Study on Co-extrusion Process using Die of Multi — Orifice for Plastic Optic Fiber Production

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Abstract

This paper introduces the process and technology of co-extrusion using die of multi-orifice for plastic optic fiber production. The performance requirements for core and cladding materials used in the process, the features of co-extrusion die, the way to design stretching and winding devices as well as the matching and optimizing of process parameters have been discussed in the paper. The paper has also studied some factors having effects on the properties of plastic optic fibers with polystyrene core.

Key words: plastic optical fiber, co-extrusion, polymer,

I. Introduction

POF is the short for plastic optic fiber or polymer optic fiber. In 1966, first type of POF product named Crofon with PMMA core was introduced to the market by Dupont. The development in the past about 40 years was aimed at some major disadvantages of POF, such as high transmission loss, low thermal resistance and narrow band width. Now various series of POF products including GI type POF, single mode POF, fluorescent POF, non-linear POF, etc. have been developed, which are widely used in the fields of light and image transmitting, sensing, and information transmission in short distance. The most typical method of POF is so called continuous ploymerizing & co-extrusion process developed by Mitshubishi Rayon Co.

Besides the above applications, POF is also largely used in illuminating, advertising, decorating, and art and craft making, and low cost POF with PS core is mostly used in such applications. So far, the total estimated value of China national market is over 1 billion Yuan. A continuous co-extrusion and coating process for making POF developed in the earlier 90 s of last century by Nanjing Fiberglass Research & Design Institute has become an ordinary method for making POF with PS core. As the rapid expanding of market demand, the drawback of the process becomes more obvious. To develop a new process with high efficiency and flexibility for POF commercial production has become an urgent subject. In view of this, a few years ago Nanjing Fiberglass Research & Design Institute began to develop a process using

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co-extrusion die with multi-orifice for POF industrial production.

II. Contents of Research

2.1 General Train of thought

The typical flow of co-extrusion fiber forming process for step index POF is shown below:

core material → core extruder _

co-extruder die → fiber-diam. Control_

pre-treatment cladding material → cladding extruder _

_stretching → winding → cutting & packing → inspecting & storing

From the above flow diagram, it can be seen that separating of core and cladding materials and coating are all done inside the co-extrusion die in order to form SI type POF. Since polymer fiber forming process is restricted by critical shear stress, and die pressure drop, the factor determining fiber forming quality, formed at die orifice, the extrusion process using single orifice die will have significant pressure drop, which shall cause polymer distortion, so co-extrusion process with die of multi-orifice becomes an inevitable choice for making POF efficiently.

The advantages of the co-extrusion process using die of multi-orifice are as follows:

·Various disturbances in the process can be effectively eliminated, and POF production of high efficiency and stability can be achieved.

·Due to its relatively lower drawing speed, it s possible to use some simple cooling methods such as blowing cold air to set the fibers, which also facilitates some simple and effective post treatments, such as POF coloring, surface finishing etc.

·By using die assembling technique, different kinds of products can be made, so the production becomes more flexible.

·The use of acetic acid, normally used as solvent for cladding coating, is avoided so the intermediate waste and contamination is significantly reduced.

2.2 Material study

In order to establish the light transmission path of optic fiber, highly transparent material must be used. Co-extrusion forming process requires that under the same temperature core material be coated with cladding material inside co-extrusion die and then both of them concurrently extruded through the co-extrusion die. Since different types of materials differ in melt index, processing temperature T and pressure P, viscosity _, critical shear stress _$_c$, stress relaxation time, orientation under stretching, etc. and also in curves of viscosity-temperature (_-T) and viscosity—pressure _-P, the emphasis of material study should be put on the matching of the two type of materials in terms of optical, thermal, mechanical and processing properties.

Optical property: in order to establish light transmission structure, a refractive index difference _n must be met by the two highly transparent amorphous polymers used in the process. To insure a proper purity of PS core material, the material should not include any additives such as fluorescent whitening agent and the like, so the optic fiber with smooth transmittance spectrum of visible light can be obtained.

Thermal property: Both PS and PMMA should have close melt temperatures and similar _-T curves within the range of processing temperature.

Processing property: the materials for making POF should meet the requirements of mass production and fast fiber forming, i.e. the fiber forming property of PS and PMMA must be perfect. For this reason, PMMA with narrow profile of molecular distribution, less content of low molecular portion and good material evenness is preferred.

