

## Review Article

# Melt Spinning of Polypropylene Fiber

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In this paper the melt spinning process and technology of polypropylene fiber, polymerization conditions, preparation of polypropylene fiber by a larger variety of processes and the stress in the spinline was presented. More emphasis was given on the various polymerization processes (gas-phase and liquid-phase polymerization), catalyst system, different forms of polypropylene, structure, properties and application of polypropylene. Polypropylene fibers are produced by a larger variety of processes than other melt-spun fabrics. Polypropylene based materials can be processed by various technologies such as injection molding, calendaring, air-quenched blow films, spinning technology, spunbond process. The influence of both process and material variables on the spinnability and the development of the structure during melt spinning of filament were also discussed.

**Keywords:** Polypropylene; Melt spinning; Ziegler-natta catalysts; Polymerization process; Air-quenched blow films; Spunbond

**Introduction**

Polypropylene, PP, is one of the three most heavily produced polymers. Polypropylene is a type of thermoplastic polymer resin and a superior quality polymer material that originates from olefins. The abundance of PP is called for because of its variety and versatility being employed today in such diverse applications as a film in disposable diapers and hospital gowns to geotextile liners, plastic applications as disposable food containers and automotive components, and fiber applications such as carpets, furniture fabrics, and twine [1,12].

The first commercial production of polypropylene was following the discovery of Ziegler-Natta catalysts. The growth of polypropylene has largely depended on the development of its polymerization catalyst. Following the invention of Ziegler catalyst, the refinement by Natta and the subsequent introduction of metallocene catalysts brought about significant improvement in catalyst efficiency and polymer quality. Polypropylene is made from the polymerization of propylene gas in the presence of a catalyst system, usually Ziegler-Natta or metallocene catalyst. Polymerization conditions (temperature, pressure and reactant concentrations) are set by the polymer grade to be produced. Karl Ziegler and Giulio Natta were awarded the Nobel Prize for their discovery of the catalytic polymerization of ethylene and propylene using titanium compounds and aluminum-alkyls as co-catalysts [1,11].

Since propylene is an asymmetrical monomer, PP can be produced with different stereochemical configurations. The different forms of polypropylene are isotactic, hemi-isotactic, syndiotactic, and atactic. The structure is based on the type of metal catalyst with tunable properties and selectivities. From a commercial viewpoint, isotactic PP has a more ordered structure and therefore higher melting point, heats of fusion, and crystallinity in comparison to its atactic or syndiotactic forms. A highly stereospecific polypropylene resin, with a high isotactic content, is generally preferred to produce fiber, film, and composite products with high performance [1,11,12].

Various production processes exist with some general similarities. They are taking place either in a gas-phase (fluidized bed or stirred reactor) or a liquid-phase process (slurry or solution). The gas-phase polymerization is economical and flexible and can accommodate a large variety of catalysts. It is the most common technology in modern polypropylene production plants. Relevant technologies are Novolen® Unipol® (gas-phase processes), Borstar® and Spheripol® (liquid-phase processes) [1,12]. Melt spinning is the simplest of the various operations under consideration because the applied stresses are uniaxial and the filaments are small in diameter allowing them to be considered at constant temperature throughout any cross-section [10].

Melt spinning of polypropylene is done, almost exclusively, with the semi-crystalline isotactic form. Melt spun Isotactic Polypropylene (iPP) filaments and fibers have many textile applications, including apparel, home furnishings, wall coverings and carpets. One of the largest markets for iPP filaments and fibers is the nonwovens industry, in both staple fiber nonwovens and in 'spun bonded' and 'melt-blown' nonwoven materials. Staple fiber nonwovens and spunbonded nonwovens compete for such applications as diaper coverstock, feminine hygiene products, surgical gowns and numerous other applications. Melt blowing is a special form of melt spinning process which produces very fine but weak fibers which are useful for filters and other applications where high surface area is important and strength is a secondary factor [1,9].

PP-based materials can be processed by various technologies such as injection molding, calendaring, air-quenched blow films, spinning technology, spun bond process [1]. Monoclinic polypropylene is produced under normal air quenching conditions, but quenching in cold water produces a paracrystalline smectic structure. Hot drawing of fibers, especially smectic fibers, spun at low take-up velocities yields very high strength fibers [10].

Polypropylene is not very stable at the melt temperature and degrades at room temperature, particularly in the presence of UV light. It is not dyeable: coloration requires the addition of pigments. Therefore, the preparation of commercially useful polypropylene fibers requires the addition of stabilizers to permit processing and adequate life, and the addition of pigments to provide the color. Hence, the use of additives has resulted in designing a wide variety of properties in polypropylene fibers. To avoid or at least reduce the rate of deterioration of polypropylene fiber, a variety of stabilizers are added, such as radical terminators, peroxide decomposers, UV absorbers and energy quenchers [1].

Polypropylene has excellent electrical and insulating properties, chemical inertness, and moisture resistance typical of nonpolar hydrocarbon polymers. It is resistant to a variety of chemicals at relatively high temperatures and insoluble in practically all organic solvents at room temperature. Absorption of solvents by polypropylene increases with increasing temperature and decreasing polarity. The high crystallinity of polypropylene confers on the polymer high tensile strength, stiffness, and hardness [12].

Polypropylene is used in applications ranging from injection-molded and blow-molded products and fibers and filaments to films and extrusion coatings. Extruded polypropylene fibers are used in products such as yarn for carpets, woven and knitted fabrics, and upholstery fabrics [1,12].

