A review on process flow parameters of UHMWPE fibre production

Gyana Ranjan Behera
The Bombay Textile Research Association, L B S Marg, Ghatkopar (W), Mumbai 400086

Abstract
Ultra-High Molecular Weight Polyethylene (UHMWPE) is an advanced form of conventional polyethylene in terms of molecular weight. The primary uses of UHMWPE fibre in the military and commercial sectors for the making of rope, composite materials, and ballistic applications. The present article reviews the detailed process flow parameters of UHMWPE fibre. The characteristics of the single-screw extruder and the twin-screw extruder are also briefly discussed in the article. This review paper may assist manufacturers/researchers in diversifying their knowledge of UHMWPE fibre to improve its functionality.

Key words:
UHMWPE, single screw extrusion, twin screw extrusion

Citation
Gyana Ranjan Behera - "A review on process flow parameters of UHMWPE fibre production", *BTRA Scan* - Vol. LIII No. 1, Jan. 2024, Page no. 5-9

1.0 Introduction:

Natural fibers like silk, cotton, and wool predominantly taken the textile marketplace a century ago because of their abundance and aesthetic appeal . Later on, the synthetic fibres such as polyester, polyamide, polyolefin and acrylic, etc. came to market for their relatively good mechanical and chemical properties .The breaking strength and Young's modulus of typical synthetic fibres are often between 1 GPa and 15 GPa. These textile fibres have restricted applications in the aerospace, protective clothing, armour and advanced composites industries due to their inadequate mechanical performance . Based on the aforesaid limitations, Staudinger, proposed the fundamental criteria for manufacturing a high strength, high modulus synthetic fiber in 1932 .The most prominent type of high modulus synthetic fibre is high modulus polyethylene (HMPE), which is usually produced by gel-spinning process and termed as ultra-high molecular weight polyethylene .

On the other hand, based on the limitations of the conventional low to medium modulus polyethylene fibres or others relevance products, high performance fibre is continuing to replace the conventional polyethylene fibre as their multi-dimensional limitations.Ultra-high molecular weight polyethylene polymer, which has more significant characteristics than typical low-density and high-density PE, therefore it has recently gained attention .The ultra-high molecular weight polyethylene shows superior mechanical properties (Table 1) due to highly oriented structure linked with high molecular weight or high molecular chain length. Due to its durability, toughness, and biological inertness, UHMwPE has been utilized to substitute metal and ceramic for different applications especially for joint replacement, for past many years .The impact energy is nearly twice as high as that of para-aramid fiber, with good abrasion resistance and low friction coefficient, but the melting point under stress is only 145-160°C. On a weight-to-weight basis, UHMWPE offers 35% higher strength than aramid fibers and the lowest density among high strength fibers .

Table 1: Physical properties of the UHMWPE fibre

Sp. gravity	0.925-0.945
Melting point (°C)	132-138
Molecular weight (10^6 g/mol)	3.5-7.5
Degree of polymerisation	>110,000
Degree of crystallinity (%)	39-75
Tensile ultimate strength (MPa)	39-48
Modulus of elasticity (GPa)	0.5-0.8
Tensile ultimate elongation (%)	350-525
Impact strength (J/m of notch)	1070

2. Chemical composition of UHMWPE polymer

UHMWPE polymer is a subset of the thermoplasticpolyethylene and also there are different forms

*Corresponding author,
E-mail: uhmwpe.btra@gmail.com

of polyethylenee.g., low density polyethylene (LDPE), linear low-density polyethylene (LLDPE), high density polyethylene (HDPE), ultra-high molecular weight polyethylene(UHMWPE), etc. The aforesaid types of polyethylene are classified by degree of polymerisation, molecular weight and chain configuration of the molecules .In comparison to HDPE and LDPE, UHMWPE has an ultra-high degree of polymerisation, resulting in a molecular chain containing up to 200,000 polyethylene repeat units. Molecular weight is therefore measured in millions (Table 1), typically falling between 2 and 7.5 million .UHMWPE polymers have a low surface energy and are composed of a hydrocarbon in a linear molecular framework with no polar molecule groups on the surface .

The UHMWPE polymer in the form of fibres / filaments are predominantly used in the manufacture of various industrial applications. The detailed process of UHMWPE fibre formations is described below.

