Lecture 35- Calendaring and Fiber spinning

Greetings, friends! Welcome to the exploration of calendaring and fiber spinning processes within the realm of polymer process engineering. These two processes hold significant importance in the field of polymer processing. Before we delve into the intricacies of calendaring and fiber spinning, let's take a moment to recap what we covered in the previous section.

Our previous discussion centered around blow molding, encompassing different segments, the basic theory, various applications, and a comprehensive examination of the advantages and disadvantages associated with this process. We also delved into the classification of blow molding, including extrusion blow molding, injection blow molding, stretch blow molding, and rotation blow molding.

In this chapter, our focus shifts to calendaring. We will explore the arrangement of calendars or calendar rolls in calendaring and discuss factors influencing calendaring operations. Additionally, we will dive into the realm of fiber spinning, covering various methods such as melt fiber spinning, dry fiber spinning, wet fiber spinning, and reaction spinning. Join us as we unravel the intricacies of calendaring in the upcoming sections.

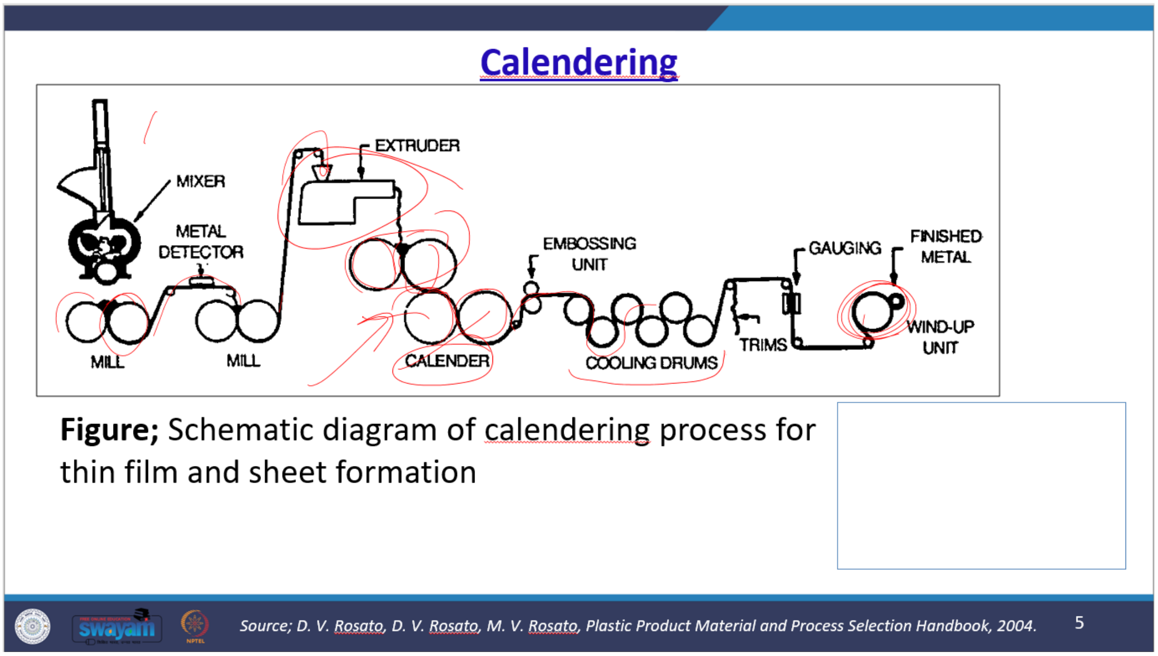
Calendaring serves as a versatile process for transforming thermoplastic materials into continuous sheets and films. It is widely employed not only in creating films but also in applying coatings on textiles, paper, and other supporting materials with plastics. Calendaring is a common and essential operation that contributes to the production of numerous everyday products.

As an alternative to the extrusion process, calendaring is particularly useful in producing thin films, typically 3 mils thick or more. During the calendaring process, the plastic melt is compounded and pressed as it advances toward the nip of a sequence of three or more heated or highly polished steel rolls. These rolls work in tandem to produce sheets or films with specific properties.

Now, let's delve into the schematic diagram of the calendaring process, specifically designed for thin film and sheet formation. The illustration includes a mixer and two-roll mills equipped with metal detectors and other essential components. The initial step involves mixing polymeric materials, a critical process in calendaring. Subsequently, the material undergoes extrusion, highlighting the significance of the extruder in this operation.

The extruded material then encounters various rolls or calendars strategically positioned and moving in designated directions. Each roll plays a crucial role in shaping and processing the material. The process also incorporates an embossing unit, adding complexity to the overall calendaring operation. The combination of these steps results in the creation of continuous sheets and films that find applications in a diverse range of products.

This schematic diagram provides a visual representation of the key components and sequential steps involved in the calendaring process for thin film and sheet formation.



Figure; Schematic diagram of calendering process for thin film and sheet formation

During the calendaring operation, additional features such as embossing, watermarks, and intricate details can be incorporated into the material. Cooling drums play a crucial role in preventing film deformation by maintaining an optimal cooling temperature. Following this, the material undergoes trimming and gauging processes before being wound up on the winding-up unit. This schematic diagram provides a comprehensive overview of the key steps involved in the calendaring process.

The primary objective of calendaring is to apply just enough energy to transform a mass of plastic into film or sheet form without generating excessive heat that could compromise the material's quality. This process is not particularly energy-intensive, with the critical step being the proper melting of the material in the extruder. The subsequent steps in calendaring are relatively straightforward.