Mechanical property: the requirements of the finished product must be met.

Properties of finally selected materials are shown in Table 1:

Table 1. Properties of cladding and cord materials

Type		Polystyrene 685	Oroglas V044
Manufacturer		Asahi	Rohm
Package weight		25 kg	25 kg
Property	Testing method	Data	
Refractive index	ASTMD-542	1.59	1.490
Melting index	ASTMD-1238	2.3g· 10 min $^{-1}$	2.5g· 10 min $^{-1}$
Light transmittance	ASTMD-1003	88%	92%
Vica softening point	ASTMD-1525	106°C	106°C
HDT	ASTMD-648	85°C	88°C
Glass transition temperature	ASTMD-3418	102°C	104°C
Tensile strength	ASTMD-638	580kg· cm $^{-2}$	640kg· cm $^{-2}$
Elongation at breaking point	ASTMD-830	2%	2%
Impact strength	ASTMD-256	1.1	1.2
Water absorption	ASTMD-570	0.02%	0.3%

2.3 Co-extrusion die

Co-extrusion die is the key to execute co-extrusion process successfully. The design of co-extrusion die is theoretically based on the analysis of pseudo plastic fluid and viscoelasticity characteristics of polymer materials.

2.3.1 Characteristics of pseudo plastic fluid

In the process of extrusion, polymer fluid is subject to pseudo plastic fluid index law under a certain temperature (shear stress is applied to two parallel laminar surfaces of a fluid, having a distance of dr and moving in a relative velocity dv):

$$\tau = k \left(\frac{dv}{dr}\right) = k\gamma$$

Here, dv/dr (i.e.γ) is the shear rate, k and n are the constant (n<1), k is the measurement of consistency of the fluid. The thicker the fluid, the higher the k value is. n is used to tell the difference between the fluid and Newton fluid. The more deviates from 1, the fluid shows less characteristics of Newton fluid. To obtain a stable laminar flow of the fluid, both materials and die should meet some special requirements. When designing a co-extrusion die and its related key parts, the initial consideration is to keep the evenness of both temperature and pressure based on the principle of equivalence of temperature-pressure. Besides, the characteristics of raw materials have to be taken into consideration in order to realize full plastisation, optimum separating and stable coating inside the die. The structure of co-extrusion die used in the study is shown in Figure 1.

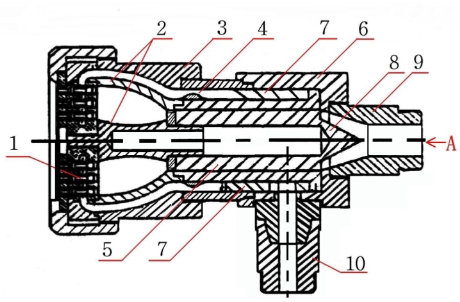

Figure 1 Schematic of Co-extrusion die
1. Forming nozzle 2. Separating cone 3. Forming part of the die 4.Flow path of cladding material 5. Flow path of core material 6, Die flow path 7. Equaling block for resistance 8. Static mixing mandrel 9. Jointing sleeve for cord material 10. Jointing sleeve cladding material,A. Feeding direction of core material B. Feeding direction of cladding material

The following discussion is focused on how to achieve a stable movement of laminar flow by referring to the above structural schematic of the co-extrusion die.

(1). Radial temperature difference _T.

From the above schematic, it can be seen that the co-extrusion die orifices are arranged in concentric circles, of which center is the die central axle, which makes the radial diameter of the whole extrusion die bigger. Since electrical resistance heater is often used for heating, and thermal conducting is the main way of heat exchange, it s impossible to avoid temperature difference _T in radial direction. Through the study, it is known that when _T > 4_, the laminar flow rate of high viscosity melt becomes unstable. In order to avoid too high _T of the material in cylindrical flow path, a static mixing mandrel is designed and put into the regular cylindrical flow path of polystyrene. Mandrel is a solid die with positive-negative spiral grooves, through these grooves PS material is separated many times, and _T between laminar layers is reduced. To prevent forming diversity caused by helical flow of melt, the end of mandrel must be designed to a multi-orifice plate structure, which shall cause the melt flow in straight line. While _T is reduced, the melt flows through the mandrel of relatively longer length and a better plasticizing is achieved by static mixing, which could be considered as the increase of L/D of the extruder. The function of the static mixing mandrel inside flow path is so important to PS that can not be substituted. Since a higher extrusion back pressure is applied to PS melt by static mixing mandrel, the plasticizing is further improved. As a result, the bending strength of optic fiber is increased obviously.

