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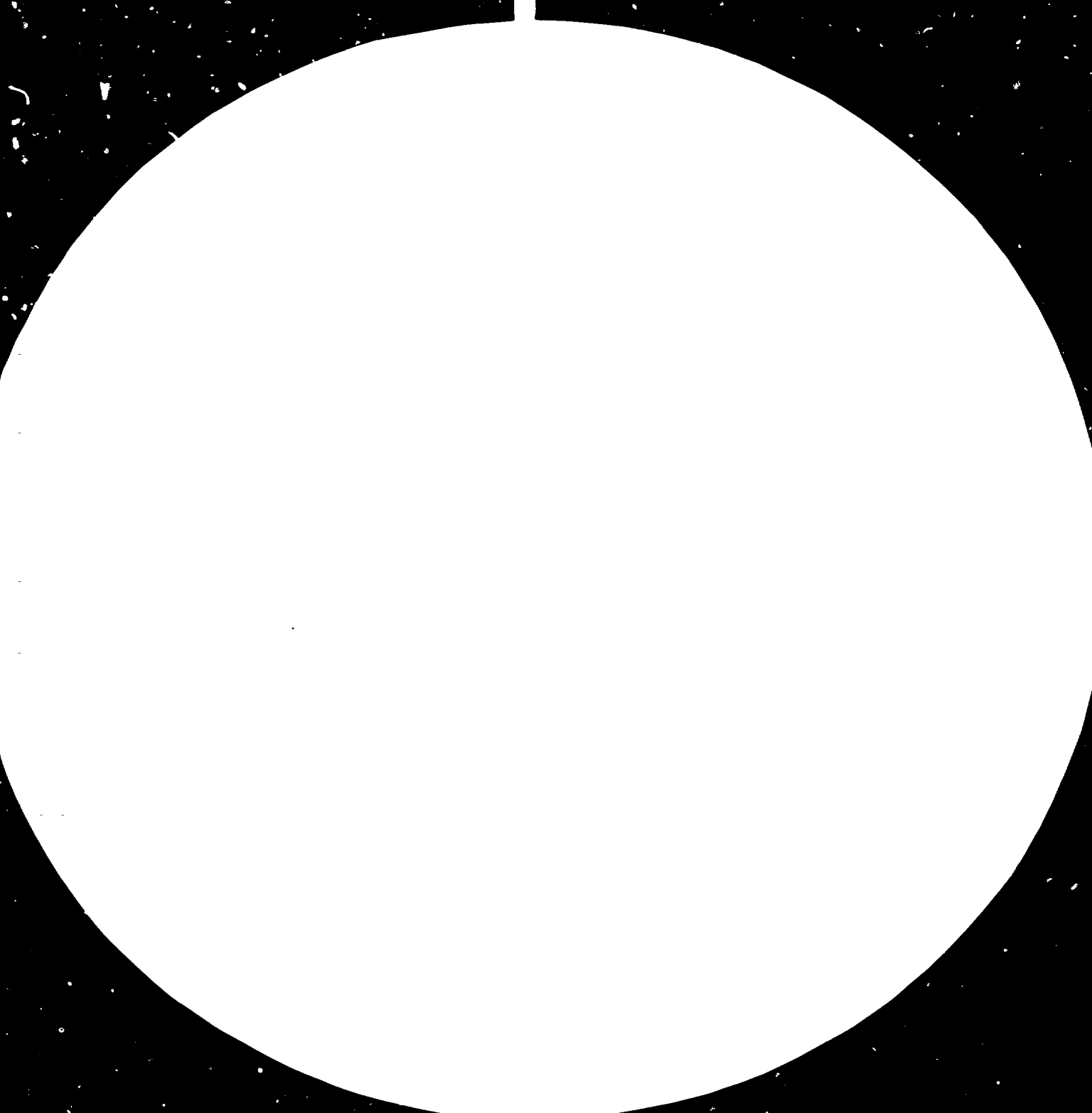
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The methods of fiber manufacturing

II

Summary:

The paper deals with and describes the various methods of transforming polymer substrates into fibers. These methods comprise the following processes:

- the melt spinning process
- the dry spinning process
- the wet spinning process
- the film-to-fiber processes and
- the suspension spinning processes

Which of these processes can be applied for transforming a given polymer into fibrous form is determined by specific properties of the polymer.

Whenever a polymer is thermoplastic and melts at a reasonable temperature, the melt spinning process will be applied since nowadays this technique is the most simple and economical one.

Whenever a given polymer does not melt without decomposition is, however, soluble in a solvent which can be easily evaporated and recovered, the dry spinning process will be applied, as the second best choice.

The wet spinning process is only used for polymers which do not melt without decomposition and which are soluble in solvents which can not be evaporated and easily recovered.

During the last decade, the film-to-fiber technology has been developed. The various techniques applied in this new technology are described.

As last resource for producing fibers from materials which are neither meltable nor soluble, the suspension spinning techniques can be applied. Such techniques are used in the manufacturing of polytetrafluorethylene or of ceramic fibers.

These processes are being described on typical examples and information is being given on the technical equipment necessary and on the sources from which such equipment can be acquired.

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For the manufacturing of man-made fibers from natural or synthetic polymers various methods are available. These methods comprise the following processes:

- the melt spinning process
- the dry spinning process
- the wet spinning process
- the film-to-fiber processes and
- the suspension spinning processes

From these, the first three are the mostly used ones, while the film-to-fiber processes and the suspension spinning processes are limited in use for producing fibers for special application areas and for manufacturing some speciality fibers.

The basic principles for the wet and dry spinning processes were already established by the pioneers of man-made fiber manufacturing at the end of the last century. It was especially owing to the initiative of the Count de Chardonnet that technical equipment able to convey, pump, meter and extrude high viscose spinning dopes into fibers was developed. The melt spinning process, however, only evolved in the late thirties of this century during the development of the polyamide and polyester fibers.

Choice of process:

The decision, which of the above named fiber manufacturing processes is used in a given case and with a given polymer, is mainly determined by the specific properties of the polymer intended to be transformed into fibrous form (cf. Table No. 1).

Table No. 1:

POLYMER PROPERTIES AND FIBER SPINNING METHODS

Polymer	Softening or melting temperature	Fiber manufacturing process
Polypropylene	170 - 175° C	melt spinning
Polyethylene terephthalate	260° C	melt spinning
6.6-Nylon	265° C	melt spinning
6-Nylon	215° C	melt spinning
Hexamethylene terephthalamide	370° C	dry spinning (trifluoroacetic acid)
Polyvinylchloride	70° C (softening) 180° C (decomposition)	dry spinning (propanone + carbondisulphide)
Polyacrylonitrile	>200° C (decomposition)	dry spinning (dimethylformamide)
Cellulose acetate (DS = 2.5)	120 - 160° C (softening)	dry spinning (95/5 acetone-water)
Cellulose triacetate	290 - 300° C	dry spinning (methylene chloride)
Cellulose	>250° C (decomposition)	wet spinning (cuprammonium)
Cellulose xanthate (DS=0.5-1.0)	250° C (decomposition)	wet spinning (sodiumhydroxide)

Whenever a polymer melts at a reasonable temperature without decomposition, such as polypropylene, polyamide 6 or 6.6 and polyethyleneterephthalate, the melt spinning process will be applied, since it is the most simple and from the environmental point of view the cleanest process, when compared with dry or wet spinning.

Whenever a polymer does not melt at a reasonable temperature and without decomposition, is, however, soluble in a solvent having a not too high boiling point, at which the dissolved polymer is stable and when during evaporation of the solvent the polymer solidifies to an extendable gel filament, the dry spinning process will be chosen, as the second best choice.

Another additional prerequisite for this type of fiber spinning, however, is that the solvent used has to be easily recoverable without too much losses.

The wet spinning process is only applied whenever the polymer does not melt without decomposition, or when the solvent for the given polymer has a too high boiling point, or when during evaporation of the solvent not enough and fast solidification to extendable gel filaments occurs. The wet spinning technique is in any case under such conditions the last choice. Wet spinning in general means the application of multi component systems, which especially in regeneration and recycling of chemicals is in most cases more difficult and technically involved.

The film-to-fiber technology for producing fibers was developed during the last 20 years, especially since isotactic polypropylene become available. For any polymer, which is meltable at reasonable temperature and forms films with good mechanical properties, such techniques are favourably applied when the quality requirements for the desired textile material are not too high. Film splitting or slitting techniques applied to polypropylene films or with certain difficulties due to intermolecular secondary bonding also to polyamide or polyester films, yield fibers with titers higher than 6 dtex and with rectangular, sometimes very irregular cross-sections. The application of such fibers is limited to end uses, where coarse and irregular fibers can be tolerated.