### Preparation of Polypropylene Fibers

Polypropylene fibers are produced by a larger variety of processes than other melt-spun fabrics. At one end of the range, the long air-quench process produces high-quality multifilament yarns, and, at the other end, fibrillating slit film produces coarser fibers. The success of the lower-cost polypropylene slit-film fiber is due to the lower price of the polypropylene resin and the unique adaptability of polypropylene to the less expensive slit-film fibrillation process. The water-quench process for monofilament has long been an established technique for producing high-denier fibers. In recent years, the spun-bonding process for producing nonwoven fabrics and, very recently, the

short air-quench system for producing fibers in less building space have been developed [1].

### Long Air-Quench Melt Spinning

Until short-quench systems were developed, there was no reason to qualify the air-quench spinning process. Now the term "long air quench" is used to distinguish spinning systems that utilize take-up speeds from 300–4000 m/min and a filament free fall length of 3–10m. The long lengths are needed for sufficiently cooling the high-speed thread line. Yarns with individual filament deniers from around 2 to 25 and total deniers from 75 to several thousand are produced by the long air-quench process. It is also used to produce staple fibers [1].

### Metering Pump

The melt spinning of polypropylene begins at the hopper of an extruder, where the polypropylene, either a uniform blend or a volumetrically or gravimetrically proportioned mixture of natural and colored material (pellets, spheres, or powder), is fed into the throat of the extruder. Resins with MFR of 3–35 are used in the process. As polypropylene is nonhygroscopic, drying of the feed material is not necessary. However, the surface moisture should be removed and nitrogen-blanketing of the extruder hopper is optional. The particulate material is then melted and conveyed through the electrically heated extruder. Normally a single-screw extruder is employed. Extruders of at least 24/1 Length-to-Diameter ratio (L/D) are desirable for polypropylene, and some resin suppliers recommend that a portion of the screw be equipped with a mixing zone. Others prefer to mix downstream of the extruder. This mixing is usually accomplished with commercially available static mixers [1].

The filtration of polymer melt is normally supplied immediately downstream from the extruder. This filtration can range from a coarse single screen supported by a breaker plate to a very fine nonwoven metal filter contained in a separate housing that allows the filter to be changed without interruption of the process. The choice of filtration depends on the process, the feed material, and the product.

After the melt leaves the filter, it travels through the transfer lines or spin manifold to the metering pumps. One extruder may feed as many as a hundred metering pumps. The transfer lines should be designed in such a manner that the material entering each metering pump has the same heat history and residence time. Also, there should be no stagnant regions within the lines. The residence time uniformity is usually accomplished by arranging the transfer lines in a "Christmas tree" pattern. In such a design, the stream from the extruder is divided several times until finally there are as many separate, identical streams as there are pump entrances. The transfer lines are usually enclosed in a space heated by a condensing organic vapor to ensure uniformity of temperature. Electrical heat may be used, but extra caution is necessary in the system design to maintain symmetrical heat flux. The transfer lines must also be designed to ensure that the pressure drop through them is not excessive. If the pressure drop is too high for the desired flow, the metering pumps will be starved. The system housing the transfer lines, metering pumps, etc., is called a *pump block or spin beam* [1]. The metering pumps are precision-made positive-displacement gear pumps, especially designed for melt spinning. They are used to ensure that a precise proportion of the melt from the extruder is delivered to each thread line and that the thread line denier does not vary with time. Modern pressure-

feedback-controlled extenders operate remarkably steadily, but not steady enough for multifilament spinning without meter pumps.

**Spin pack:** After leaving the metering pumps, the melt travels through short transfer lines and into the spin pack. Almost every fiber manufacturer has its own specific design of spin pack. The top-loading packs have replaced bottom-loading packs for convenience of installation; but when small polymer rates are employed, bottom-loading packs are still preferred because of better thermal contact with the spin beam. Bolted flanges hold the bottom-loading pack in place and melt flows into it vertically. The packs are sealed by gaskets that are crushed when the flange bolts are tightened. Top-loading packs rest on a ledge, and melt flows into them horizontally. During installation, the pack is lowered into its cavity and one horizontal screw crushes the gasket on the opposite side to seal the transfer line pack inlet [1].

Good pack design ensures that the melt inside the pack flows in a symmetrical manner with respect to the spinneret. If the spinneret is round, the melt flow in areas above the spinneret should be symmetrical with respect to the spinneret axis. If the spinneret is rectangular, the flow should be symmetrical with respect to the planes passing through the center lines in both the length and width directions. Care should also be taken to eliminate stagnant areas.

The pack filter, the breaker plate, and the spinneret are contained in the lower portion of the pack. These components, along with the metering pumps, are the *heart of the melt spinning* process. The filter rests on the breaker plate and may be composed of woven wire, nonwoven wire, sintered metal, or sand. The major function of a polypropylene filter is filtration; there seems to be little need for shearing polypropylene. The breaker plate should contain as much open area as possible and should be thick enough to withstand the pressure drop developed through the filter. For flat and relatively thin filters, the only portion of the filter that is used is the portion just above the openings in the breaker plate. The melt flows through these openings, and funnels of flowing melt develop in the filter above them. Regions outside these funnels are relatively stagnant. Rise in pressure is rather rapid in pigmented polypropylene, and longer spin pack life is realized with extended-area filters. There must be a gap between the breaker plate and the rear of the spinneret. This ensures that the pressure drop along melt stream lines from the bottom of the breaker plate to the entrances of spinneret counterbores is negligible in comparison with the pressure drop through the spinneret orifices [1].

**Spinneret:** The spinneret orifices or capillaries are contained in the lower part of the spinneret and are round for producing round fibers or in almost any shape desired. Triangular, trilobal, and octalobal fiber cross sections are common and are designed for luster and fiber “feel” characteristics. The face of a spinneret is generally coated with a silicone spray to prevent resin from adhering to the spinneret [1].