An important consideration, especially when working with stiff PVC, is the gap between the first two rolls. This gap produces a web of plastic, and the thickness is further decreased by pressing it through the second and third nips, as illustrated in the diagram. The ability to control the gap between rolls is crucial in achieving the desired thickness and properties of the final film or sheet during the calendaring process. Understanding and controlling these parameters are crucial for achieving desired outcomes in the calendaring process.

The spacing between the final set of rolls, known as a gauging rule, plays a crucial role in determining the sheet's final thickness. Once this thickness is set, the sheet or film web undergoes a cooling process, pulled around a chilled roll by a take-off roll. Depending on the intended application, the web may possess characteristics such as rigidity or flexibility and can be either polished or embossed. Precise control of temperature, pressure, and rotational speed for the entire roll is essential for proper calendaring.

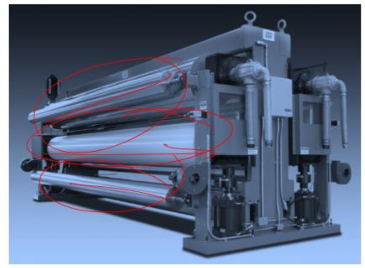
To add a textured or embossed pattern to the surface, an engraved roll is utilized. Plastics with relatively low viscosities, when melted, may not be ideal for calendaring due to potential issues and defects arising from low viscosity. Additives can be introduced to influence processability and enhance calendaring performance.

Expertise in managing these factors allows for increased calendaring speed, making the process more productive. This enhanced capability also enables the handling of thicker sheets, resulting in film and sheets with tighter thickness tolerances and improved uniformity. The accompanying image depicts an actual calendaring machine with various rolls.

During the compression of the plastic melt into a thin film or sheet web, considerable force is applied to the rolls. It is imperative to ensure that any metal or hard surface materials, including microscopic particles, are thoroughly removed. Failure to do so may lead to impressions forming on the rolls, potentially creating unintended embossed patterns on the film or sheets over time.

Calendering

- ✓ To compress the plastic melt into thin film or sheet web constructions, very strong forces are applied to the rolls.
- ✓ Any metal or hard surface material, including microscopic particles, must be completely removed.
- ✓ The rolls will be destroyed by a micron-sized metal fragment or a small scratch.



Figure; Showing real calendering machine

Source;https://www.google.com/search?q=calendering+machine&sxsrf 9

The rolls used in the calendaring process are highly susceptible to damage, even from micron-sized metal fragments or minor scratches. The quality and fineness of the resulting product are directly influenced by the condition of these rolls. It is crucial to exercise extreme caution throughout the entire calendaring process to prevent contamination of the processing equipment or the plastic being processed.

Continuous preventive maintenance is essential for ensuring the longevity of these production lines, necessitating a relatively clean operating environment within the facility. Dust and dirt can pose challenges as they may deposit on the rolls or the surface of the produced film, potentially leading to deformed products. Surface imperfections, known as bankmarks, result from the amount of plastic present in the nip formed between two rolls. As previously mentioned, the nip was illustrated in the earlier figure.

Bank markings, characterized by roughness on the sheet surface, can be caused by incorrect temperature or bank size. To minimize these issues, it is essential to optimize the formulation, including calendaring speed and roll temperature, ensuring that the rolling banks of stock at the calendar nip entrances behave in an orderly manner. This optimization process helps achieve a smoother and more precise calendaring operation, reducing the likelihood of imperfections in the final product.

In the complete equipment setup, there is typically a Banbury mixture, followed by heated rolls, chilled rolls, and finally, windup rolls. Earlier, we discussed the schematic diagram and various components of this process. The windup roll serves a critical role in controlling the tension on the film and sheet as it moves away from the calendar rolls.

The cost per rupee or pound of film or sheet is generally more economical once the equipment is installed and running continuously, compared to other techniques, including extrusion. This cost-effectiveness is realized at the end of the line. Two common methods for winding into rolls are center core winding and surface batching. In center core winding, one end of the mandrel is fitted into a power-driven socket. It is crucial to maintain uniform sheet or film tension to ensure a consistent thickness in the final product.

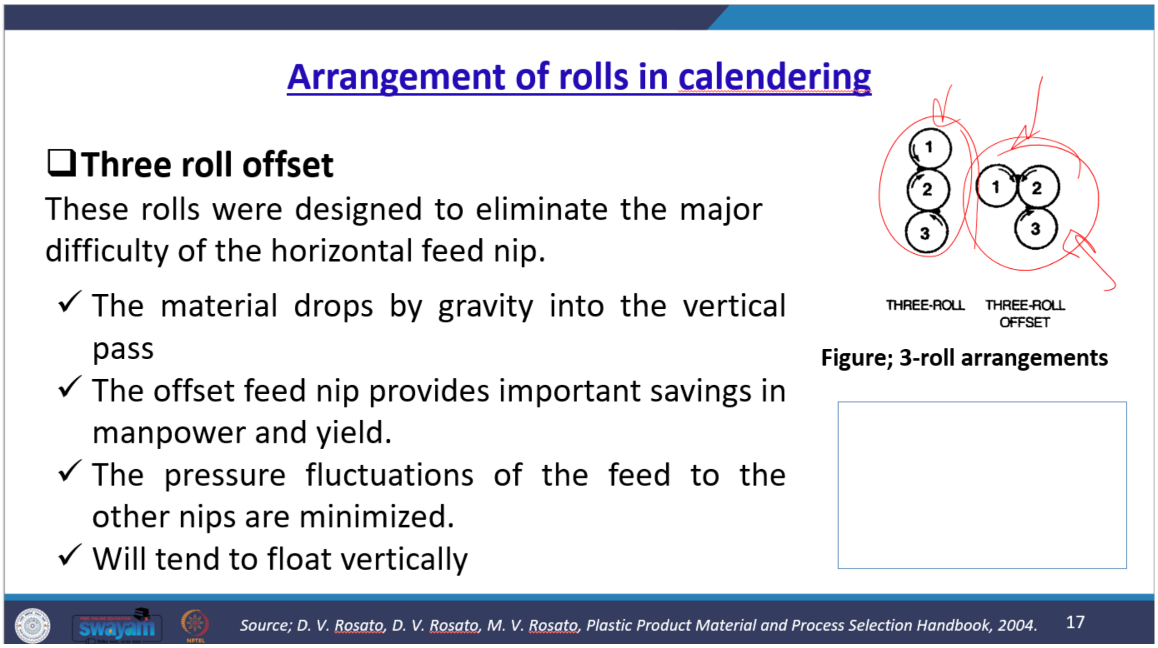
Let's now touch upon the aspect of trimming. Trimming can be executed either on the calendar itself or at a later stage when the sheet is cold, just before the winding process. Proper trimming is essential to achieve the desired final dimensions and quality of the film or sheet. This step plays a crucial role in refining the product and ensuring it meets the specified requirements.