The suspension spinning technique is applied for the manufacturing of speciality fibers from organic or inorganic macromolecular substances, especially when these are neither soluble nor meltable. Such polymer will be ground to fine powders, which are then suspended in high concentrations in a fiber forming spinning dope and spun under conditions suited for fiber forming in the carrier dope. After fiber formation, the fiber forming material coming from the carrier dope, in the case of using viscose the cellulosic material is finally burned away, and the incorporated powder is solidified by sintering. Such suspension techniques are applied for the manufacturing of polytetrafluorethylene fibers or of certain ceramic fibers, just to give a few examples.



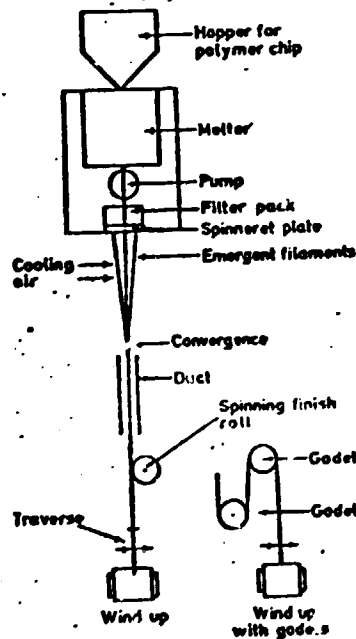
The principles of melt spinning:

The melt spinning procedure comprises the following processing steps:

- the preparation of the spinnable polymer melt,
- the extrusion of the melt through spinneret holes,
- the extension of the polymer streams leaving the spinneret holes,
- the solidification of the extended filaments, and
- the winding up of the solidified filaments on a bobin or on similar take-up equipment

The scheme of a melt spinning process is shown in the following Figure No. 1.

Figure No. 1:



Scheme of a melt spinning process

The polymer melt is extruded through a channel of the spinneret hole with a constant output rate  $W$ , with a cross sectional diameter at the exit of the hole of  $d_o$ , at an average extrusion velocity of  $V_o$  and an extrusion temperature of  $T_o$ . The take-up device placed at the distance  $L$  from the spinneret collects the filaments with a constant linear take-up velocity  $V_L$ . The corresponding filament diameter and filament temperature at the take-up point is  $d_L$  and  $T_L$ , respectively. Between the exit of the spinneret hole and the take-up place along the spinning path  $L$ , the drawing, the cooling, the solidification and the formation of the supramolecular structure of the filaments takes place.

There are many variables involved in the melt spinning which have an influence on the fiber formation and the resulting fiber dimensions and fiber properties. Some of these variables are mutually dependent. Under the steady state conditions under which fiber spinning takes place the equation of continuity holds:

$$\rho_o A_o V_o = \rho_L A_L V_L = W ,$$

wherein  $\rho_o$  and  $\rho_L$  are the polymer densities at the spinneret hole exit and the take-up point, respectively,  $A_o$  and  $A_L$  are the cross-sectional area of the melt filament and the wound up filament,  $V_o$  and  $V_L$  the average velocity of the melt stream at the spinneret exit and the take-up speed, respectively, and  $W$  is the mass output rate.

The mass output rate  $W$  is determined by the dimensions of the spinneret hole, namely its radius  $R_o$  and its length  $l_o$ , by the

pressure difference  $\Delta P$  under which the extrusion takes place, and by the viscosity  $\eta$  of the polymer melt at the velocity and temperature conditions of the extrusion. A somewhat modified form of the Hagen-Poiseuille law applies:

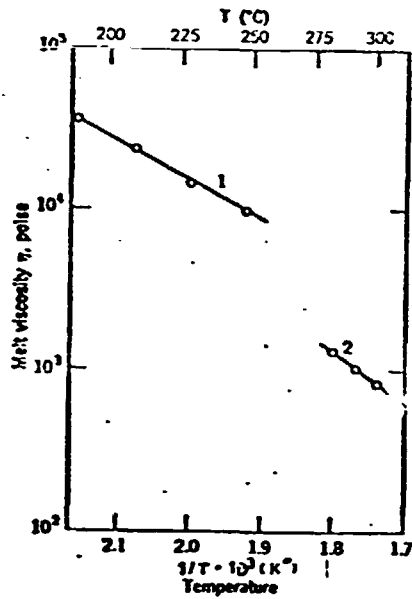
$$W = \frac{n}{-3n + 1} \eta R_0^3 (\Delta P R_0 / 2 \eta l_0)^{1/n}$$

Polymer fluids used in fiber spinning most often exhibit "structural viscosity", i. e. the apparent viscosity decreases with increased flow rate due to molecular orientation by shear forces in capillary flow. For such systems  $n < 1$ , and the actual output rate  $W$  is larger than that calculated from the Hagen-Poiseuille formula in its original form valid for liquids with Newtonian behaviour. One of the most important characteristics of fiber-forming thermoplastic polymers is the rheological behaviour in molten state, i. e. the behaviour under flow conditions. Principally, there are two groups of polymers used for melt spinning:

- (1) Linear polycondensates, such as polyamides, polyesters and polyurethanes with moderate molecular weights in the range of 10.000 to 25.000, and
- (2) linear polyolefines and polyvinyl compounds, such as polyethylene, polypropylene, polystyrene, polyvinylchloride, etc., with higher molecular weights between 30.000 up to 200.000.

When melted, materials belonging to the first group, form melts with rather low viscosity  $\eta$ , being at commonly used extrusion temperatures in the order of  $10^3$  poises (cf. Figure No. 2).

Figure No. 2:



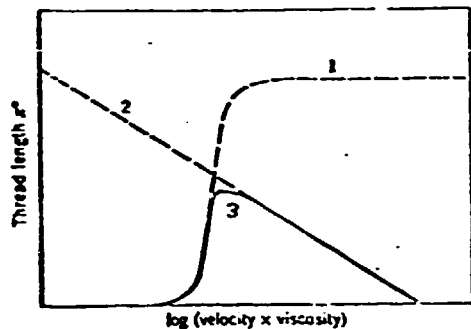
Temperature-dependent viscosity of fiber-forming melts:  
1 = polypropylene  
2 = polyethylene terephthalate

These melts show only slight non-Newtonian flow characteristics, such as viscosity reduction with flow rate, and exhibit only minor elasticity characteristics and rather short relaxation times in their response to external stresses.

The second group of fiber-forming polymers exhibit due to their substantially higher molecular weight in their melts high viscosities of  $10^4$  poises and more. These melts show strongly expressed non-Newtonian flow characteristics, high elasticity and long relaxation times.

The spinning of polycondensates, belonging to the first group is therefore in most cases very good and without problems. The upper spinnability limit due to cohesive fracture is (cf. Figure No. 3) due to the lower molecular weight, the low viscosity and short relaxation time usually not reached.

Figure No. 3:

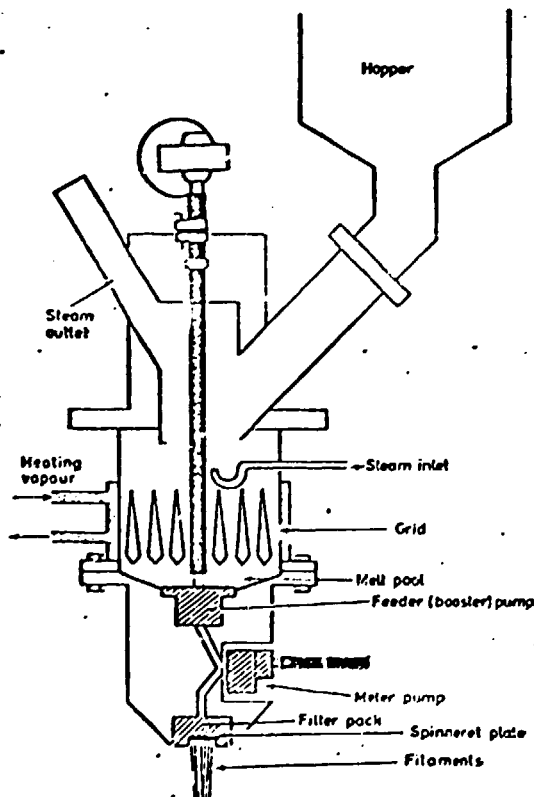


Spinnability of melts and solutions of polymers:  
Dependence on viscosity and spinning velocity

- 1 - capillary breakup
- 2 = cohesive fracture
- 3 = practicable spinnability limits.