There are no general criteria for the design of spinneret orifices. Diameters of round capillaries are usually 200–400 $\mu\text{m}$ . The L/D is normally 2–5; capillaries with large values of L/D are expensive to produce and give unnecessarily high-pressure drops. The entrance angle to the round orifices is usually 40–90°. Orifices of modified shape are generally placed at the center of flat-bottomed counterbores. To produce yarns with good interfilament uniformity, the orifices must be uniform.

Die swell is always present in polypropylene spinning because its melt is viscoelastic. The viscoelasticity also gives rise to melt fracture if temperatures are too low or if orifice shear rates are too high. Melt fracture must be avoided [1].

**Quenching:** After exiting the spinneret capillaries, the filaments begin their descent to the winder or take-up position. The filaments first enter the quench cabinet, usually 1–2m in length, where they are solidified. Further cooling takes place in the quench stack between the cabinet and the point of finish application. The quench zone is a very important part of a melt-spinning process. With polypropylene, the emerging filaments are from 70 to 170°C above the melting point (165°C). This difference between spinning temperature and melting point is much higher than it is for nylon or polyester [1].

Careful consideration should be given to the aerodynamics of the quench cabinet. There is normally a cross-flow of air all along the fiber bundle length. The cross velocity is usually higher in the regions near the spinneret. The thread line, traveling at high speeds, develops an air boundary layer rapidly, and the cross-flow becomes ineffectual after the boundary layer develops sufficiently. Turbulence or unstable flows anywhere along the thread line can cause filament non-uniformity.

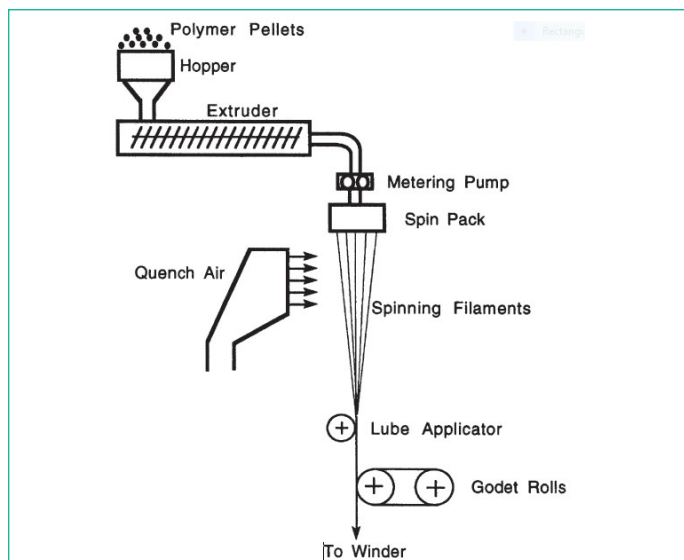
In many cases, the spin pack and spinneret are round. The allowable diameter of these spinnerets is limited, because with too large a diameter the quenching of the interior filaments and the filaments downstream of the cross-flow is inadequate. In recent years, quenching of a large number of filaments produced from a circular spinneret has been improved by blowing air radially outward from an air source placed on the spinneret axis. Also, rectangular packs have been introduced for producing large bundles of filaments [1].

Although some orientation is introduced into the melt during its passage through the spinneret orifices, most of this orientation is lost at the orifice exit because of strain recovery. This unconstrained recovery gives rise to die swell. The orientation in the undrawn yarn is a result of the stretching of the filament between the position of maximum diameter just below the orifice exit and the position of final diameter. However, the development of crystalline orientation in polypropylene continues beyond the position of the final diameter. The resin properties and the spinning conditions determine the amount of orientation in undrawn yarn. Any condition that gives higher stress in stretching the fiber gives higher degree of orientation. Resins of higher molecular weight, larger quench rates, and larger stretch rates give higher spin-line stresses. The take-up speed is one of the most influential parameters affecting orientation [1].

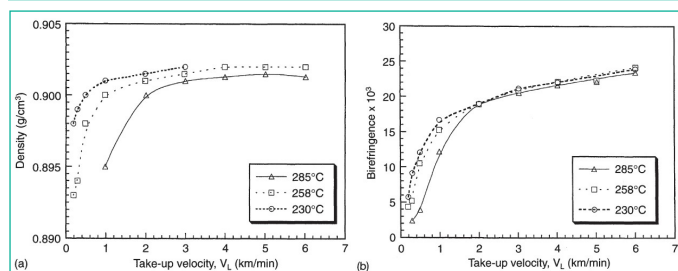
**Finish application:** Immediately after exiting the quench stacks (or in some cases at the bottom of the quench cabinet), the yarn receives an application of finish. The finish is applied by contacting the yarn to a rotating roll partially immersed in finish or by metering it onto the running thread line with precision gear pumps. The finish, usually an aqueous emulsion, is normally applied at the 0.5–1.5% level. Functionally, finishes serve as antistatic agents and lubricants. The finish must remain colorless on the yarn and be heat-stable. In addition to the functional ingredients, emulsifiers and antibacterial agents are always present in a finish makeup [1].

Finish application is considered the last operation common in the spinning process; after this step, the yarn processing can be varied widely, depending largely on the end-product to be made. The undrawn yarn is wound onto a spool and transferred





**Figure 1:** Schematic of the melt spinning process of polypropylene.



**Figure 2:** Influence of spinning speed and extrusion temperature on (a) the density, (b) the birefringence of melt spun iPP filaments.

to another area for further processing. These yarns are simply drawn into “flat” yarns with no crimp or bulk, or they are draw-textured on machines similar to those used for draw-texturing polyester; or heavier yarns are drawn and jet-bulked for use in carpets. Instead of being transferred for further processing, yarns are drawn and bulked in a continuous operation with spinning. Staple fibers are normally spun as continuous filaments in the long air-quench process. In modern staple processes, the thread lines formed from a number of spinnerets are combined into a large tow and “piddled” into a large can for subsequent drawing on a horizontal fiber line [1].