Economically, it is advantageous to conduct trimming at the calendar stage. This is because the material, being at its existing temperature, can be easily conveyed back to the calendar feed nip to set the rolls and extruder feeder for recycling or blending with virgin plastic in granular form. The trim material typically accounts for up to 5 % of the width, depending on the efficiency of the production line.

Various arrangements of rolls exist in the calendaring operation, differing in the number of rolls, their configurations, true length, and arrangements such as conventional, inverted, reverse, fed inverted L, and Z, among others. The large diameter heated rolls play a crucial role in converting the high viscosity plastic melt into film or sheet.

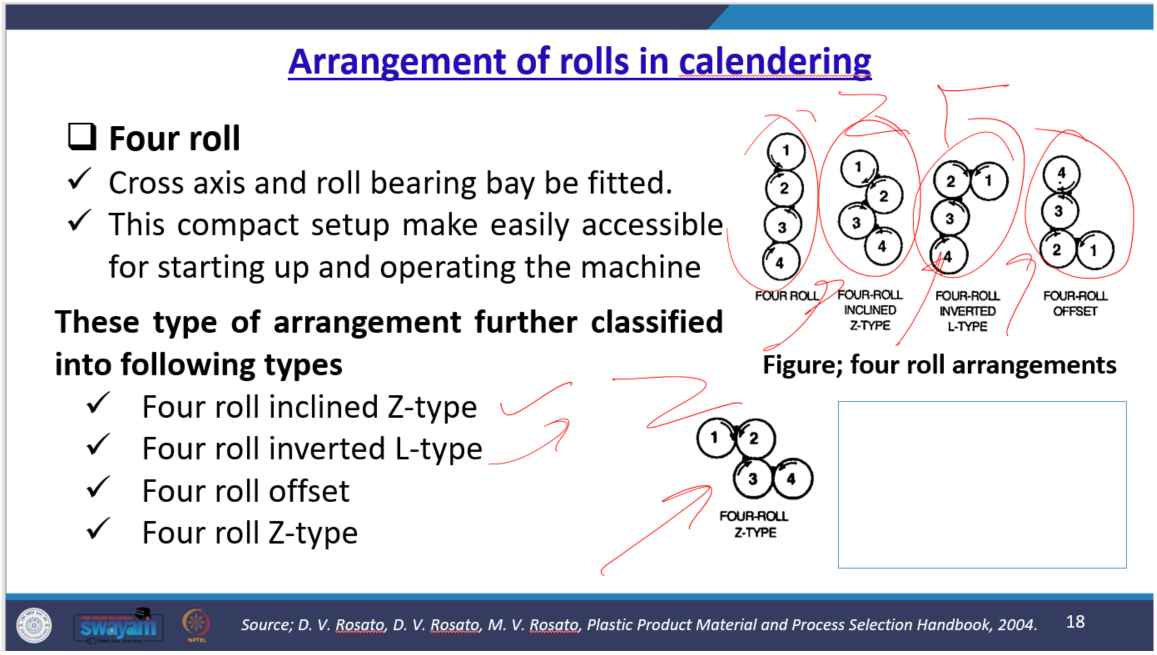
In the earlier days of calendaring, three rolls vertical rubber machines were commonly used. However, issues arose, including problems in processing plastic when feeding through a horizontal nip, leading to gauge variation due to the flexibility in the rubber. Temperature variations occurred due to the use of cored rolls, and there was no capability for cross-axis or roll bending adjustments. Additionally, roll floating was observed due to pressure variations in the field nips. These challenges prompted the development of newer and more advanced calendaring technologies to address these limitations and enhance overall efficiency.

In current practices, there is a tendency for the rolls to float horizontally. The three-roll offset configuration has been designed to overcome the significant challenges associated with horizontal field nips. In this setup, the material drops by gravity into the vertical pass, as illustrated. The offset field nip in the three-roll offset configuration offers significant savings in terms of manpower and yield. This design enhancement contributes to improved efficiency and streamlined operations in the calendaring process.



The pressure fluctuations from the feed to the other nips are minimized in configurations designed for vertical floating. In the realm of four-roll setups, various combinations exist, such as the four-roll incline Z type, L type, and four-roll offset. These configurations may incorporate cross-axis adjustments and roll bearings, ensuring a compact setup that is easily accessible for machine startup and operation.