The lower limit due to capillary breakup into drops appears sporadically only when due to high spinneret temperature  $T_0$  or thermal degradation of the polymer the viscosity of the melt drop to a too low level. The generally higher fluidity of the melts of these polymers also allows the use of grid melters with gravity feed (cf. Figure No. 4) instead of screw extruders.

Figure No. 4:



Grid melter as used for 6.6-nylon (gravity feed)

In comparison, the spinnability of molten polymers belonging to the second group is usually limited by cohesive fracture and very seldomly by capillary breakup. The die swell and melt-fracture effects are very strongly expressed as result of the higher elasticity of the melts. Long relaxation times lead to serious limitations of draw rates and deformation ratios. The high viscosities and in consequences the high pressures required in the extrusion of these polymers make in fiber spinning the use of screw extruders (cf. Figure No. 5) often in connection with gear pumps (cf. Figure No. 6) necessary.

Figure No. 5:

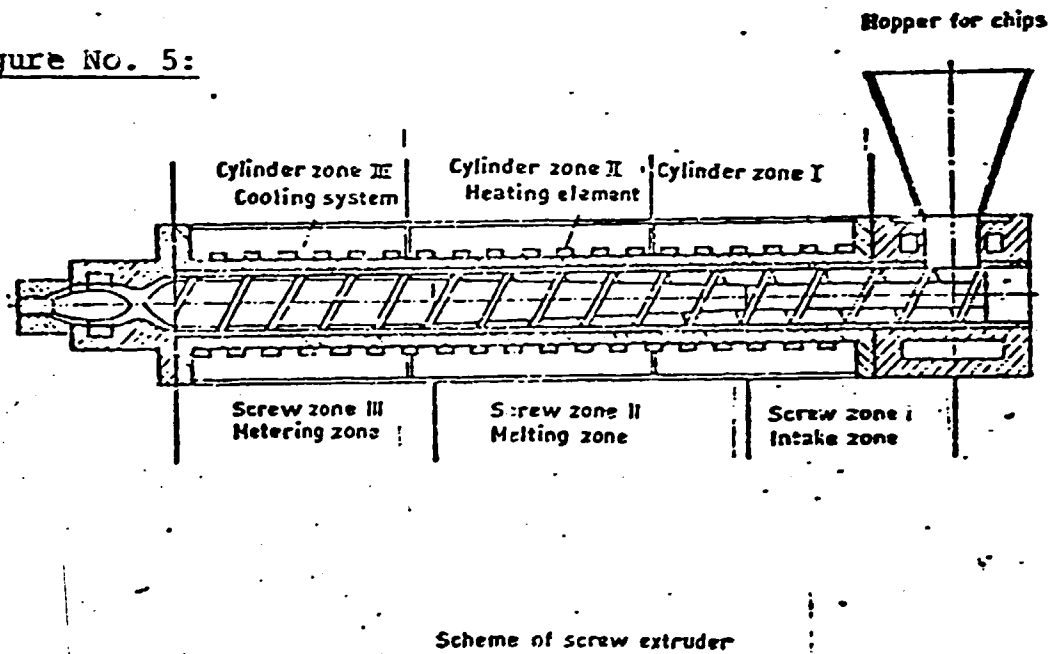
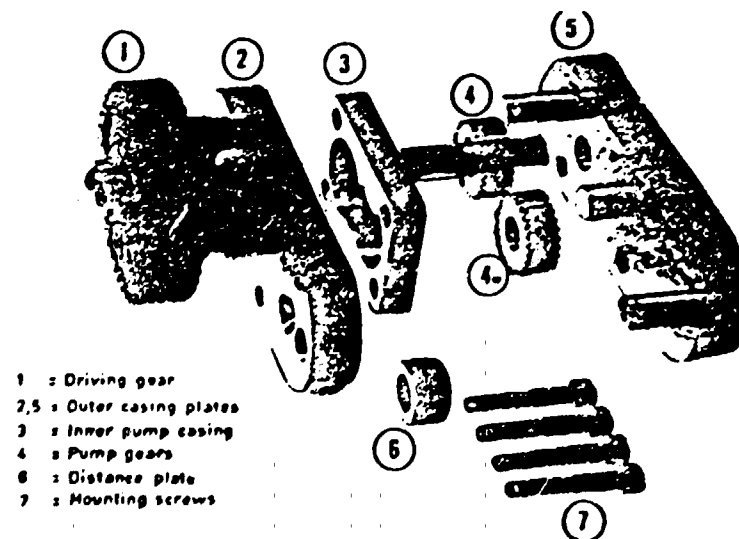


Figure No. 6:

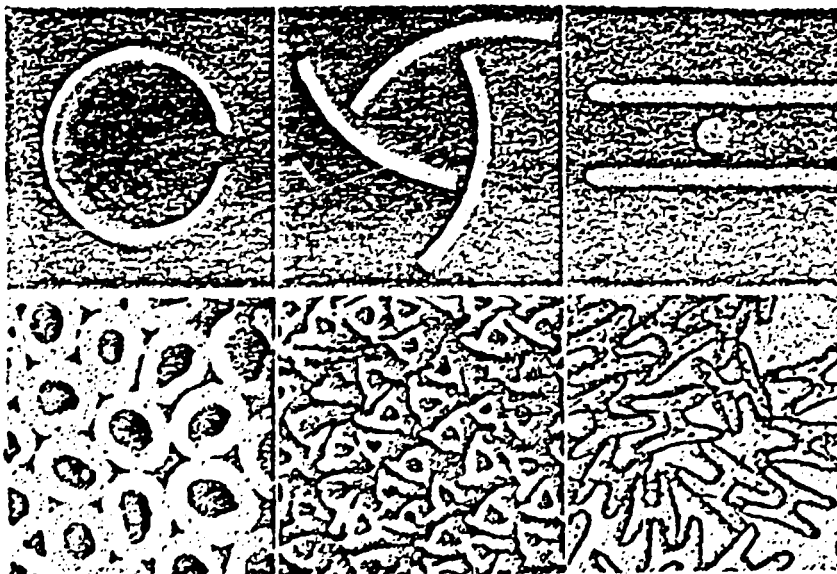
The parts of a spinning gear pump



The physics of flow during spinning dope extrusion is most important for the understanding and the controlling of fiber spinning. However, it would go beyond the scope of this basic lecture to deal with this subject in more details. Recently, Andrzej Ziabicki has published a most interesting book entitled "Fundamentals of Fiber Spinning" printed by Wiley & Sons, New York - London, which is sold for US-Dollars 39,50.

The spinneret holes in melt spinning are generally larger than in dry or wet spinning and range in dependence from the characteristics of the polymer and from the fineness of the fibers to be spun from 0.1 to 0.8 mm in diameter with channel length of a few millimeters. Normally, round holes are in use. Noncircular holes are used to make filaments of various cross-sectional shape. Y-shaped holes will yield a three-lobed cross-section which may be almost triangular, and a C-shaped hole will produce a hollow filament (cf. Figure No.7).

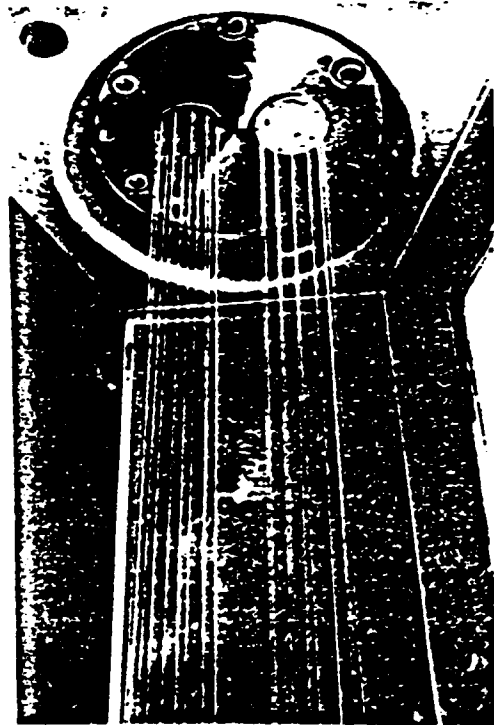
Figure No. 7:



Noncircular spinneret orifices and resulting fiber cross sections

In the case of spinning multi-filament yarns or staple fibers the cooling of the extruded melt filaments after leaving the spinneret holes is performed in most cases in a gaseous medium of air, inert gases or steam in a vertical spinning shaft of 1 to 5 m length (cf. Figure 8).

Figure No. 8: Melt spinning (spinneret at top of spinning tube)



Source: Reichmann U.S. Spinn Corp.