**Drawing and annealing:** There are many variations of the drawing and annealing process, depending on the yarn denier, spinning speed, etc. However, most processes carry out the same two basic functions: (1) orientation of the filaments to increase the strength and decrease the elongation and (2) annealing of the filaments to relax at least partially the frozen-in stresses and perfect the crystalline structure, and consequently decrease the residual shrinkage. Polypropylene is very visco-elastic, and the short residence time in the in-line annealing zone may not be long enough for sufficient relaxation; further heat treatment may be necessary [1].

The draw-twister, capable of processing more than 100 yarn packages simultaneously, is the oldest, most common unit for drawing polypropylene yarns. The draw-twister consists of a creel for holding the undrawn packages, two or more sets of rolls, a lay rail that supports the ring with its traveler, and a vertical spindle for holding the pirn onto which the yarn is wound. The yarn is wrapped around the rolls several times. The yarn wraps are separated with the aid of a small off set separator roll, and the drawing roll is rotated faster than the feeding roll. Depending on the orientation of the undrawn yarn, it is stretched, usually two to six times its original length, between

the two rolls. Some machines are equipped with a third set of rolls, allowing a two-stage draw to be employed. In the usual case, the feeding roll is heated so that the relaxation times of the yarns will be decreased for better drawing. The drawing roll is usually heated to a temperature higher than that of the feeding roll. This heating (annealing) decreases the residual shrinkage of the yarn. After leaving the drawing roll, the yarn travels under the ring traveler and onto the rotating vertical pirn. Twist is imparted to the yarn because the surface speed of the pirn is higher than the yarn speed and the traveler moves around the ring that surrounds the pirn. The lay rail traverses vertically to lay the yarn along the length of the pirn. A draw-winder is similar to a draw-twister, but the yarn is wound onto a horizontal spool whose surface travels at the yarn speed. The yarn contains no twist.

As mentioned earlier, yarns may be drawn in-line with spinning. The drawing scheme is similar in principle to that of the draw-twister, except that the feeding and drawing rolls must travel at much higher speeds to be economical. In this case too, the yarns have no twist. To provide filament coherence, the yarns are passed through air jets to entangle the filaments at intermittent lengths along the thread line [1].

Staple is typically drawn on a horizontal fiber line. A fiber line consists of two or more roll stands, perhaps a heating zone between the roll stands, a crimper, and a cutter. There may also be an oven between the crimper and the cutter. Each of the roll stands consists of five to seven large rolls arranged in two rows, which are commonly driven on a large common frame. Circulating liquids or condensing vapors heat the rolls. The heating zones between the roll stands may be hot-air or steam ovens, hot-liquid baths, or hot plates. The crimper is either a common stuffer box crimper or a jet-crimping device, and the cutter is usually of the rotating pressure-cutting type. One or more tows of yarn are drawn simultaneously. The tows travel a serpentine path from one roll to another and are drawn and then annealed between the roll sets. On exiting the last roll set, which rotates with a lower surface speed than the drawing roll to allow the yarn to relax, the yarns are fed directly to the crimper and finally to the cutter. The staple is then transferred to the baler for packaging. In some processes, the yarn may be heat-set in an oven after it is crimped.

Lower-denier polypropylene may be draw-textured on conventional draw-texturing machines, which were developed for polyester. On these machines, undrawn yarns are creled and fed by a roller system to a heated plate. The yarns are drawn and twisted simultaneously on this hot plate. The twist is supplied by a rotating pin around which the yarn is wrapped or by rotating disks that contact the yarn. On the other side of the twisting device, the twist is removed, but the yarn remembers its deformation on the hot plate and retains a bulk or crimp. The yarn then travels through the second heater and onto the spool. This process is known as false-twist draw texturing [1].

Heavier-denier BCF yarns are generally spun for tufted or woven carpeting. Typical processes for producing BCF yarns consist of means for drawing the yarn coupled with a stream or hot-air jet-texturing device for imparting bulk. The bulked yarn is removed from the jet-crimping device and wound onto a disposable tube. There are many variations of the BCF process.

There are variations of the spinning process that have not been mentioned here, e.g., bicomponent spinning. Usually, this operation is carried out by employing two extrusion systems

that keep the resins separate until just before the streams exit the spinneret. Sheath-core or side-by-side yarns can be spun by this process. Simpler bicomponent yarns are spun with mixed incompatible resins from mixed-pellet blends [1].

### Short Air-Quench Melt Spinning

A short air-quench process was developed for polypropylene. The primary purpose of this design is to save building space and reduce labor costs; the entire system can be located on one floor. In principle, the short quench process is basically the same as the long quench process; but, because of the shorter distance available for quenching, no more than a meter or so, the spinning speeds are drastically reduced. Factory literature lists a maximum spinning speed of 150m/min for these machines, although most operating speeds would be lower than that. To make up for the loss in production due to lower spinning speeds, spinnerets with thousands of orifices are used.

Some of the spinning units are built in modular form with a small extruder for each one or two spinnerets. However, larger extruders are used for feeding larger numbers of spinnerets.

The units are primarily designed for making staple fibers (3–100 denier), but some manufacturers suggest their use for making textured or bulked yarns. In any case, the spinning units are placed in-line with the conventional drawing, annealing, and bulking systems downstream [1].