These arrangements are further classified into different types, including the four-roll inclined Z type and the four-roll inverted L type, each offering specific advantages and applications in the calendaring process. The flexibility and adaptability of these configurations contribute to the overall efficiency and performance of the calendaring machine.



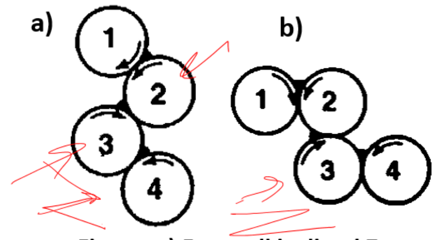
In the inverted L type configuration, the arrangement resembles an inverted "L" shape, as illustrated. The Z type features four rolls in a Z-shaped configuration, offering a specific setup for calendaring operations. The four-roll offset design is characterized by an offset arrangement, contributing to the machine's overall efficiency.

Additionally, there are configurations like the four-roll inclined Z type and the four-roll Z type, each designed to address specific needs in the calendaring process. These configurations play a crucial role in eliminating the floating of the three rolls, achieved through the use of fitted bearings. The design choices aim to enhance stability, precision, and control during the calendaring operation, contributing to the quality and efficiency of the final product.

Arrangement of rolls in calendering

❑ Z-TYPE roll

- ✓ Developed in offset rolls
- ✓ Eliminate the floating no.3 roll on calender fitted with bearings.
- ✓ Each roll can be preloaded on to its bearings at a point that is the resultant of the materials pressures and roll weight.



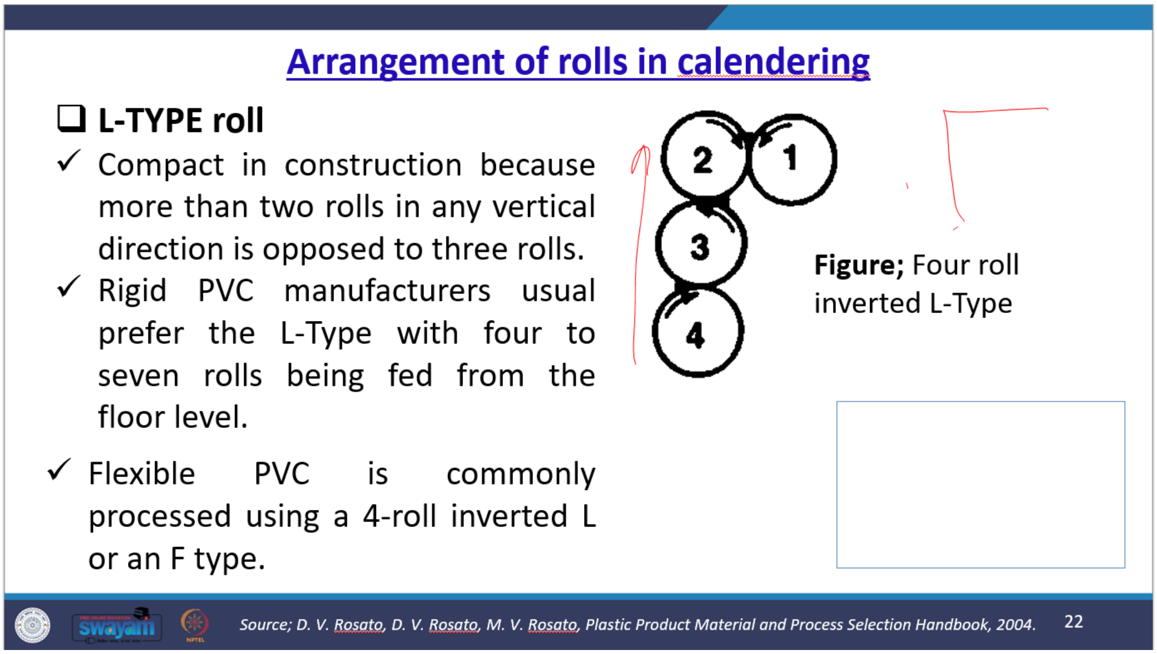
Figure; a) Four roll inclined Z-type b) Four roll Z-type

Source; D. V. Rosato, D. V. Rosato, M. V. Rosato, Plastic Product Material and Process Selection Handbook, 2004. 19

In the three-roll configuration, each roll can be preloaded on its bearing at a point that represents the resultant of the material's pressure and roll weight. This design offers several advantages, including a reduced height requirement for roll installation, a more compact plant space, and lower building costs. Simple machine construction is another benefit, as there is less need for compensation for roll bending. These configurations also lead to lower heat loss in the film and sheets due to shorter melt travel, and they can operate at different speeds to optimize performance on the melt.

However, there are a couple of disadvantages to consider. Access to roll number two and three may be limited in the case of inverted Z configurations, and feeding can be more challenging in inclined Z types as the nip does not hold as much material.

Now, let's explore the L type roll, as depicted in the inverted L type. This configuration is compact in construction, with more than two rolls arranged in the vertical direction as opposed to three rolls. In the manufacturing of rigid PVC, the L type with four to seven rolls is often preferred and fed from floor level. On the other hand, flexible PVC is commonly processed using four-roll inverted L or an F-type configuration. Each of these configurations offers specific advantages based on the material being processed and the desired outcome.



The universal five-roll L calendar finds application in processing both rigid and flexible PVC films. This configuration offers heat stability, superior film control, and a desirable surface appearance. Notably, this system has the capability to allow plasticizer-saturated vapors to escape through the suction hood located above the calendar, passing through filters before being released into the atmosphere.