The cooling effect is sometimes enhanced by blowing the cooling gas perpendicular onto the fibers with respect to their spinning direction. On the other hand, in spinning elastic melts of low fluidity the upper part of the spin shaft has often to be heated in order to prevent too rapid cooling thus avoiding difficulties in drawing. Thick monofilaments or bristles are commonly spun into rapidly acting liquid cooling baths.



The take-up velocity used in fiber formation by melt spinning of thermoplastic polymers range from 100 m/min in the case of thick monofilaments and liquid bath cooling up to several thousand m/min in the production of multifilaments using gaseous cooling medium.

The lack of solvents and of coagulation or precipitating agents together with the high spinning velocities make the melt spinning technique the most convenient and efficient of all the spinning procedures. The only factor, which seriously limits the application of melt spinning is the melting temperature and the stability of the resulting fluid melts. Melting and extrusion temperatures much higher than 350° C are difficult to achieve. Typical melt and spun polymers are the linear polycondensates, such as polyamides, polyesters and polyurethanes, and thermoplastic polymerization polymers, such as polyethylene and polypropylene.

The thermal decomposition of a polymer below the reasonable fluidity temperature normally excludes the application of melt spinning techniques. In a few cases, however, this difficulty can be overcome by replacing the pure undiluted polymer by plasticising systems. Polymers containing a few percent of low molecularized plasticising agent, yield sufficient fluidity at temperatures below their destruction point, thus allowing extrusion. Although in this case the spinning fluid is a very concentrated solution, such a process can be considered as "melt spinning", because, as in pure melts, the mechanism of solidification consists practically of cooling

rather than of evaporation of the plasticised agent. A polymer, which only melts normally under decomposition, but can be extruded with the help of plasticising agents, such as water, dimethylformamide or others is polyacrylonitrile (cf. Figure No. 9).

Figure No. 9:

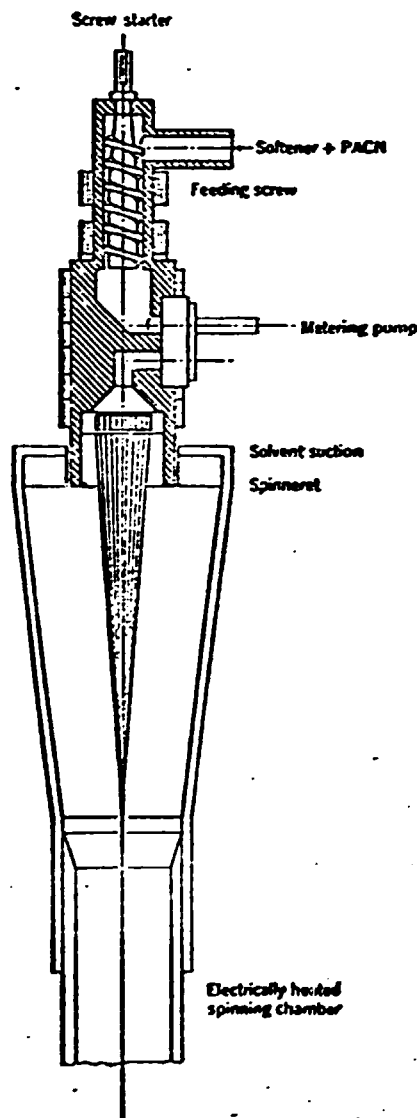


Diagram of spinning head for 'melt spinning' of PACN with plasticiser.

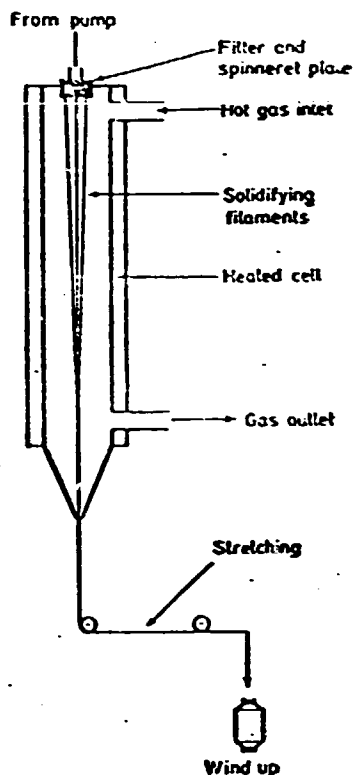
Due to the high speed at which melt spinning can be normally performed up today, the fiber manufacturing process is interrupted at the primary take-up point. In producing monofilaments or multi-filament yarns the unstretched product is wound on bobbins or similar take-up elements or in case of manufacturing staple fibers collected in cans. In a second processing step, which is mostly performed at much slower speed, mechanical and thermal after treatments are undertaken, leading to molecular orientation along the fiber axis and improving the physical properties of the fibers. This after treatment consists of 2- to 6-fold drawing of the melt spun fibers, followed by heat setting and tempering treatments. In some cases the fibers are also texturized to enhance bulk, cover and wear comfort. Details of these treatments will be dealt with in later lectures, describing the manufacture and use of viscose, polyester, and polyamide fibers.

The principles of dry spinning:

A number of fiber-forming polymers can not be melt-spun because they decompose on heating before, or close to, the melting temperature. These polymers, such as cellulose acetate, polyacrylonitrile, etc., may be spun from solution by either the "dry" or the "wet" spinning process.

In the dry spinning process a concentrated polymer solution is extruded through the holes of a spinneret in most cases vertically downward into a spinning shaft in which a current of hot gas usually flowing parallel to the extruded gel filaments evaporates the solvent. The principle of dry spinning is illustrated schematically in the following Figure No. 10.

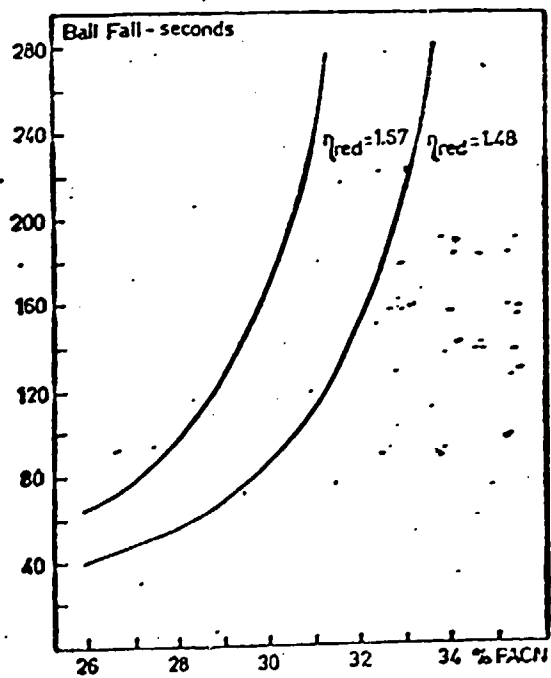
Figure No. 10:



Scheme of a dry spinning process

The spinning dope used in dry spinning should be highly concentrated to assure good fiber formation and to minimize the quantity of solvent to be evaporated and recovered. There are, however, practical limits to the concentration of polymer solutions, as can be seen from Figure No. 11 showing the increase in viscosity of polyacrylonitrile solutions with increasing concentration.

Figure No. 11:



Concentration-dependent viscosity of PACN-dope

A solution which is too concentrated may have highly visco-elastic, jelly-like properties, thus giving rise to cohesive fracture in extrusion under tension and be difficult to pump.

The preparation of homogeneous concentrated polymer solutions is in many cases not easy. When handled in the wrong way the particles of the solid polymer can form a solvent-swollen congealed mass which restricts penetration by further solvent inhibiting dispersion and dissolution. The proper technique asks in a first step for proper dispersion of the polymer powder in the solvent under non-swelling conditions, such as in the case of dissolving polyacrylonitrile the application of temperature is near or below 0° C for the dimethylformamide solvent. Mechanical stirring and heating the solvent is then used to complete dissolution. When the polymer is sensitive to oxidation air may have to be excluded to prevent degradation or discoloration.

Generally, spinning solutions for dry spinning should be as high in concentration as practically possible. The practically experienced range lays between 15 % and 35 % depending on the polymer used.

The ideal solvent for dry spinning should be thermally stable, inert and non-toxic and have a low boiling point and a low latent heat of evaporation. It should be a technically in large quantities produced and cheaply sold product. Good recovery for recycling in the process should be possible. The recovery rate is very essential for the economies of a dry spinning process.

The properly prepared solution has to be filtered to remove gel particles or other solid impurities, and degassed to clear from air bubbles or other evaporable impurities. To reduce viscosity in order to make pumping and filtration easier the spinning dope will be heated to elevated temperatures.