To further save space, some units are designed to enable the spinnerets to extrude filaments in a horizontal or vertically upward direction. This allows the extruders and other spinning equipment to be located closer to the floor.

The products produced from some of these machines are apparently not as high in quality as those produced from long air-quench systems [1].

### Water-Quench Melt Spinning

The manufacture of large monofilaments, certainly larger than 100 denier, must be carried out in a water-quench process because of the inherent limitation of forced convective heat transfer with gases. Conventional screw extruders are used for melting and conveying the polypropylene resin, just as in the case of the melt-spinning processes described above. Often, however, there are no metering pumps used in the process [1].

**Spinning and quenching:** In the normal polypropylene operation, one large spinneret is employed (may be two or three), with the number of spinneret orifices corresponding to the number of filaments desired. The spinnerets are usually heated electrically. When filament uniformity is important, condensing organic vapors are used for heating. Monofilaments of polypropylene usually go into such products as chair webbing, ropes, etc., and wider limits of uniformity are normally acceptable in these products. If uniformity in size is critical, metering pumps should be used, and extra care must be taken in ensuring that the melt entering the spin pack is uniform, the orifices are uniform and clean, and the temperature is uniform [1].

After exiting the spinnerets, the filaments travel a short distance and enter a water-quench tank. Guides are arranged within the tank to ensure the filaments travel a proper distance for quenching. For a uniform product, the distance between the spinnerets and the water should be held constant. The water temperature should be maintained within close limits throughout the tank, and care should be taken to ensure the water contains no turbulent regions [1].

**Draw resonance:** There are two unique aspects to the water-quenching of polypropylene. As with other thermoplastic melts, this material exhibits draw resonance under certain spinning conditions. Polypropylene apparently is more susceptible to this phenomenon than many other materials. Under certain conditions, the filament will be uniform all along its length. If the take-up speed is increased, a critical value of speed will be reached when the filament diameter begins to oscillate in a regular manner. The amplitude of diameter oscillation can reach 10–50% of the nominal diameter of the filament. The instability seems to be related to a critical value of the ratio  $V_T/V_E$ , where  $V_T$  is take-up velocity and  $V_E$  is extrusion velocity. The critical ratio is affected by resin properties, extrusion temperature, filament nominal diameter, distance between spinneret and bath, and perhaps other process parameters [1].

When polypropylene is water-quenched under certain conditions, a difference in crystalline order is obtained. In air-quench systems, yarns with a crystallinity of around 55% are obtained. The crystals are usually distributed throughout the yarn as lamellae and are normally in the monoclinic  $\alpha$ -form. In the rapidly cooling water-quench process, a less ordered smectic or paracrystalline structure is produced with a morphology that is basically fibrillar. Under certain drawing conditions, these smectic structures lead to high-strength fibers.

The orientation of the spun monofilaments and, consequently, the draw ratio necessary for producing a satisfactory product depend on the stretch rate during spinning and quenching, just as they do in the air-quench process. The larger the stretch rate, the higher the spin-line stress, the higher the orientation, and the lower the required draw ratio [1].

**Drawing:** After the filaments leave the quench tank, they must be wiped or blown free of water in preparation for hot-drawing. Wet sections of the yarn will not be heated to the same temperature as the dry sections. The process for drawing monofilaments is very similar to ST. Roll stands and hot ovens, baths, or plates are used for the filaments. The yarns are usually annealed on heated rolls or in an air oven. A two-stage yarn may be used, with a total draw ratio commonly around 6:1. A finish must be applied to the filaments for lubrication and static control. The filaments are wound individually on tubes or flanged bobbins [1].

### Spun-Bonding Process

The term “spun-bonding process” appears to have several definitions. Perhaps the most general one, and the one used here, is defined as the method wherein the production of fibers and fabrics or webs is combined. The usual spun-bonding process consists of laying down a web or mat of continuous filaments and then bonding the fibers within the fabric either mechanically, thermally, or chemically. The so-called *melt-blowing* process, in which short, fine fibers are laid down, also fits the general definition of a spun-bonding process [1].

**Spun-bonding:** The typical spun-bonding process includes a spinneret with a means of conveying the continuous filaments out into the form of a web, or else several spinnerets arranged in a row whose length may approximate the width of the web to be produced. In either case, the process of melting and fiber formation is identical to that used in conventional melt spinning.

The steps beyond filament extrusion are diverse and are usually proprietary. The yarns are pulled from the spinneret, per-

haps by air jets, given an electric charge, and are then laid down on a moving screen. Alternatively, the yarns may be pulled away by rolls and drawn between a set of rolls before they are fed to the air jets. In the former case, the yarns are usually only partially oriented, even though they are stretched at very high speeds. After they are formed, the fabrics are thermally bonded by calendaring, or needle-punched, or chemically bonded [1].

**Melt-blowing:** The melt-blowing process produces nonwoven fibrous webs from any thermoplastic resin but has been used most extensively with polypropylene, which appears to be particularly suited for melt-blowing.

In this process, a long rectangular die or spinneret containing a large number of capillaries in a single row all along its length is attached to a conventional screw extruder. Molten polymer is fed directly from the extruder through a filter and through the capillaries. Hot air at near-sonic velocities is forced through adjustable slots all along the length of both sides of the die. Fiber attenuation and breakage (usually) occur as the hot melt issues from the capillaries into the convergent high-velocity air streams. Some of the hot air is captured and recirculated. There are also cooling air ducts located along both sides of the die. This air is directed toward the filaments at a position further from the die and aids in quenching. The fibers are collected on a continuous, moving wire screen under which a suction chamber is located to aid in the removal of large volumes of air. The web is fed from the collecting screen to a take-up roll or a hot calendaring system. More than one extruder–die combination is used to give laminates of the same or different materials [1].