3. Stages of the UHMWPE fibre formation

As the melt of UHMWPE exhibits extreme high melt viscosity, conventional melt extrusion methods cannot be used to produce spun filaments/fibres .Therefore, In the late 1970s, Smith and Lemstra invented the gel-spinning technique for conversion of ultra-high molecular weight polyethylene (UHMWPE) polymer to fibres . The gel spinning is widely commercially accepted process for the manufacture of UHMWPE fibres. In general, the gel spinning of UHMWPE polymer takes 5 to 6 steps which includes the following steps .

a) Dissolution of UHMWPE polymer
b) Single/twin screw extrusion and spinning
c) Extraction/removal of solvent
d) Multistage drawing/drafting
e) Winding of finished fibre/filament

a) Dissolution of UHMWPE polymer

Dissolution/gelation involves dissolving UHMWPE polymer chips/granules in a suitable solvent, especially from petrochemical sources, to make a solution which is then extruded to form fibres .There are numerous petrochemical solvents can be used to dissolve the UHMWPE polymer. The investigated solvents for the dissolution of the UHMWPE polymer are in liquid paraffin, decalin, dodecane, p/o-xylene, 1,2,4-trichlorobenzene, mineral oil, naphthenic oil, tetralin, dioctyl phthalate, butyl benzylphthalate, dibutyl sebacate, trichlorobenzene, 1,2-dichloroethane, stearic acid, cyclopentane, hexadecane, diphenyl ether and kerosene, etc. . However, the decalin and paraffin oil are the most widely accepted solvents for the preparation of UHMWPE solutions .

Throughout the gel-spinning technique, a low concentration (e.g., 1 to 5% concentrations) of semi-diluted UHMWPE polymer solution is squeezed through a spinneret to produce a gel-like filament that is then quenched in a water bath, as shown in Figure 1. The detailed description of extruder is explained below.

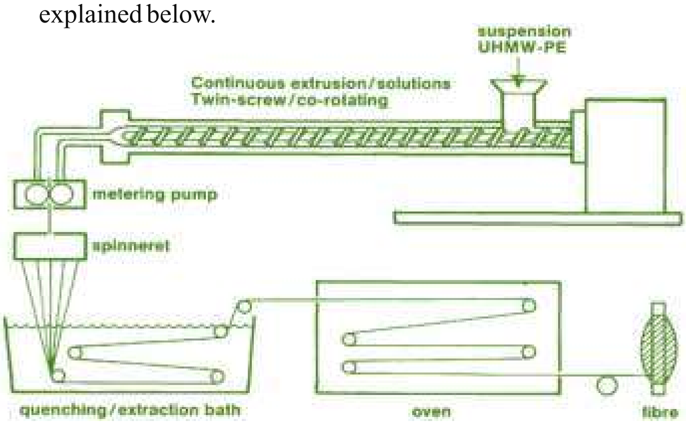

Figure 1: Schematic diagram of the gel-spinning of UHMWPE fibre

b) Single/twin screw extrusion and spinning

There are two types of extrusion systems e.g. twin screw and single screw systems, are used to convert the UHMwPE polymer gel to the required fineness of filament through tiny single/multi hole spinneret. Theoretically, elevated spinning temperature will produce more uniform dissolution of the spinning solution. Moreover, relatively high temperatures can cause the fibre to crack and reduce the viscosity of the dope. The gel spinning temperature is generally close to the polymer single crystal dissolution temperature, resulting in superior extension effects .Furthermore, the ideal spinning temperature of UHMWPE is between 150°C and 250°C and, it should be set below the boiling pointof spinning solvent.For example, the spinning temperatures UHMWPE with paraffin oil and decalin typically ranges from 130 °C to 195 °C and 125 °C to 170°C, respectively .The fineness of the fiber/filament is determined by the diameter of the spinneret and the draw ratio, nevertheless, the speed of the fiber/filament extrusion is entirely determined by the speed of the twin screw and single screw systems, which are addressed in the next section.