Various factors affect the calendaring operation, and one crucial factor is pressure. High pressure, at least around 6000 PSI, can cause the rolls to bend or deflect. This bending may lead to smoothness issues or deformations in the final product. Consequently, the film or sheets may end up thicker in the middle than at the edges. The thrust exerted by the material depends on several processing factors, including the method of feeding stock into the calendar, plastic temperature, melt flow behavior, required thickness, and the speed of the calendaring lines.

Rheological properties also play a significant role in calendaring since melting is a key aspect. Compensating for variations in thickness requires the floor's surface to have a specific profile, typically a crown. The amount of crown needed varies depending on the rheological properties of the plastic material being processed. Attention to these factors ensures a more controlled and precise calendaring process, contributing to the quality and consistency of the final product.

The amount of crown in the rolls is determined by the difference in roll section radius between the ends and the center. Rolls are often crowned to have a greater diameter in the middle, ensuring uniform contact with the material. Sometimes, adjustments and control to correct distortion are essential. Crossed rolls, slightly angled rather than parallel, can increase the nip opening at both ends of the roll.

To minimize deflection under high operating conditions, stiffer rolls are used, typically made of high-modulus-of-elasticity steel or featuring dual steel construction. A technique involves bending the rolls, applying the bending moment to the end of each roll by having a second bearing on each roll neck.

Temperature is a critical factor, as high temperatures can lead to a decrease in viscosity, affecting the proper shaping of the product. Calendars require high and consistent temperatures with minimal variation across the rolls during the application of high pressure on the stock. Uneven temperature and pressure along the roll's length could result in variations in product thickness. Adjusting roll temperature and speed is crucial to controlling the final product dimensions.

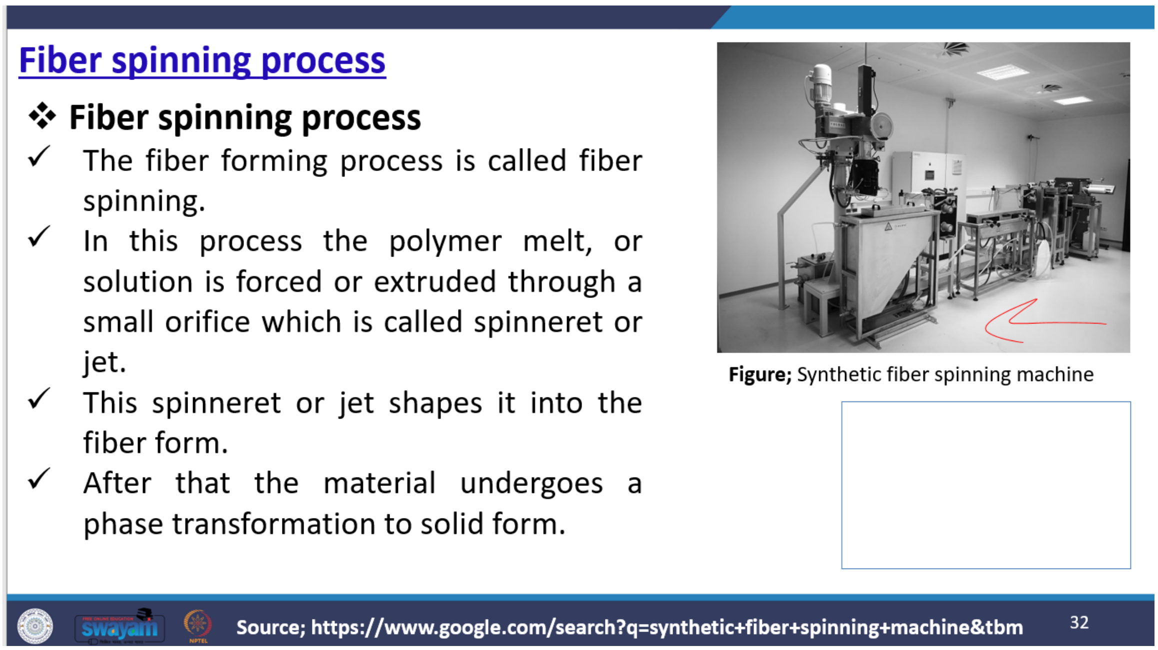
Cooling rolls in the line allow for slower cooling to room temperature, preventing a shock cooling situation for certain plastics that could reduce the physical and mechanical properties of rigid PVC materials. The embossing roll, preceding the cooling rolls, allows the film to drop vertically into the embosser with three rolls, and temperature accuracy is typically controlled within a range of 1 degree Celsius. This precision ensures the desired embossed pattern and overall quality of the final product.

The first calendar nip in the calendaring process must be well-fused, homogeneous, and maintain a uniform temperature. The optimum average temperature for good fusion depends on the formulation, with rigid PVC typically requiring a temperature range of 180 to 190 °C at the first calendar nip.

The speed effect is crucial, and adjusting roll temperature and speed plays a significant role in controlling the final product dimensions. Roll loads range from 1000 to 2000 pounds per linear inch for soft sheeting and can approach 5000 pounds per linear inch on larger rolls for thin rigid materials processed at 166 °C.

In the calendaring process, the speed of the stripper roll must be varied in relation to the calendar speed to eliminate the degree of roll cycling, especially when the sheet is thinner. The stripper roll speed is maintained at a constant ratio with the calendar speed to ensure a consistent and controlled process.