The process produces a web with a width the same as the length of the die. The weight of the fabric is determined by the output of the extruder and the speed of the collecting screen.

The average orientation of the fibers relative to the machine direction depends on the air flow and screen speed. The diameter of the fibers can be as small as  $0.5\mu\text{m}$ , depending on process conditions. The length of the fibers also varies according to process conditions. Obviously, the lower the polymer flow rate and the higher the air flow rate, the finer and shorter are the fibers. Continuous fibers are produced at very low air rates. The temperature and flow rate of the cooling air affect the hand of the web: higher temperatures and lower rates give a softer fabric. A similar effect is obtained by decreasing the distance between the die and collecting screen. As a result of all of the possible operating variations, the process is very versatile.

Under extreme conditions, very light weight webs of very fine fibers are produced and very stiff, almost cardboard-like sheets may also be produced. The major deficiency in the process is that under any condition only undrawn fibers are produced [1].

### Fibers from Film

The techniques for producing relatively coarse but very useful fibers or fiber-like tapes from films have been developed. Obviously, the first step in this operation is the production of a film. Films are manufactured in two conformations—sheet and blown films. Because the blown film operation is more complicated and because it produces a less fibrillatable film due to a more ordered crystalline structure and lateral orientation, it is not widely used and will not be discussed further [1].

**Sheet film extrusion:** Sheet films are produced from long, narrow-slit dies, which are usually attached directly to a conventional single-screw extruder. There is normally a filter be-

tween the extruder and the die, and sometimes a static mixer is used. Metering pumps are almost never used. The die opening, or a restrictor bar upstream of the opening, can be adjusted along the die length so that the film thickness is maintained uniformly across its width. The film thickness is measured by a gauge and the gauge readout is used for manual die adjustments, or a gauge signal is used for automatic control. Resins with MFR of 1–4 are commonly used for these films.

The film is normally quenched in a water bath but may also be quenched on chilled rolls. The chilled rolls are expensive and their use is restricted. The quench tank for films is very similar to that used for monofilament. The molten film exits the die an inch or so above the water level and film guides route the sheet through the tank so that the tank water temperature is uniformly and constantly controlled and the water is free from turbulence. The film leaves the tank at a speed usually no greater than 45m/min. The speed is limited because of “water carry-over” by the film. If the film is wet, difficulties will be encountered in drawing. Resin manufacturers control the wettability of films with additives and, consequently, the running speed. Drying methods, such as blowing with air, are applied as an added precaution just after the film leaves the water-quench tank [1].

**Drawing and annealing:** Before drawing, the film is usually pulled through a set of knives for slitting to the desired width for drawing. The slitting knives are held in a bar and may be rectangular (similar to razor blades) or round. In some cases, the blades are heated. Drawing and annealing are carried out in ways similar to those used for processing ST and monofilament. Heat is applied with ovens, rolls, plates, etc., and the tapes are drawn and relaxed between large roll stands [1].

Processes for drawing the film before slitting are limited in usage. The drawing is carried out on rolls spaced very closely, in order that the contraction of the film in the width direction is not as great as it is in the more widely used processes. The lower lateral contraction gives a material that more closely resembles blown film with regard to fibrillation tendency. In unrestrained drawing of incompressible tapes, both the width and thickness are reduced by the factor.

$$\sqrt{1}/\text{draw ratio}$$

**Fibrillation:** After the yarn is drawn, it is fibrillated. A large number of devices have been invented for fibrillating tapes in-line to give them a more fiber-like character. In various processes, the tapes are rolled, twisted, brushed, pulled, treated with air jets, subjected to ultrasonics, or contacted with rotating rolls that have cutting or punching devices on their periphery. The most prevalent method is that which uses rotating rolls. This method is simple, easy to control, and gives a more uniform product. The peripheral cutting devices can consist of pins, hacksaw blades, razor blades, or fine threads or serrations cut on the lands of a fluted roll. In operation, the running tape is fed over the rotating roll, which rotates so that its contacting surface travels in the tape direction at speeds of one to three times the tape speed. Oriented polypropylene is very adaptable to this fibrillating process. Strong, very fiber-like tapes with a denier of 300 and up are produced. If the fibrillated tapes are pulled laterally, a network structure is revealed [1].

There are other, infrequently used processes for producing fibers from films or tapes that should be mentioned. In one of these, the film in the molten state is pressed between two rolls. One of the rolls is smooth and the surface of the other



contains closely spaced, shallow peripheral grooves. The film is then embossed all along its length and, in subsequent stretching and perhaps mechanical treatments, it separates along the grooves. Relatively fine monofilaments (6–10 denier) are produced in this manner. Groups of the monofilaments are taken up together to form a heavier yarn. A variation of this process is the direct extrusion of embossed tapes from specially designed orifices, which are subsequently drawn and fibrillated with air jets. In another process, fibers are cut with blade or notched bars at very close intervals to give continuous filaments.

In some instances, chemicals, blowing agents, or other polymers are blended with polypropylene to enhance fibrillation or, in certain cases, to retard it. Additives may also be used for modifying the physical properties of the film fiber. Processes have been suggested for using blowing agents as the major means of fibrillating films, but these methods have not yet proven acceptable [1].

### Stress in the Spinline

Because of the many process and materials variables, melt spinning is a complicated process requiring, in general, detailed mathematical simulation for its understanding. The stress developed in the spinline largely controls both the spinnability and the resulting morphology of the spun filaments [2,3]. Higher stresses can lead to instabilities that cause the spinline to break. They also generally lead to greater deformation rates which produce higher molecular orientation. The higher molecular orientation leads to faster crystallization kinetics (stress-enhanced crystallization) which sometimes leads to higher crystallinity.