(2). Heating and temperature field:

Electrical resistance heater made of stainless steel was used in the study. In order to reduce shear stress applied to PS in statistic mixing mandrel and the pressure drop, the die temperature field was divided into two zones, i.e. flow path zone and forming zone of die orifices, of which temperature were controlled individually to insure a reasonable temperature gradient. The temperature of flow path zone generally is 6-8_ higher than in the zone die orifices. A proper temperature field is related to heating power. The heating power can be calculated by an experimental formula:

$$N = GC\,(t - t_o) / 3600\,\eta \cdot \tau$$

Where, G: mass of extrusion die mass, kg,

t: working temperature of extrusion die, °C,

η: heater s efficiency, generally between 0.3 — 0.5,

C: specific heat capacity of the die material, kj / kg · °C

t_o: initial temperature of extrusion die, set at 20 °C

τ: heating time, h.

(3). Position and method of temperature control:

The position should be close to flow path or forming zone and a temperature control system with PID self-setting function was provided. The fluctuation of heating temperature should be ≤±0.5_ and the radial temperature difference (_T) of the die ≤±2_.

(4). Evenness of pressure:

The flow direction of PMMA melt is at a right angle (90°), with that of PS melt. The melt flowing in a regular cylindrical path encounters uneven resistance in the flow direction, which results in uneven pressure. So a resistance equaling block was used and arranged in the path, of which function is to apply additional resistance to PMMA. In the study a lot of work was done for eliminating dead corners of flow path

2.32 Characteristics of viscoelastic fluid

The characteristics of viscoelastic fluid include the behaviors of polymers during extrusion process, such as inlet effect, expansion effect at die orifices and melt fracture, etc., which are related with the design and correction of the orifices of the co-extrusion die:

(1). Inlet effect.

As the polymer melt flows into the entrance, a secondary annular flow will be formed in the area of die orifices. Under high speed shearing, a not proper inlet angle α will make the secondary annular flow of the polymer fluid more violent, resulting in unstable forming process. Based on material characteristics and experiments the entrance angle of the die orifices has been set at 60¡.

(2) Expansion effect at the die orifice.

The polymer fluid in a high sear field will have so-called Barus effect due to flow orientation and elastic deformation of large moleculars, which results in the diameter of the fully relaxed extrudate after the die orifice bigger than that of die orifice. This expansion effect will bring about bigger residual stress in the extrudate, and, in turn, the worse optical and mechanical properties of POF.

The study has proved that the expansion effect of the extrusion die can be reduced simply by extending the length of forming zone of the extrusion die. However, the pressure drop _P of the extrusion die will be increased simultaneously, and that can have bad effect on the stability of forming process. The alternative method of reducing the dimension of extrusion die will again increase the residual stress of POF product.

By using the forming die of regular circular cone and setting the aspect ratio L/D at 6-8, and the taper of 6¡, the result was that the critical shear stress of the polymer had been effectively improved, which facilitated high speed fiber forming.

2.4 Stretching & winding devices

According to the requirements of co-extrusion fiber drawing process using multi-orifice die, stretching and winding operations should be preformed in a continuous and stable way. The design of an integrated device for stretching and winding with double collet is shown in Figure 2.

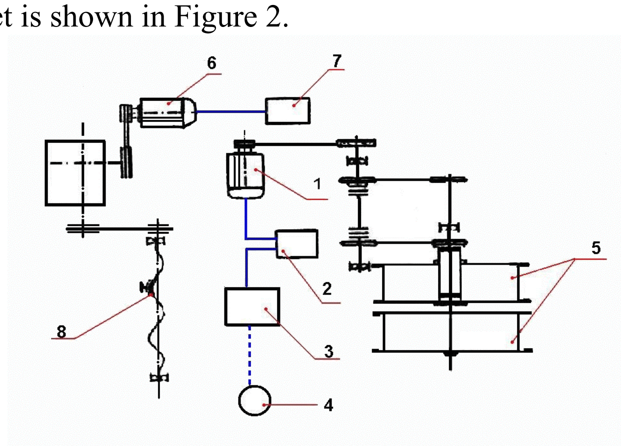

Figure 2. Driving system of stretching and winding device

1. Main electric motor 2. Frequency converter
3. Control circuit for constant linear speed 4. Hall speed meter
5. Fiber winding collet 6. Electric motor for traverse
7. Controller for rotating speed 8. Traverse