The thus prepared dope is metered by gear pumps to the individual spinning positions and pressed through spinneret holes. In dry spinning these normally round holes are generally somewhat smaller than in melt spinning, namely from 0.1 to 0.3 mm in diameter and 1 to 3 mm in length.

The spinning positions including filters, spinneret and the guide system for the hot spinning gas, are assembled in a common unit, the so-called "spinning head" and are heated by circulating liquids or vapour, such as water, steam or for higher temperatures steam of high boiling liquids, i. e. azeotropic mixture of diphenyl and phenoxybenzene.

In dry spinning the filaments are extruded downwards into a heated tube, the so-called "spinning chimney".

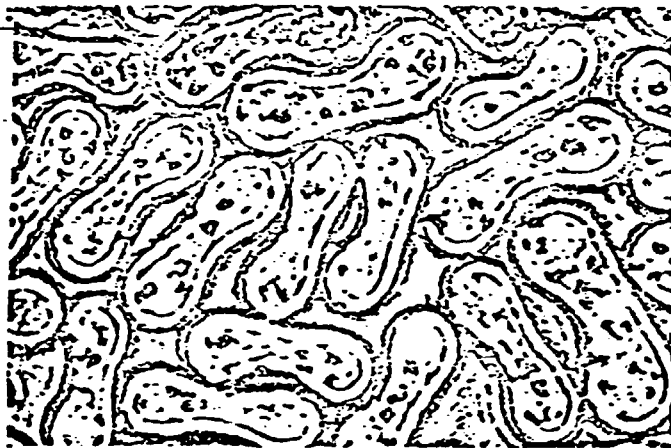
Here they are exposed to a circulation current of hot gas which runs the same directions as the spinning filaments. The hot gas evaporates the solvent from the surface of the spinning gel filaments. Hot air or an inert gas, such as nitrogen or steam are used. When air is used great care is needed that the concentration of the solvent vapour does not reach the explosion limit.

The temperatures of the spinning dope and of the hot gas are chosen to match the physical properties of the solvent and to provide optimum spinning conditions with respect to the solidification of the spinning gel filaments. In spinning cellulose acetate from acetone the spinning dope temperatures at the spinneret of approx. 55 to 60° C and of the hot gas of about 95 to 100° C at the gas inlet and approx. 60° C at the gas outlet are commonly used. For acrylic fibers from dimethylformamide the corresponding temperatures might be 110 to 130° C for the spinning dope temperature, 250 to 300° C for the hot spinning gas at the inlet and 130 to 150° C for the spinning gas at the outlet.

Very important in dry spinning is to choose conditions under which the solidification of the surface occurs in a not too far distance from the spinneret face in order to prevent the clueing together of individual filaments should they touch each other under unstabilities of the spinning process which in practice can not be completely avoided. On the other hand the solidification should not lead to a too dense skin in order to allow solvents from the inside to diffuse to the surface and to be removed by evaporation. Furthermore, too fast and too complete solidification producing a hard skin of solid polymer can effectively interfere the extensibility in drawing. Evaporating of the solvent from the surface the core of the filament remains still liquid or gel-like. The diffusion of the solvent to and through the surface skin reduces the volume of the core and causes the skin to fold giving an irregular fiber cross-section. The result of this is practically

a flattened "dog-bone" section, when circular spinneret holes are being used (cf. Figure No. 12).

Figure No.12



"Dog-bone" cross-section of dry-spun fibers

Also in dry spinning non-circular spinneret holes can be used. In order to retain any imposed shape the skin must be formed in such cases very rapidly.

After proper solidification the filaments coming from the spinneret can be made to converge at some point down the spinning tube. Spin finish is applied when the filament bundle leave the spinning chimney and the filaments either wound on bobbins or other take-up elements in the case of production of monofilaments or continuous filament yarns. In case of staple fiber manufacturing filament bundles coming from various spinning positions are collected to a thicker cable and stored in spinning cans.

The take-up speeds for the freshly spun fibrous materials are in dry spinning at the take-up or collecting point in the range of 500 to 1000 m/min. The ratio between the extrusion



speed and the take-up speed is mostly in the range of 1 : 5 up to 1 : 10.

The freshly spun and wound up monofilaments or filament yarns or the freshly spun cables, stored in cans, retain in most cases till small quantities of the solvent which has to be washed out in the following after-treatment. The after-treatment of dry spun filaments has also here the purpose to establish by drawing a proper degree of molecular orientation along the fiber axis, to eventually crimp the fibers, and to heat set the fibers to prevent dimensional changes in use. Also in the case of dry spinning the equipment necessary for the after treatment is completely different whether one produces monofilaments or continuous filament yarns or staple fibers.

The principles of wet spinning:

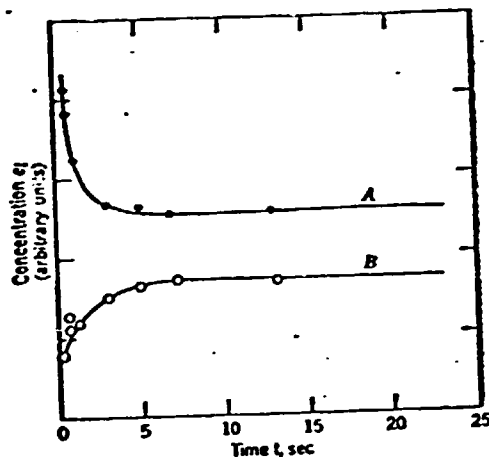
The wet spinning process starts with the preparation of a concentrated polymer solution which is properly degassed, filtered, and metered accurately to spinneret assemblies. The fluid jet emerges usually horizontally into a liquid spin bath, which is miscible with the fluid in which the polymer is dissolved but being either a non-solvent for the polymer or being a coagulant.

The preparation of the spinning dope follows the same general principles discussed before in describing dry spinning procedures. The spinning dope for wet spinning has generally not as high

concentration as in dry spinning. Normally it contains about 5 to 25 % of polymer depending on the nature of the latter. The orifices of the spinneret are in wet spinning generally smaller and range from 0.05 to 0.2 mm in diameter.

The jet of polymer solution leaving the spinneret hole and coming in contact with the coagulant spin bath is undergoing a solvent/non-solvent interchange (cf. Figure No. 13).

Figure No. 13:



Time-dependent composition of a wet spun PACN-fiber  
A = concentration of solvent (DMSO)  
B = concentration of precipitating agent (Butanol)

Solvent diffuses out from the surface, and non-solvent diffuses into the coagulating gel filament. A thin surface film of polymer gel is formed very rapidly. Continued exposure to the non-solvent causes phase separation and as the two way diffusion proceeds, the gel layer thickens through to the center of the fiber.

In case of spinning viscose rayon yarn or staple fibers the spin bath contains aside the coagulant of sodium sulphate solution also the chemical reagent sulphuric acid causing

regeneration of the cellulose xanthate back to cellulose. Here the fiber formation is a combination of coagulation and of chemical reaction.

In wet spinning, as in other spinning technologies, the filaments must be given uniform treatment if good quality products are to be spun. Fresh and sufficient supplies of spin bath must be provided to all places of the spinneret face. This is especially important in staple fiber spinning where spinnerets with up to 100.000 holes are in use.

Special positioning pattern of the holes in the spinneret plate or combination of small spinnerets in one assembly plate are being used. The spinneret plates do not have to stand up very high pressures and are made of relatively thin metal sheet material. In same case, as in viscose fiber spinning, they have to withstand corrosive liquids and are therefore made from gold, platinum or tantalum alloys.

For practically all commercial fibers spun by wet spinning technology water is used as major ingredient of the spin bath. Spinning from an organic solvent straight into water, however, can cause too rapid precipitation of solid polymer leading to difficulties in achieving adequate mechanical properties by drawing. Therefore, in most cases solutions of the polymer solvent in water are used as spin baths to delay coagulation and gelation. When acids or inorganic salts are used to cause and enhance coagulation the concentration is the controlling factor for precipitation and solidification.

The actual path length of the freshly extruded filaments in the spinning bath can be quite short, often less than one meter. The temperature of the spinning bath can vary depending on the type of polymer-solvent system and the optimum conditions of coagulation and solidification necessary for achieving the desired fiber properties. Normally, spinning bath temperatures between 20° and 50° C are used.

Following the coagulation and solidification in the spin bath, often additional baths are used to complete the hardening process, or when chemical reactions are involved to complete these reactions, and to wash out residual solvent or reagents.