The spinline stress,  $\sigma_{zz}$  is related to the viscoelastic properties of the polymer and to the processing conditions. As a first approximation can be written:

$$\sigma_{zz} = \eta(T, E) \frac{dV}{dZ} \quad (1)$$

where  $dV/dz$  is the velocity gradient along the spinline ( $V$  is velocity of the running spinline at any given distance  $z$  from the spinneret),  $\eta(T, E)$  is a temperature and deformation rate dependent elongational viscosity of the resin. According to equation (1), the spinline stress is expected to increase, for given process conditions, as  $\eta(T, E)$  increases. This suggests that resin characteristics that affect the viscoelastic properties of the polymer such as molecular weight and polydispersity will have important effects on the spinning process.

Neglecting radial variations in the filaments, the spinline stress at a given distance  $z$  from the spinneret is also given by:

$$\sigma_{zz} = \frac{F_{rheo}}{\pi D^2 / 4} \quad (2)$$

Where  $D$  is the equivalent filament diameter and  $F_{rheo}$  is the rheological force acting in the filament.  $F_{rheo}$  is given by an overall force balance on a single filament in the spinline [4]:

$$F_{rheo} = F_o + F_{inert} + F_{drag} - F_{grav} + F_{surf} \quad (3)$$

where  $F_o$  is the rheological force at the exit of the spinneret,  $F_{inert}$  is the inertial force produced by the acceleration of the polymer mass along the spinline,  $F_{drag}$  is the drag force caused by the fiber moving through the cooling medium,  $F_{grav}$  is the

gravitational force acting on the spinline and  $F_{surf}$  is the surface tension force at the fiber/cooling medium interface.

Under normal spinning conditions,  $F_{inert}$  and  $F_{drag}$  are the major components of the rheological force. Clearly, equation 3 indicates that for a given polymer, the spinline stress increases rapidly as filament take-up velocity increases due to an increase in both the inertial and air drag terms.

### Influence of Process Variables

The key variables of the melt spinning process are (1) take-up velocity, (2) length of the spinline, (3) cooling conditions along the spinline, (4) extrusion temperature, (5) mass throughput per spinneret orifice, and (6) the size and shape of the spinneret holes. These process variables interact with the resin characteristics to control the processability and the structure and properties of the as-spun filaments. The important resin variables are those that affect the rheological and crystallization behavior of the polymer [9].

The processing variable effects are considered from the point of view that changes in them are made with all other conditions held constant.

### Take-Up Velocity

The take-up velocity is generally the most important process variable. As shown in Figure 2, the speed at which the molten resin is drawn down significantly affects the resulting crystallinity, as measured by density, and overall molecular orientation, as measured by birefringence. It should be noted that the results shown in Figure 2 are for a constant mass throughput, so that the final filament diameters are decreasing with increasing take-up velocity and the cooling rate along the running spinline is increasing. As the spinning speed increases, the spinline stress increases and both crystallinity and molecular orientation increase in spite of the increase in cooling rate which should suppress the development of crystallinity. This is strong evidence that the stress and molecular orientation lead to stress-enhanced crystallization. Online measurements of temperature, birefringence and X-ray diffraction patterns [2,6] show that crystallization begins at higher temperatures in the spinline than under quiescent conditions with similar cooling rate. This is further evidence of stress-enhanced crystallization.

The crystal structure of melt spun iPP is most often the monoclinic form [3]. However, if the fiber is quenched rapidly or the stress in the spinline is low, as for the lower spinning speeds of Figure 2, a conformationally disordered (condis) or smectic structure is formed. The smectic structure is not thermally stable and transforms to the monoclinic form when annealed above 70°C.

### Extrusion Temperature

Figure 2 also shows the effect of changing the melt extrusion temperature of the polymer. As the extrusion temperature is increased, the elongational viscosity in the upper part of the spinline decreases, thereby lowering the stress in the spinline and reducing the molecular orientation and crystallinity developed at a given spinning speed. However, as the spinline stress is increased (by increasing the spinning speed), the density and birefringence tend to become independent of the extrusion temperature, indicating that the increased stress due to increased spinning speed eventually overrides the decreased stress due to higher extrusion temperature [9].

## Mass Throughput

Increasing mass throughput per spinneret hole, while keeping take-up speed constant, produces larger filament diameter (continuity condition) and lowers the stress in the spinline. This in turn leads to lower filament birefringence. Increasing mass throughput also reduces the cooling rate in the spinline due to the greater amount of material that must be cooled. The slower cooling rate would increase crystallinity and density due to more available time for crystallization. However, the lower stress decreases molecular orientation and causes less stress-enhancement of the overall crystallization rate. The final crystallinity results from a balance between these two factors which also depends on the nature of the cooling process and the characteristics of the specific resin [9].

## Cooling Conditions

As with the take-up velocity, the cooling conditions have a significant influence on the crystallization behavior during the spinning process. As the cooling air temperature decreases or volume of air blown across the filament increases, the cooling rate of the spinning filaments increases. This moves the solidification point in the filament closer to the spinneret. As the freezing point moves closer to the spinneret, the deformation rate increases since the filament must reach its final diameter closer to the spinneret; this produces an increase in the spinline stress. This increase in stress closer to the spinneret results in an increase in molecular orientation which is more readily frozen-in due to the higher cooling rate. There is again a balance between the retardation of crystallinity development due to faster cooling and the enhancement of crystallinity development due to increased stress [9].