Twin screw extrusion

The twin-screw extruder consists of two Archimedean screws, is frequently used in gel-spinning to complete the dissolving of UHMWPE in the solvent. Because of its strong shearing effect, the mixed material's mass and heat transfer are transferred at a higher rate, which can greatly reduce the amount of time needed for UHMWPE to dissolve and create a uniform spinning solution even for higher gel solution concentration .When used in compounding, twin-screw extruders (TSE) usually operate at screw speeds between 200 and 1000 rpm . The typical zones of twin screw extruder are shown in Figure 2 wherein Zonal components divide several unit processes that run in the length of the shaft .The initial and final zone helps to convey the materials however, the middle zone signifies that the material is evenly mixed and subsequently processed before leaving the mixing area.

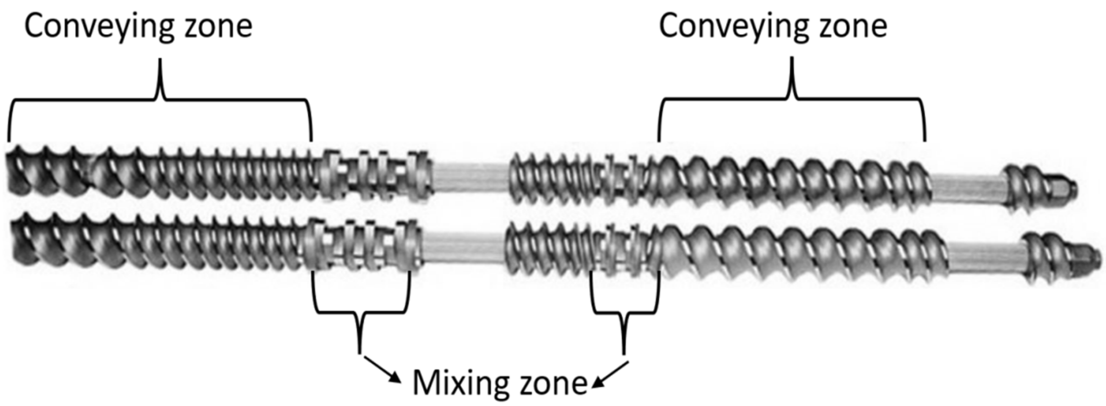

Figure 2 A typical diagram and different zones of twin screw extruders

Single screw extrusion

Single screw extruders (SSE) are constructed of solely one Archimedean screw as an extruder (Figure 3) that operates at screw speeds ranging from 50 to 150 rpm . There are two primary flow channels in the single screw extruder, the first is the solid conveying channel and the second is transition/melting channel, as shown in Figure 2. Furthermore, many high-performance screws include the metering zone .

The UHMWPE solution in the feed section move with the revolving screw of a single-screw extruder. Furthermore, due to its low coefficient of friction between the metal and the UHMWPE solution, it is difficult for UHMWPE solution to be pushed forward. As a result, in 1971, the Mitsui Petrochemical company created a special single screw extruder with gradient grooves in the barrel to stop UHMWPE from slipping while being extruded. The grooves' depth and width are progressively getting narrower in the direction of extrusion, which is advantageous for applying pressure .Many more customized single screw extruders are being developed to overcome UHMWPE delivery difficulties. However, such extruders just raise the coefficient friction between the polymer and the barrel without changing the conveying mechanism, resulting in increased screw and barrel wear, driving load, and friction heat. Currently, the most practicable processing device for UHMWPE is a single screw extruder with a large thrust screw and specific screw constructions to enhance conveying capability, considering its high energy consumption .

c) Extraction/removal of solvent

The extraction of gel fiber is critical in gel spinning. An appropriate extractant can lessen the effect of solvent residuals on gel stretching. Natural drying and the use of extractants are recognized as effective methods for removing solvents, which leads to the reduction of solvent residues in the gel fiber. Based on diffusion and penetration principles, the extractant can displace the gel fiber solvent .