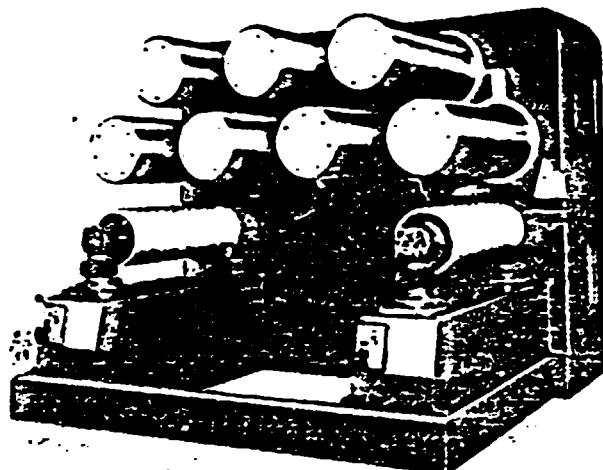
As long as the freshly formed filaments are still in a gel state, the bath liquid should be supplied without turbulent flow so that the extruding filament assembly is steady and individual filaments do not rupture or touch each other until solidification is sufficiently advanced.

After filament formation and sufficient solidification the filament cables are taken from the spinning bath and submitted to an one- or multistep stretching treatment orienting the fiber-forming polymer molecules into and along the fiber axis. This stretching treatment can either be carried out in air or in liquid bath often at elevated temperatures. The drawing is usually performed in monofil or multifilament yarn spinning between two rollers rotating at different speeds; in staple fiber spinning the filament assemblies coming from various spinning positions are combined to cables of several

millions of filaments and stretched between roller assemblies each consisting of 3 to 7 rollers (cf. Figure No. 14).

Figure No. 14:

SEVEN-ROLLER DRAW STAND OF SUPERHEAVY CONSTRUCTION WITH PNEUMATICALLY OPERATED ROLLERS



In the freshly spun state the filaments are still swollen by solvent/non-solvent liquid mixture, which plasticises the polymer molecules or fibrils increasing their mobility. The stretch ratios normally applied range in practice depending on the type of polymer system from 1 : 1.5 up to 1 : 5.

The spinning speeds in wet spinning are restricted by the considerable viscous drag on the gel filaments in the spin bath liquid and by the time needed for coagulation and solidification. Since the solvent/non-solvent exchange is widely a diffusion controlled process spinning speed is, to the speeds of melt or dry spinning, comparably slow and ranges mostly between 10 to 100 m/min.

For economic reasons, solvents and chemicals used in wet spinning have to be recovered and recycled in the process from the spinning solution and from washing and after-treatment baths.

The principles of film-to-fiber processes:

The direct way to produce man-made filament or staple fibers by extrusion of a polymer spinning dope or melt through small spinneret holes is well known and widely applied. If during the last two decades a large number of industrial companies and research institutions began to study the possibilities of producing fibrous products by the way of polymer films, there must be a special reason for this. Such reasons are mainly the relatively lower investment costs of film extrusion equipment, the possibility of performing fiber production in a one-step-operation, the relatively low processing costs and some special properties of the fibrous product obtained by this way.

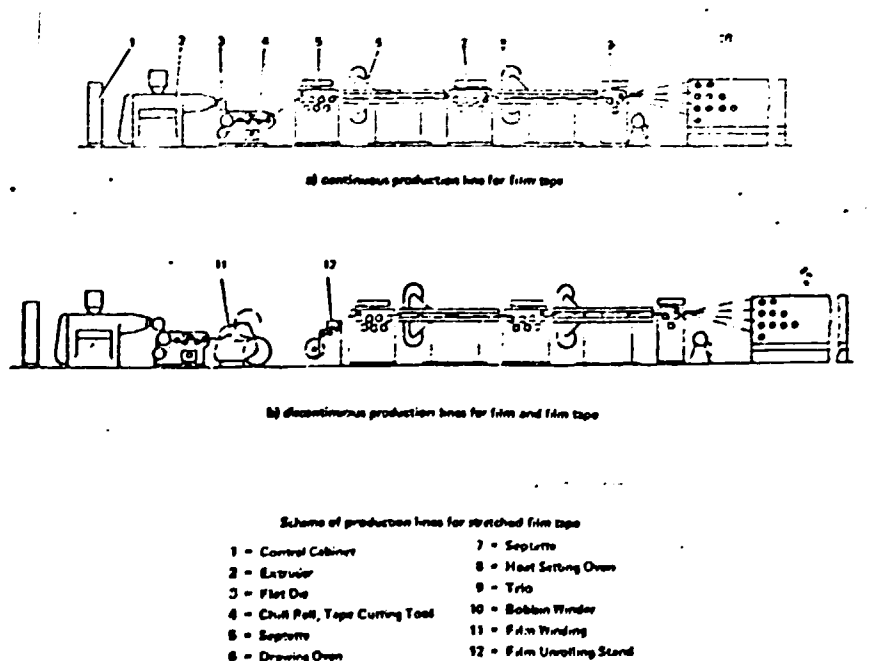
Film-tape and film-tape products: The first steps towards the production of fibrous products suitable for textiles and related uses by the way of polymer films was the development of film-tapes or ribbons. Until the early fifties, the production of film-tapes or ribbons was limited to paper or to film from regenerated cellulose, polyvinylchloride and polystyrene. However, these materials yield products of too low tensile strength or unsatisfactory wear properties and were thus in no way competitive to hard fibers, such as hemp, Manila or Sisal, or they were too high in price in order to compete successfully in most fields of application, such as for binder-twine, ropes or mats.

However, when in the early fifties the high density polyethylene and the isotactic polypropylene came into commercial reality, the situation changed completely. These polymers, being relatively inexpensive and having good cristallization and orientation ability, gave excellent films. Due to their limited tendency to develop intermolecular bonds or forces, highly orientated films from these polymers show high anisotropy of strength and can be easily cut into tapes or ribbons or slit into fine capillaries of high longitudinal strength. A further advantage of the polyolefines were their relatively low density.

In a matter of a few years, a large number of companies, involved in the production of strings, ropes and mats, as well as involved in extrusion equipment manufacturing, developed processes and machinery for the production of film-tape and film-tape products.

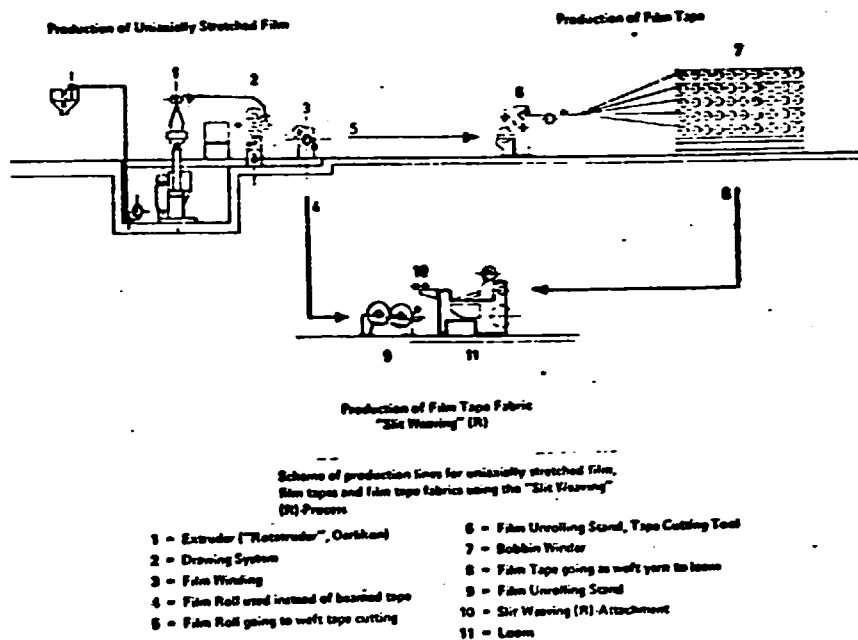
In principle, the processes for film-tape manufacturing can be dinstiguated into:(cf. Figure No. 15):

Figure No. 15:



- a) Processes, where tape cutting is done before the stretching operation, and
- b) processes, where tape cutting is done after the film stretching (cf. Figure No. 16).

Figure No. 16:



An interesting possibility was shown during the last years in the development of the new Slit-Weaving<sup>(R)</sup>-process, for which uniaxially stretched film is applied directly on the loom in conjunction with a tape cutting device, producing a warp tape directly on the loom, as illustrated in the lower part of Figure 16.

