting, tubular films, and foams (Stevens 1985). Both extrusion and injection molding employ a screw as a transport mechanism. These techniques are the most commonly used methods to process plastics because the screw geometry performs all of the elementary steps of polymer processing, conveying, pumping, melting, and blending (Turkovich and Erwin 1983).

Compounding

Melt blending wood and thermoplastics usually requires an input of physical energy, via high shear forces, for the polymer to melt (Morton-Jones 1989). Compounding is generally performed in melt blending equipment where sufficient heat will melt or soften the plastic, and allow for more dispersive mixing (Park and Balatinecz 1997). Terms such as compounding, mixing, kneading, and shearing are all used to describe the blending procedure based upon the specific equipment used. Wood flour is used extensively because of availability, cost and ease of dispersion into the matrix. Fibers and larger particles require longer and higher intensity mixing to disperse the fibers (Pabedinskas et al. 1993).

The methods in which the components of a thermoplastic composite are mixed vary depending upon the type of manufacturing process. Twin-screw extruders provide mixing capabilities during extruding or injection molding processes. Intensive shear mixers, e.g., the Gelimat or Szego mill, can achieve preparation of wood fiber and thermoplastics before injection molding (Park and Balatinecz 1997). Park and Balatinecz (1997) investigated the use of two-ring roller grinding mills. Both the Szego mill and the Gelimat mixer melt blend with a kneading or shearing action. The Gelimat, a batch high intensive shear mixer that generates enough heat from shearing to melt LDPE, provided efficient mixing to distribute the wood filler used in the study. The Szego mill with a continuous ring roller requires external heat to achieve melting of high melt polymers.

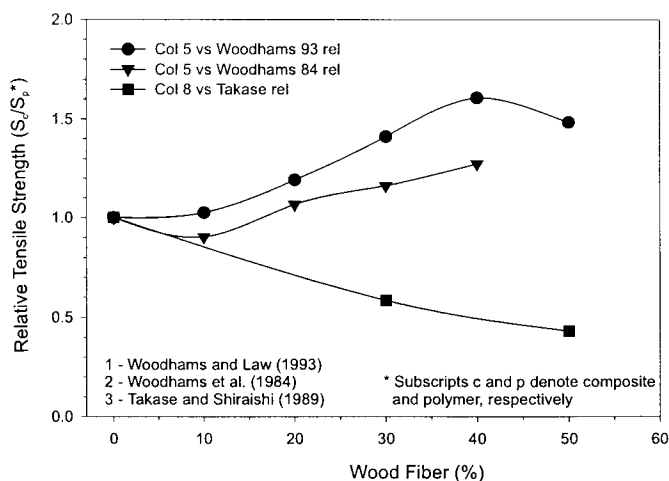


Figure 4.—The influence of dispersing techniques on tensile strength of PP-woodfiber composites.

The process provided equivalent results to the Gelimat mixer with the added production benefits of a continuous method.

Extruder Types

Single-Screw Extrusion.—Modern extruders utilize a screw to convey the raw material. The screw can be viewed as a parallel plate helically wound about a shaft. The channel between the screw flights represents the area subjected to shearing flow from the relative motion of the screw with respect to the barrel walls (Turkovich and Erwin 1983). The friction developed on the surface of the barrel and screw flights allows the material to be pushed forward and not simply rotate with the screw (Martelli 1983). The rate of forward conveyance is proportional to the screw flight diameter and angle, the channel depth, and screw rotation speed.

Single-screw extruders are highly suitable for continuously processing a wide range of thermoplastic materials into an equally wide range of finished and unfinished products. The single-screw extruder primarily acts as a drag pump and is suitable for working with highly viscous fluids at the high pressures and temperatures required for processing polymers (Stevens 1985). To increase the frictional surface, the length of the barrel is extended. The ratio of the barrel length to the screw diameter (L/D) becomes an important variable in single-screw extruding. A large L/D ratio creates more friction and thus imparts a more forward conveyance under the same extruding conditions (Martelli 1983).

Twin-Screw Extrusion.—Twin-screw extruders are commonly used where single-screw extruders fail to produce the desired pressure and mixing. Twin-screw extruders can be intermeshing or non-intermeshing. Non-intermeshing extruders operate similar to single-screw extruders where forward conveyance is primarily dependent on the friction developed between extrusions and the barrel. However, with intermeshing screw extruders, the threads of the screws are engaged to displace material from one screw to the next, thereby providing a means of mixing the material.

The rotation of the screws can be classified either as co-rotating or counter-rotating. Co-rotating screws are driven in the same direction, while counter-rotating screws rotate in opposite directions (Martelli 1983). Counter-rotating twin-screw extruders are capable of generating the high pressures necessary for specific profile applications. Co-ro-

tating twin-screw extruders do not generate the same high pressures, however, with proper screw design, they can give excellent mixing and a narrow range of dwell time. The shorter dwell time subjects all the material to the same shear and temperature histories (Rosen 1993).

Output of twin-screw extruders is roughly proportional to speed and not reduced by backpressures developed in single-screws. In intermeshing twin-screw extruders, conveyance of the material is not dependent on frictional forces because the adjacent screw displaces the material within the screw channel. The interaction of the two screws also influences the shear history of a twin-screw extruder. Counter-rotating models produce relatively low shear because directional movement of the screws in the intermeshed zone is the same for both screws. In contrast, the opposite directional movement of the two screws in the intermeshed region of co-rotating screws produces a high shearing action. The low shear of counter-rotating twin-screws lead to a reduction in energy input and temperature rise during processing. Although the manufacture cost of twin-screw extruders can be high due to precise machining, it is an effective means of compounding heat and shear sensitive polymers, i.e., PP, for chemical reactions and for shaping processes at minimum temperatures (Stevens 1985).

Huber (1996) states that the intermeshed twin screw co-rotating extruder has the capabilities to compound, melt thermoplastic, and disperse wood fibers effectively throughout the matrix. In the same process, thermal degradation and fiber breakage are minimized. Yam et al. (1990) utilized the same twin-screw extruder with different configurations of the screw flights. As a rule, for screw flights angled from 45 to 90°, conveying ability decreases with increased flight angle. With a majority of the extruding stages composed of high flight angles (90°), the fiber breakage becomes excessive from the longer dwell times.

Conclusions

Although wood has long been used as filler in thermoplastics, wood-plastic composites have developed primarily over the last decade. One of the primary forces driving this development has been the need for durable wood composites. The processing advantages thermoplastics have, however, present considerable opportunities in direct manufacture of products.

Polyolephins are currently the preferred thermoplastics in WPC formulations, driven primarily by economic and thermal processing limitations. Wood fiber provides mechanical advantages over flour and particles; however, an effective coupling agent must be used to attain the benefits. Even without coupling agents to improve the stress transfer between the wood and thermoplastic components, wood flours greatly improve thermal, stiffness, machining, and cost properties.

Current processing technologies focus on the compounding of wood thermoplastic using either batch or continuous methods. The compounded material can then be formed using extrusion, compression, or injection molding techniques. Twin-screw extruders can be used to simultaneously compound and form the material into a finished part.

Processing steps play a large role in forming the material structure. Many compounding steps degrade the wood element. Final material structure has a large influence on the material properties. Continued research is needed in the relationship between processing methods, material structure, and properties.

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