In the case of volatile solvents, evaporation is normally performed at high temperatures to remove the solvents from the gel filaments. However, non-volatile solvents, such as paraffin oil usually show difficulty during its removal and recovery from the gel fibre. Considering that this type of spin solvent does not evaporate easily, the gel form filaments are often immersed in a secondary solvent with a boiling point lower than the UHMWPE gelling temperature . The secondary solvent e.g., n-hexane which typically has a boiling point of less than 100 °C

d) Multistage drawing/drafting

It has long been understood that the final tensile characteristics of polymeric materials are determined by the molecular weight as well as the extension together with the alignment of the macromolecules .The aim of the hot drawing process is to produce a high draw ratio while producing fibers with the smallest possible diameter .After drawing, the solution spun filaments have outstanding mechanical properties, with tensile strength and Young's modulus in the range of 3.0 GPa and 90 GPa,

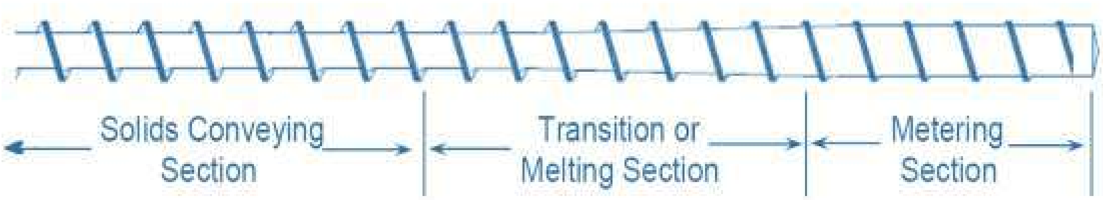

Figure 3 Typical zones of single screw extruder

respectively .During the drawing process, the crystal tends to get longer in the direction of the drawing and gets shorter in the transverse direction. As a result, larger UHMWPE crystals in the as-spun fiber will provide greater elongation, which will enhance the mechanical qualities of the fiber .Since the UHMWPE solution contains a substantial quantity of solvent in the gel stage, ultra-drawing is required to produce the ultra-high strength and modulus fibre .Usually, multistage drawing of 3 to 4 stages is used for UHMwPE polymer extrusion . In the beginning of high temperature drawing stage, microscopic voids mostly appear in the lamellar stack. As the high temperature drawing process starts to maximise the high draw ratio and high temperature (110 °C to 130 °C), the microvoids are destroyed by the process of melting and recrystallization. .The optimum drawing temperatures for gel spun UHMWPE fibers ranged from 80 °C to 148 °C .In the case of low temperature, the molecular chains cannot be pulled sufficiently to achieve high strength, and if the temperature is too high, the fiber may melt .

e) Winding of finished fibre/filament

Usually, the obtained filaments or fibres are wound on a bobbin to store or transport it. Moreover, past study indicates that if the extrusion and winding speeds are not synchronized properly, the tensile strength may drop as the winding speed increases . Therefore, the optimum speed of winder should be maintained based on the delivery rate of fibre/filament.

4. Applications of UHMWPE

Owing to their high-performance characteristics, these polymers find application in harsh environments such as food processing, rope making, medicinal materials, and many military and civil applications including composites and ballistic applications . Because UHMWPE fibers have unique functional characteristics including high tensile strength, high modulus, low density, ability to absorb energy, high wear, and cutting resistance, they are widely employed in high-tech industries such as aerospace, safety protection, military and national defence . The UHMWPE polymer in the form of fibre composite is widely accepted in the field of bullet-proof applications and its tensile strength is believed to have the prospect of surpassing Kevlar fibre composites in the future . Since the UHMWPE polymer exhibits excellent intrinsic properties such as biocompatibility and chemical inertness which has led to its use in biomedical applications .The low melting point of UHMWPE (130°C-136 °C) limits its use in medical applications, although these limitations can be overcome by reinforcing with composite materials such as carbon nanotubes .

5. Conclusions

Textiles have been doing a fantastic job in both the apparel and industrial sectors, wherein the recent focus has been more on high performance fibres and their applications. The market for one of the high-performance fibres, i.e., Ultra High Molecular Weight Polyethylene fiber (UHMWPE) is predicted to expand significantly in the future years. The UHMWPE fiber has a variety of uses, nonetheless, it is often used in protective applications such as ballistic, cut-resistant, and defence or military applications. The vigorous research with the understanding of the concept of UHMWPE polymer and its spinning is essential. The current article concisely discussed the chemical composition of UHMWPE polymer and the methods involved for the conversion of polymer gel to fiber/filament including the potential applications of UHMWPE. The UHMWPE polymer is chemically composed of polyethylene molecules with longer molecular chains, resulting in ultra-high molecular weight. The linear ultra-high molecular chain length is responsible for higher fibre strength, modulus and high impact resistance.

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