Film-Yarns and fibers: The idea, of going a step further, namely producing fine filaments or fibers by the way of the film is not new. The pioneering work for filament and fiber processing by the way of polymer films was already done at the beginning of the fourth decade of this century by Heinrich Jacqué et al.



Jacqué and his coworkers had observed that films of polyvinylchloride or of polystyrene, being monoaxially stretched at elevated temperature to high draw-ratios, gave materials of high orientation and high strength in the direction of draw. At the same time these films show strongly reduced tensile strength in the cross-direction, splitting easily when exposed to mechanical actions, such as brushing, rubbing or twisting.

Somewhat later, a closely related process for the production of fibers from polyvinylidene films was developed in the United States of America. At the same time, O. B. Rasmussen started his very interesting work on film-fiber processing, which has given remarkable stimulation and a large number of useful ideas to the further development of textile yarn and fiber manufacturing by the way of film.

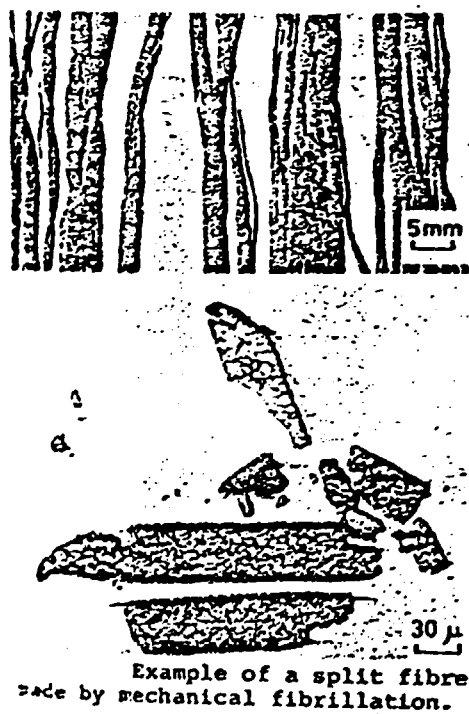
In the last decade, a large number of machine and fiber manufacturers (i. e. in Great Britain, Japan, Germany, the USA and many others) have independently developed film, yarn and fiber processes and machinery performing such processes.

In accordance with the principle characterizing film-to-fiber separation, one can distinguish three main types of film-to-fiber processes:

1. the processes, applying random mechanical fibrillation,
2. the processes, applying random chemo-mechanical fibrillation, and
3. the processes, applying controlled mechanical film-to-fiber separation.

Among the processes, applying random mechanical fibrillation, all processes can be listed, in which the polymer film is separated by purely mechanical action, such as brushing, rubbing, twisting, air-jet treatment, and others. The main prerequisite for the application of these means for fibrillation, is the creation of high tensile strength anisotropy by applying high draw ratios. Furthermore, polymers have to be used, such as polyolefines, which have due to their chemical structure no or only limited tendency to form secondary bonds between the individual molecules. The resulting yarn-like products have in most cases a network-like texture and a very wide distribution in fiber length, fiber thickness or cross-section of the fiber segments, such as illustrated by the Figure No. 17.

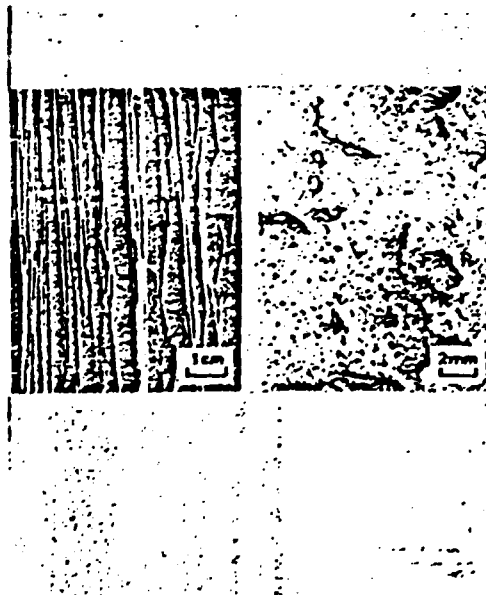
Figure No. 17:



Products of this type are mainly used for the production of binder-twine, cords, ropes, mats or nets.

Among the processes, applying random chemo-mechanical fibrillation, all processes can be summarized in which additions are made to the polymer, introducing statistically distributed inhomogenities into the film, acting in the drawing treatment as weak spots enhancing the tendency for length-wise splitting. Such additions can either be compounds decomposing at the extrusion temperature forming gases leading to voids in the film. Also the use of soluble salts added to the polymer has been suggested. Another way to introduce weak spots into the polymer film, is the addition of incompatible polymers. In the following Figure No. 18 an example of the texture of a split fiber yarn, produced by applying chemo-mechanical fibrillation, is given. Here also the products have network-structure and the cross-sections of the fibrous segments of the network show high non-uniformity.

Figure No. 18:



Example of a split fibre made by chemo-mechanical fibrillation.

Products, made by this way, are also applied in the manufacturing of twines, ropes, mats or nets.

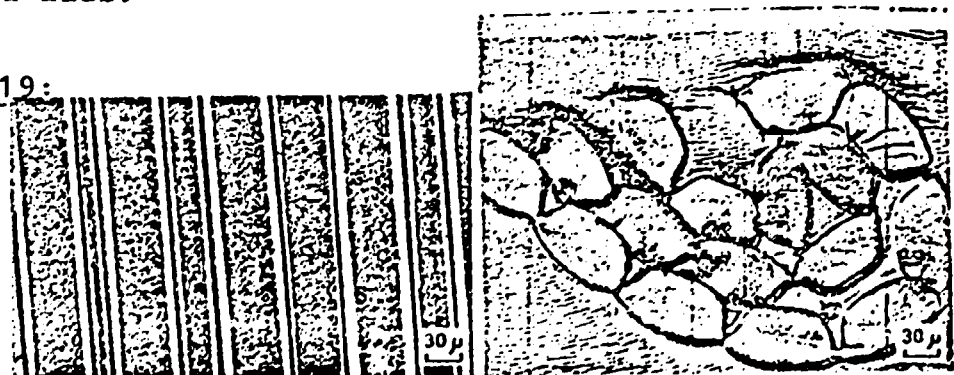
The processes, applying controlled mechanical film-to-fiber separation, use more or less accurate slitting, cutting or separation procedures, resulting in products, having more or less regular network-structure or being preferably continuously separated.

According to the basic principle of the film separation techniques applied in the controlled mechanical film-to-fiber separation, one can distinguish three methods:

- (i) The first method uses the introduction of well defined weak structures into the film with the help of profiled dies during extrusion or with profiled rollers following the extrusion. Processes, based on such means, have been developed by companies in the United Kingdom and Germany. In subsequent stretching the profiled film separates along the length grooves into more or less completely separated continuous filaments.

The following Figure No. 19 shows the cross-section through the length groove structure of a film, extruded by using profiled dies.

Figure No. 19:



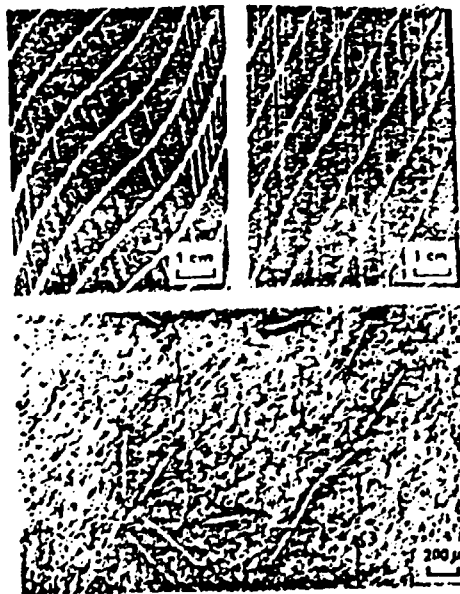
Slit fibres made with controlled mechanical film to fibre separation.

In the uniaxial drawing of the profiled film, separation into more or less completely separated filaments occurs, having very uniform cross-sections.

With the use of profiled rollers also more complicated structures, such as networks of various kinds, can be produced.

- (ii) In the second method of controlled film separation, a freshly extruded or only partially stretched film is passed through or treated with rotating needle rollers. The teeth or needles penetrate the film and slit it into more or less regular networks of defined fibers. The structure of these products can vary over a wide range from statistical networks as produced by statistic mechanical fibrillation to very regular network structures, as shown in the following Figure No. 20.