## Length of Spinline

The length of the spinline is important for two reasons. First, the spinline must be long enough to allow the polymer to freeze before being contacted by guides or godet rolls. Because of this, the spinline length is controlled by the efficiency of spinline cooling; longer spinline are required for slower cooling. However, longer spinline also increase the gravitational contribution to  $F_{rheo}$  which increases the spinline stress. In most cases, especially for fine filaments, spinline length will have relatively little effect on the structure and properties of the spun filaments due to the low value of  $F_{grav}$  relative to other contributions to  $F_{rheo}$  [9].

## Filament Shape

The filament shape and die orifice design affect the heat transfer rate between the filament and surroundings. The larger the surface area for a given volume of material, the faster the polymer will transfer heat away and crystallize. This case is similar to the effect of increasing the cooling rate by other means described above [9].

## Influence of Material Variables

The important resin variables are those that affect the rheological and crystallization behavior of the polymer. For iPP, these include (1) molecular weight and its distribution, (2) isotacticity,

(3) comonomer type (ethylene is common) and content, (4) content, if any, of a nucleating agent, and (5) presence and amounts of antioxidants and stabilizers. The latter are necessary to control thermooxidative degradation during the spinning process. This term paper will also consider the influence

of both process and resin variables on the spinnability and the development of the structure and properties of the melt spun filaments [9].

## Molecular Weight

Both Molecular Weight and its Distribution (MWD) strongly affect the spinnability of iPP. Generally, spinnability, as measured by the maximum take-up speed at which spinning can be carried out in the absence of instabilities, increases as molecular weight distribution is narrowed.

There tends to be a maximum in the spinnability with increase in molecular weight. At very low molecular weight, the spinline exhibits instabilities due to low melt strength. For high molecular weight, various other instabilities, including melt fracture and spinline breaking, arise due to the high stresses in the spinneret capillaries and in the spinline.

Increasing Mw produces higher spinline stress and molecular orientation in the melt which, in turn, causes crystallization rates to increase and crystallization to occur closer to the spinneret and at higher temperatures. There is also an effect of MWD; broader distribution resins with the same MFR develop higher crystallinity at equivalent spinning speeds. This appears to be caused by broader MWD resins being more susceptible to stress-enhanced crystallization [9].

## Percent Isotacticity

As percent isotacticity decreases, both the crystallization rate and ultimate crystallinity of iPP generally decrease. During melt spinning this causes the crystallization to occur farther from the spinneret and at lower crystallization temperature [8,9]. The resulting as-spun filaments have lower density, but their overall molecular orientation and birefringence are mostly unaffected.

## Propylene/Ethylene Copolymers

The addition of ethylene units to form a Random Copolymer (RCP) lowers the crystallinity that can be developed, by virtue of the lower stereoregularity of the chain. This is analogous to the effect of stereo defects when decreasing the isotacticity of the chain [9].

## Nucleating Agent Additions

The addition of nucleating agents raises the crystallization temperature and the resulting crystallinity substantially for quiescently crystallized iPPs. These effects also occur during melt spinning of iPP fibers [8], but they are more pronounced under conditions of low spinline stress (i.e. low spinning speeds). At high spinning speeds and/or other conditions that produce high stresses in the spinline, the differences due to nucleating agents are smaller, but not eliminated, arising from the influence of stress in raising the rate of crystallization [9].

## Structure Development during Melt Spinning

Depending on the threadline cooling rates, the spun filaments of polypropylene were either smectic (para-crystalline) or highly crystalline. The crystalline form is the monoclinic  $\alpha$ -form. The smectic form occurred only when rapid cooling rates were achieved by quenching the molten threadline into water. For the smectic form there is a transformation in crystal structure from an unoriented paracrystalline to highly oriented partially monoclinic type with increasing take-up velocity. For filaments spun into ambient air, crystallization to the monoclinic form occurs in the threadline. This is easily demonstrated



with on-line measurements. During crystallization the birefringence rises rapidly, eventually approaching the birefringence of the as-spun filament [10].

Polypropylene filaments spun under a variety of conditions. Under conditions which give rise to low spinline stress such as low take-up velocity and high extrusion temperature, the small angle pattern exhibits a continuous ring of nearly uniform intensity. These are the same conditions which lead to low orientation. As the spinning conditions are changed so as to increase the spinline stress, the patterns evolve to definite "two-point" patterns [10].

### Conclusion

This paper summarizes that polypropylene is one of the three most heavily produced polymers. The abundance of PP is called for because of its variety and versatility being employed today in a diverse application. The growth of polypropylene has largely depended on the development of its polymerization catalyst. Polypropylene production started by following the invention of Ziegler catalyst, the refinement by Natta and the subsequent introduction of metallocene catalysts brought about significant improvement in catalyst efficiency and polymer quality. Polypropylene is produced by various polymerization processes. But the gas-phase polymerization is the most widely because it is economical and flexible and can accommodate a large variety of catalysts.

Melt spinning is the simplest of the various operations under consideration because the applied stresses are uniaxial and the filaments are small in diameter allowing them to be considered at constant temperature throughout any cross-section. Polypropylene fibers are produced by a larger variety of processes than other melt-spun fabrics. Polypropylene based materials can be processed by various technologies such as injection molding, calendaring, air-quenched blow films, spinning technology, spun bond process. In recent years, the spun-bonding process for producing nonwoven fabrics and, very recently, the short air-quench system for producing fibers in less building space have been developed. The preparation of commercially useful polypropylene fibers requires the addition of stabilizers to permit processing and adequate life, and the addition of pigments to provide the color. Hence, the use of additives has resulted in designing a wide variety of properties in polypropylene fibers.

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#### Declaration of Conflicting Interests

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