Shifting to the fiber spinning process, fibers are materials whose length is at least 100 times their diameter. Synthetic fibers, whether organic or inorganic, undergo processing to take on the form of fibers or thread lines. The fiber spinning process is fundamental to the production of synthetic fibers, and various methods, such as melt spinning, dry spinning, wet spinning, and reaction spinning, are employed to transform these materials into the desired fiber form.

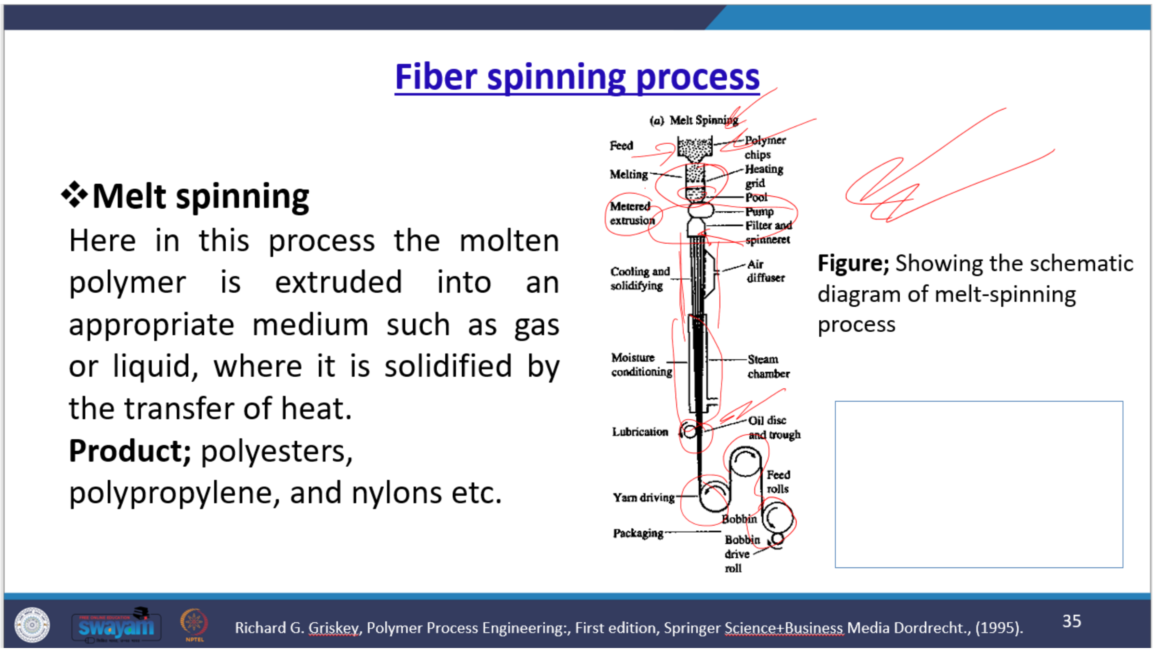


Fibers in the fiber spinning process can be categorized as either staple or short fibers, or continuous filaments, which are very long fibers. The nature of the material, whether organic or synthetic, influences the various ways in which fibers can be formed.

The fiber forming process is termed fiber spinning. In this process, the polymer melt or solution is forced or extruded through a small orifice known as the spinneret or jet. The synthetic fiber spinning machine, as illustrated, exemplifies this process. The material, after passing through the spinneret, undergoes a phase transformation to solid form, resulting in the formation of fibers.

The fiber spinning process involves applying heat to the polymer melt, forcing it through the spinneret, and then cooling it to form fibers. Once formed, the fibers are wound up into a spool, pin, or taken up into woven materials. Subsequent operations may be performed to bring the fibers to their final performance level.

The classification of fiber spinning processes includes melt spinning, dry spinning, wet spinning, and reaction spinning. The selection of a particular spinning process is closely related to the material being spun and the technique used for solidification. Each spinning method has its unique advantages and is suited to specific types of fibers and applications.



Let's delve into the melt spinning process. In melt spinning, the molten polymer is extruded through a series of steps. First, polymer chips or granules are fed into the system. In the melting zone, these materials undergo the transition from solid to molten form. The molten polymer then enters the pool and undergoes metered extrusion before reaching the spinneret, where fibers are formed. Cooling follows, and additional steps such as moisture conditioning and lubrication are implemented to prevent agglomeration during the rolling process. A small quantity of oil is sprayed through the oil disc to facilitate smooth yarn movement, leading to the woven or rolled outcome.

Integral to melt spinning is the extrusion of molten polymer in an appropriate medium, solidifying it through heat transfer. Materials such as polyester yarns, polypropylene, and nylons are produced using this process.

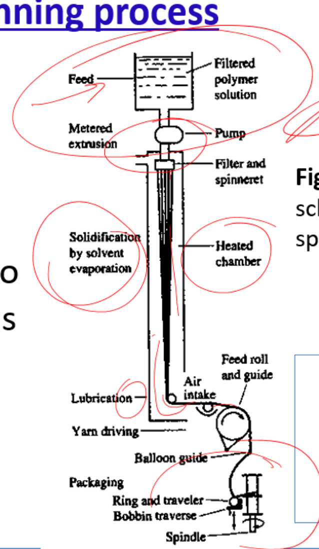
The process begins with melting polymer pellets or granules or pumping molten polymer to spinning units that meter the polymer flow. The molten polymer passes through a sand or screen pack before reaching the spinneret, where fibers are formed. After extrusion, the filaments are quenched and cooled in a fluid medium like air, inert gases, or water. In some cases, the fiber is drawn separately to achieve the desired properties.