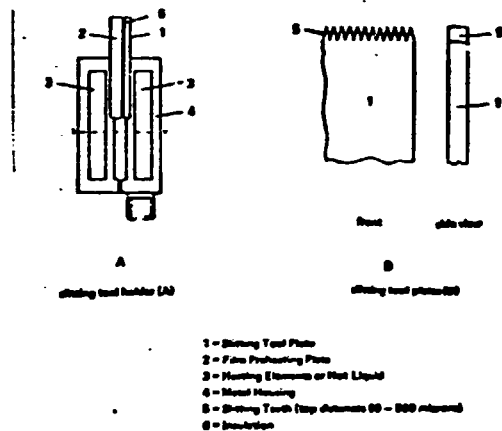
Figure No. 20:



Slit fibre yarn made with controlled film to fibre separation.

(iii) The third method of controlled film-to-fiber separation is based on the use of very fine saw-like cutting or slitting tools. An example of such slitting tool is given in Figure No. 21.

Figure No. 21:



The kind of product, obtained by such film-to-fiber separation method is shown in the following Figure No. 22

Figure No. 22:



The side view and the cross section show that the resulting fibers are very regular, approaching the regularity of conventionally spun man-made fibers. Such fibers can be profitably produced with coarse titers for technical uses and for outdoor upholstery, mats and carpets, as well as for twines and ropes.

The principle of the suspension spinning processes:

The suspension spinning method is applied whenever the fiber forming material is neither meltable nor soluble. The material can then be ground up very finely, suspended in a carrier spinning dope, such as viscose or polyacrylonitrile dope. This suspension is then spun into filaments. The carrier polymer is burned away and the fiber forming powderous material sintered to form a stable filament. Such spinning methods are used in the manufacturing of polytetrafluorethylene or of ceramic fibers.

PRODUCTION PLANTS FOR SYNTHETIC FIBERS

1. Engineering:

Barmag Barmer Maschinenfabrik AG  
Leverkusener Str. 65  
D-5630 Remscheid 11

BRD

Chiyoda Chemical Engineering &  
Construction Co., Ltd.  
Hibiya Kokusai Bldg. 2 - 3  
Uchisaiwai-cho  
Chiyoda-ku  
Tokyo 100

JAPAN

Didier Engineering GmbH  
Industrieanlagenbau  
Alfredstraße 28  
D-4300 Essen 1

BRD

Fleissner GmbH & Co.  
Wolfsgartenstraße 6  
D-6073 Egelsbach

Tel.: (06103) 4141  
Telex: 04-15 069  
04-15 021

BRD

Humphreys & Glasgow Limited  
22 Carlisle Place  
London SW1P 1JA

ENGLAND

Vereinigte Österreichische  
Eisen- und Stahlwerke -  
Alpine Montan AG  
Werksgelände  
4010 Linz

AUSTRIA

Zimmer Aktiengesellschaft  
Borsigallee 1 - 7  
D-6 Frankfurt/Main

BRD



1.1 Complete plants:

Ateliers Roannais de Constructions  
Textiles (ARCT)  
Rue Cuvier  
Impasse Champrimis  
F-42300 Roanne

FRANCE

Automatik Apparate-Maschinenbau  
H. Hench GmbH  
Ostring 19  
D-8754 Großostheim 2

BRD

Barmag, Remscheid  
see above

Blaschke & Co GmbH  
Schorndorfer Straße 24  
D-7056 Weinstadt-Endersbach

BRD

Didier Engineering, Essen  
see above

Karl Firscher  
Apparate- und Rohrleitungsbau  
Holzhauser Straße 159 - 165  
D-1000 Berlin 27

BRD

Fleissner, Egelsbach  
see above

Lurgi Apparate-Technik GmbH  
Gervinusstraße 17/19  
D-6000 Frankfurt/Main

BRD

Synthetica-Chemieanlagenbau AG  
Postfach 244  
Eptingerstr. 41  
CH-4132 Muttenz 1 (Basel)

SWITZERLAND

Zimmer, Frankfurt  
see above

1.2 Erection:

Didier Engineering, Essen  
see above

Fischer Karl, Berlin  
see above

Zimmer, Frankfurt  
see above

1.3 Consultation:

Didier Engineering, Essen  
see above

Fischer Karl, Berlin  
see above

Zimmer, Frankfurt  
see above

2. Spinning plants:

2.1 Complete plants:

ARCT, Roanne (F)  
see above

Automatik Großostheim  
see above

Barmag, Remscheid  
see above

Blaschke, Weinstadt  
see above

Didier Engineering, Essen  
see above

Fischer Karl, Berlin  
see above

Fleissner, Egelsbach  
see above

Lurgi, Frankfurt  
see above

Synthetica, MuttENZ (CH)  
see above

2.2 Spinning nozzles:

Dürener Metalltuch  
Schoeller, Hoesch & Co.  
Postfach 447  
D-5160 Düren

BRD

W. C. Heraeus GmbH  
Heraeusstraße 12 - 14  
D-6450 Hanau

BRD

Vöest-Alpine, Linz  
see above

Metallwerk Plansee AG & Co. KG  
A-6600 Reutte

AUSTRIA

2.3 Spinning heads:

ARCT, Roanne (F)  
see above

Automatik, Großostheim  
see above

Barmag, Remscheid  
see above

Blaschke, Weinstadt  
see above

Didier Engineering, Essen  
see above

Synthetica, MuttENZ (CH)  
see above

Zimmer, Frankfurt  
see above

2.4 Spinning discs:

Heraeus, Hanau  
see above

2.5 Spinning funnels:

Barmag, Remscheid  
see above

Tempelmann  
Ges. für techn. Glas  
Lütkenheiderstraße 11  
D-58 Hagen

BRD

Zimmer, Frankfurt  
see above

2.6 Reeling machines:

ARCT, Roanne (F)  
see above

Barmag, Remscheid  
see above

Blaschke, Weinstadt  
see above  
Fischer, Karl, Berlin  
see above

2.7 Spin-draw-winding machines:

ARCT, Roanne (F)  
see above

Barmag, Remscheid  
see above

Blaschke, Weinstadt  
see above

Industrie-Werke Karlsruhe Augsburg AG  
Geschäftsbereich Chemiefasermaschinen  
Gartenstraße 71  
D-75 Karlsruhe 1

BRD

2.8 Stretching mills:

ARCT, Roanne (F)  
see above

Automatik, Großostheim  
see above

Barmag Remscheid  
see above

Blaschke, Weinstadt  
see above

Didier Engineering, Essen  
see above

Fleissner, Egelsbach  
see above

Synthetica, MuttENZ (CH)  
see above

2.9 Draw-texturising machines:

ARCT, Roanne (F)  
see above

Barmag, Remscheid  
see above

Didier Engineering, Essen  
see above

2.10 High-speed winders:

ARCT Roanne (F)  
see above

Barmag, Remscheid  
see above

Blaschke, Weinstadt  
see above

IWKA Chemiefaser, Karlsruhe  
see above

2.11 Tow take-off and canning machines:

ARCT, Roanne (F)  
see above

Fleissner, Egelsbach  
see above

IWKA Chemiefaser, Karlsruhe  
see above

2.12 16-fold spinning technique:

ARCT, Roanne (F)  
see above

Automatik, Großostheim  
see above

Didier Engineering, Essen  
see above

Synthetica, MuttENZ (CH)  
see above

Zimmer, Frankfurt  
see above

2.13 Spinning pumps:

Barmag, Remscheid  
see above

"Feinprüf" Feinmeß- und  
Prüfgeräte GmbH  
Brauweg 38  
D-3400 Göttingen

BRD

2.14 Pump testing stands:

Feinprüf, Göttingen  
see above

3. Staple fiber plants:

ARCT, Roanne (F)  
see above

Barmag, Remscheid  
see above

Blaschke, Weinstadt  
see above

Didier Engineering, Essen  
see above

Fischer, Karl, Berlin  
see above

Fleissner, Egelsbach  
see above

Lurgi, Frankfurt  
see above

Zimmer, Frankfurt  
see above

4. After-Treatment bowls:

ARCT, Roanne (F)  
see above

Fleissner, Egelsbach  
see above.

5. Tow folding units:

ARCT, Roanne (F)  
see above

Fleissner, Egelsbach  
see above

6. Steaming and heat-setting plants:

ARCT, Roanne (F)  
see above

Fleissner, Egelsbach  
see above

7. Opening units:

ARCT, Roanne (F)  
see above

Fleissner, Egelsbach  
see above

8. Tow drawing systems:

ARCT, Roanne (F)  
Automatik, Großostheim  
see above

Blaschke, Weinstadt  
see above

Fleissner, Egelsbach  
see above

Synthetica, MuttENZ (CH)  
see above