2.5 Process parameters

The perfect design of co-extrusion die ensured full plastisation and good separation of the polymer inside the die, and stable extrusion and forming of the POF while the integrated stretching and winding device ensured constant stretching tension and speed, which helped in keeping good balance of the material input and output of the process. For POF production on commercial scale, first of all, the proper extruders and assessors have to be selected. Secondly commissioning of the established production line of POF has to be done in order to determine all process parameters to insure that the final POF product with good light —transmittance and less diameter fluctuation can be produced.

(1). The extrusion equipment selection should be based on material characteristics and production capacity.

(2). In order to obtain optimized and matched parameters, process parameters should be adjusted according to different material characteristics and process features, which involves the study on the effects of temperature, stretching speed, stretching ratio, cooling temperature, etc. on the forming process. Through the study, it is known that temperature is the key factor having big influence on flow characteristics and plastisation of the polymers, and optic and mechanical properties of POF as well. The temperature of extruder itself depends on the materials to be used. However, the temperature of extrusion die is not only related to the forming quality, but also the extrusion pressure. In practice, first, a proper process temperature is chosen, and then the other parameters are adjusted and tuned in order to get a good compatibility of all parameters, which is usually verified by light transmittance, discreteness of fiber diameters and bending strength of POF, etc.

Table 2. Range of temperature parameters of co-extrusion fiber forming

Parameters	I	II	III	IV	V
Core material tempt. (°C)	175 ~185	195 ~205	205 ~210	175 ~200	170 ~192
Cladding material tempt.(°C)	180 ~190	205 ~220	210 ~230	175 ~200	170 ~192

Table 3. Range of process parameters of co-extrusion fiber forming

Core extruder	SJ4525/SJ6525 $\varepsilon = 2.8$
Cladding extruder	SJ2025 $\varepsilon = 2.8$
Core extrusion speed (kg/hr)	12 ~ 35
Cladding extrusion speed (kg/hr)	1 ~ 4
Stretching linear speed (m/min)	40 ~ 160
Stretch ratio	60 ~ 160
Max. Production capacity (kg/24hr)	900

III. Discussion

The goal of the present study on POF production process using a co-extrusion die of multi-orifice is to establish a method of high efficiency and good stability to produce POF products of different types and specifications having high transmittance and perfect mechanical properties. Our study and practice have revealed that the main

factors having effects on the final properties of POF include:
(1). Materials selected.

The intrinsic loss of optical fiber depends on the materials while the feasibility of the process also depends on them. So the essential condition for making qualified optical fiber is to use qualified and matchable core and cladding materials.

(2). Process.

Not alike coating process, the advantages of co-extrusion process lie in that the optical structure of POF is realized inside the die without the problem of coating quality. Besides, the co-extrusion method is a continuous process, in which the auto feeding of raw materials is under hermatic condition, eliminating the environmental contamination (such as dust) of POF production.

(3). Design of extrusion die.

Extrusion die is a key component for cladding and forming process of POF with desired dimensions. So, a well designed and preciously assembled die will ensure good performance of POF, which mainly include the quality and thickness of cladding, eccentricity and discreteness, and mechanic properties of POF.

(4). Process parameters.

Selecting the proper process parameters is very important to insure the balance of material input and output in the co-extrusion process. When the raw materials are chosen, the bad selection of process temperature and extrusion speed could be fatal to the quality of POF. For instance, the mechanical property of POF (i.e. bending strength) will be deteriorated by a too high temperature and on the other hand, the optical property of POF operating reduced by using a too low operating temperature.

(5). Operating regulation.

A strict operating regulation must be formulated and followed for commercial production in order to reach a high efficiency of the POF production and save materials. Besides, the raw materials have to be kept in a proper environment to ensure good quality of POF.

IV. Conclusion

After almost 3 years of trail production, it has been proved that the co-extrusion process using a die of multi-orifice is a feasible and reliable method for commercial production of POF with PS core, of which high efficiency and adaptability shall meet the increasing market demand and lead to good economic benefit.