Moving on to the dry spinning process, this schematic diagram illustrates the key steps. In dry spinning, polymer solution is extruded into a heated gas, where the solvent is removed, and the fiber solidifies. This process is another technique for transforming polymer solutions into fibers, with the removal of solvent playing a crucial role in the solidification of the resulting fiber.

Fiber spinning process

❖Dry spinning process

This process involves the extrusion of polymer solution into a heated gas, where the solvent is removed, and fiber solidified.

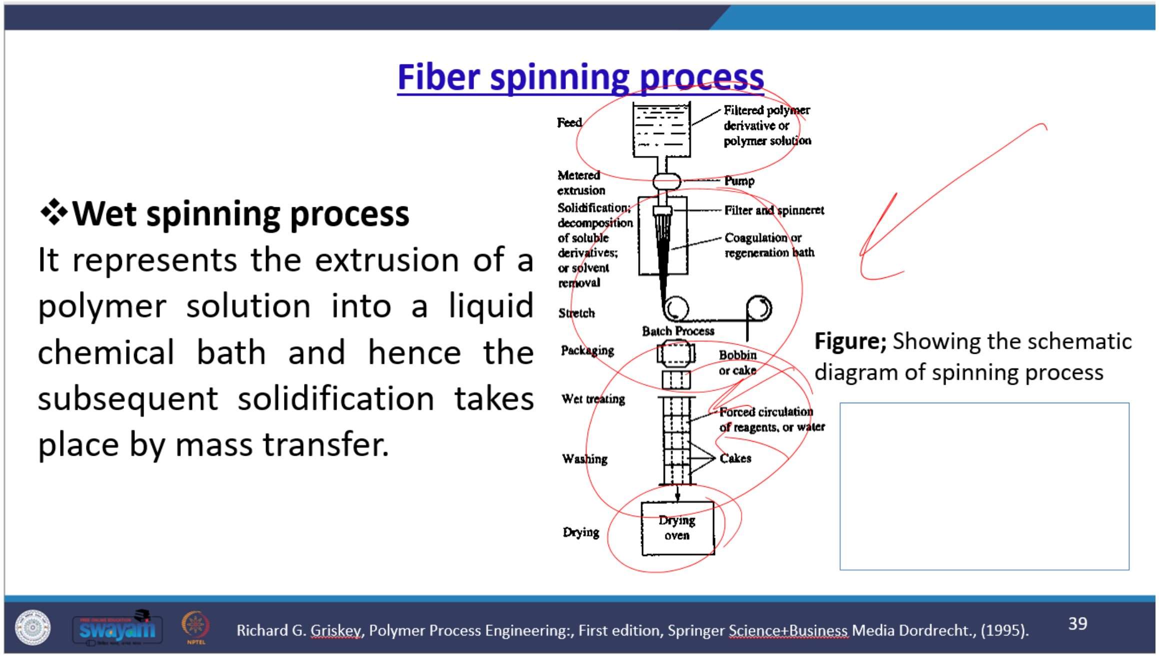


Figure; Showing the schematic diagram of Dry-spinning process

Now, let's explore the wet spinning process. The figure illustrates the key steps of wet spinning, which involves the extrusion of a polymer solution into a liquid chemical bath, leading to subsequent solidification through mass transfer. In this process, there is a forced circulation of reagent and water, along with the formation of cakes, followed by a drying oven.

In the wet spinning process, fibers are formed by extruding a highly viscous polymer solution through the spinneret into a liquid bath for solidification. The solidification occurs through diffusional interchange between the extruded polymer filament and the bath. This method provides a unique way to produce fibers with specific properties, and the choice of polymer, solvent, and bath composition plays a crucial role in determining the characteristics of the final fiber product.

In summary, fiber spinning processes such as melt spinning, dry spinning, and wet spinning offer distinct methods for transforming polymer materials into fibers, each with its unique set of advantages and applications. The choice of the spinning process depends on the specific requirements of the desired fiber and the properties sought in the final product.



The process of coagulation is integral to wet spinning. During coagulation, one or more components from the bath diffuse into the fiber while the solvent exits the forming filament. The result is a solid fiber. In the case of viscose rayon, a chemical reaction is superimposed on the diffusional process. However, for simplicity, we will focus on the diffusional process. In the wet spinning process, temperature effects and heat transfer play a relatively smaller role compared to other principal spinning processes.

Moving on to the reaction spinning process, this technique involves the extrusion of partially reacted material, known as a pre-polymer, into a heated fluid medium. Solidification occurs through a chemical reaction. Reaction spinning can resemble either dry or wet spinning processes. For instance, in nature, creatures like spiders, silkworms, and ants eject or spin a pre-polymer that then undergoes a reaction, forming the final polymeric material. This process mimics the natural spinning behaviors of certain organisms and is used to create fibers with specific properties through controlled chemical reactions during solidification.

Let's compare the different spinning types we discussed in the previous slides:

1. **Melt Spinning:**
   - **Phase Transformation:** Solidification of melt.
   - **Materials:** Nylon, polyester, polypropylene, glass fibers, etc.

2. **Dry Spinning:**
    - **Phase Transformation:** Evaporation of the solvent with solidification.
    - **Materials:** Cellulose acetate, cellulose triacetate, polyacrylonitrile.
3. **Wet Spinning:**
    - **Phase Transformation:** Counter-current diffusion in a bath with solidification.
    - **Materials:** Polyacrylonitrile.
4. **Reaction Spinning:**
    - **Phase Transformation:** Material reacts and solidifies.

Now, let's discuss the fiber requirements and spinability. Synthetic fibers must possess specific characteristics to be considered useful materials. These include a high thermal softening point to facilitate processing or ironing, a high initial modulus of elasticity or stiffness, and reasonable tensile strength over a broad temperature range. The tensile strength of a fiber is often defined in denier, providing a measure of its strength and thickness. These requirements ensure that synthetic fibers can withstand various processing conditions and applications, making them versatile and suitable for a wide range of uses.

Properties	Textile applications	Industrial applications
Tensile strength (g/denier)	5	7-8
Initial modulus (g/denier)	30-60	50-80
Elongation at break	Less than 10%	8-15%
Temperatures (Creep or softening point)	At least 215^{o}C	250^{o}C
Others properties	Good abrasion and moisture resistance	Chemical resistance

Denier is a measure of the size of a fiber and is defined as the weight in grams of a 9000-meter length of the fiber. Denier is proportional to both the density and the cross-sectional area of the fiber, meaning that a larger denier corresponds to a greater cross-sectional area of the fiber.

Now, let's look at the property ranges for synthetic fibers:

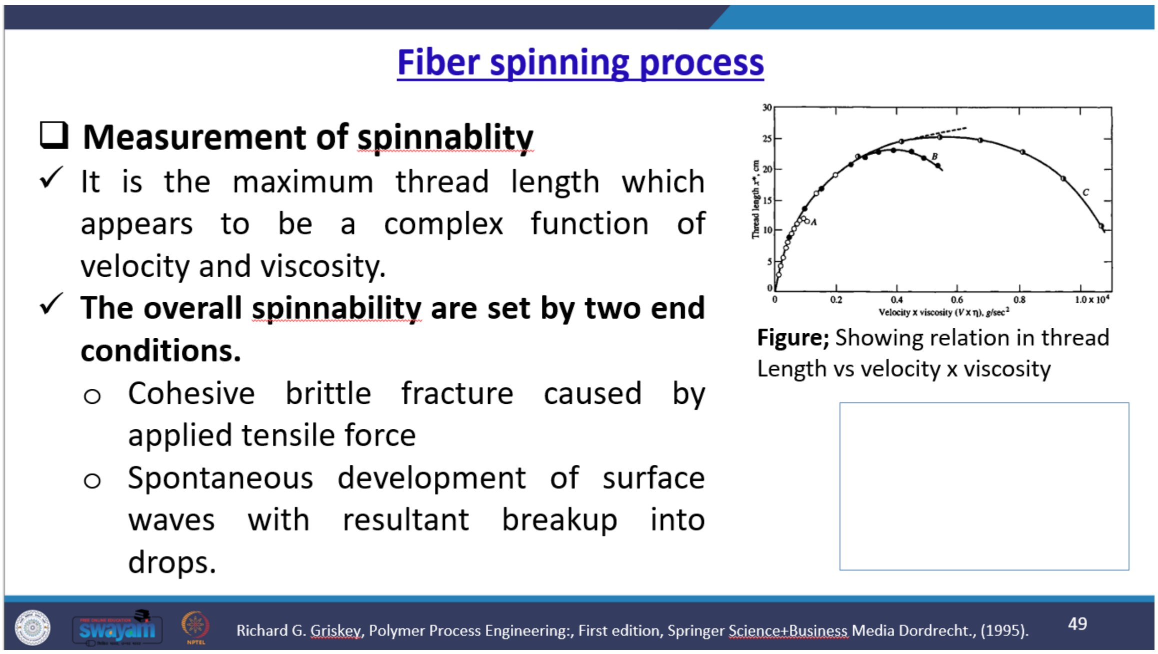
1. **Tensile Strength (gram per denier):**
    - Textile Application: Must be at least 5.
    - Industrial Application: Ideally in the range of 7 to 8.
2. **Initial Modulus (gram per denier):**
    - Textile Application: 30 to 60.
    - Industrial Application: 50 to 80.
3. **Elongation at Break:**
    - Textile Application: Less than 10%.
    - Industrial Application: In the range of 8 to 15%.
4. **Temperature Creep or Softening Point:**
    - Textile Application: At least 215°C.
    - Industrial Application: 250°C.

Other desirable properties include good abrasion resistance, moisture resistance, and chemical resistance. These criteria ensure that synthetic fibers meet the specific requirements for various applications, providing durability and performance in both textile and industrial settings.

Spinnability of a synthetic fiber is a crucial aspect in the manufacturing process. A polymer is considered spinnable if it demonstrates chemical and thermal stability under the spinning conditions and is capable of yielding continuous fluid or semi-solid fibers that can be easily transformed into solid polymers.

However, there exists a spinnability limit. If the viscosity of the spinning fluid is too low—indicating a high melt temperature or a diluted solution—the fluid may be extruded in individual drops. On the other extreme, excessively high viscosity can lead to the cohesive fracture of the spinning fiber. The measurement of spinnability involves determining the maximum thread length, which appears to be a complex function influenced by viscosity and velocity.

In essence, achieving optimal spinnability requires a delicate balance in the viscosity and other spinning parameters to ensure the continuous and uniform formation of fibers during the spinning process. This balance is crucial for the successful production of high-quality synthetic fibers.



In summary, the overall spinnability of synthetic fibers is influenced by two key end conditions: cohesive brittle fracture caused by applied tensile force and the spontaneous development of surface waves leading to breakup into drops. These conditions highlight the delicate balance required in the spinning process to avoid undesirable outcomes and achieve successful fiber production.

This chapter has delved into the critical operations of fiber spinning and calendaring in polymer processing. Both processes play pivotal roles, and their proper execution is essential for producing high-quality synthetic fibers. If you wish to explore these topics further, we have provided references for your convenience. Thank you for your attention and consideration.