Expert system for the optimisation of melt extruded net structures

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Net structures were produced by replacing the static die (spinneret) with two concentric dies (consisting of slots) rotating in opposite directions in a melt extrusion process. A series of net structures and filaments were produced from a square die slot shape. Similarly, a series of filaments were produced from the corresponding static square die slot using a laboratory melt extruder. The effect of die rotation on the filament geometries was investigated. Finally, an expert system was developed based on empirical observations and theoretical modelling, which allows the filament cross-sectional area and its shape to be characterised with regard to the die slot dimensions and extrusion parameters. Moreover, the net geometry has also been predicted and visualised using the same expert system.

Keywords: Die slot, Expert system, Filament, Land length, Melt extrusion, Net

Introduction

Polymers are the most rapidly growing materials in terms of use and innovations in processing technology, one of the main applications of polymers is in the production of net structures. These may be used for reinforcement, drainage, filtration or a combination of systems. The net structures are generally classified according to their production method. Punching techniques such as Tensar[1] are used for large-scale nets and grids and the production method consists of two or three stages. Here a polymer sheet has a regular series of holes punched out followed by orientation in either just the machine direction or both machine and cross directions producing the final grid. Weaving techniques, for example leno weave, may also be employed to produce the larger holes in the net structures. However, the simplest way of producing the net structure is by replacing the static die or a spinneret normally used for filament production by two concentric counter-rotating dies[2] in a melt extrusion process. In this process, polymer chips are fed to a hopper from which they pass into a single screw extruder. The single screw extruder screw has two tasks: first to melt the polymer and second to pump the molten polymer through the die head at a constant rate. The die head consists of a concentric disk and an annulus consisting of slots, rotating in opposite directions. When the slots in the disk and the annulus are offset from each other, the filaments of the net are formed. However, when the slots are adjacent, a joint is formed between the two filaments. Finally, the net structure is drawn under water and given some stretch and orientation by means of drawing rollers to produce the required net structure. This technique is mainly employed for the net structures required in geotechnical applications. This single-stage process can result in an increase in the production rate[3] and a reduction in power consumption,[4] and an improved quality of net can be achieved with the rotation of the die as the molecules of polymer align themselves in the direction of flow, thus enhancing the mechanical properties of net structure.

In a melt extrusion process, the filament shape and dimensions are mainly dependent upon the corresponding die slot shape and dimensions. However, the pressure drop and flow rate of the polymer inside the die slot also characterises the filament geometry. In the case of the rotating die system, the filament shape is also influenced by the rotational speed of the die.

Furthermore, in rotating die systems, product development has required an iterative process in the development of new dies. Generally, the die requires several modification steps or complete remanufacture before the required net structures are produced. This involves significant cost, time and labour. The development of a computer model defining the effect of die shape and rotation on the final filament properties will allow prediction of net structure from a given die slot and process parameters.

Therefore, the work reported here is the development of an expert system for computing the filament geometries under a given set of process parameters. Moreover, the net geometry was also predicted and visualised using the same expert system.

Experimental

Aim

The aim of this investigation was to develop a process model based on empirical observations and theoretical modelling, which will allow the filament cross-sectional

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Published by Maney on behalf of the Institute
Received 15 September 2004; accepted 30 March 2005
DOI 10.1179/174328905X48513

Table 1 Experimental design for rotating dies

Sample number	Die speed, rpm	Extruder speed, rpm	Take-up speed, m min^{-1}	Temperature, °C	MFI, g min^{-1}
1	1·5	25·5	2·48	195	0·035
2	4·5	25·5	2·48	195	0·035
3	1·5	50·9	2·48	195	0·035
4	4·5	50·9	2·48	195	0·035
5	1·5	25·5	5·0	195	0·035
6	4·5	25·5	5·0	195	0·035
7	1·5	50·9	5·0	195	0·035
8	4·5	50·9	5·0	195	0·035
9	1·5	25·5	2·48	225	0·035
10	4·5	25·5	2·48	225	0·035
11	1·5	50·9	2·48	225	0·035
12	4·5	50·9	2·48	225	0·035
13	1·5	25·5	5·0	225	0·035
14	4·5	25·5	5·0	225	0·035
15	1·5	50·9	5·0	225	0·035
16	4·5	50·9	5·0	225	0·035
17	1·5	25·5	2·48	165	0·7
18	4·5	25·5	2·48	165	0·7
19	1·5	50·9	2·48	165	0·7
20	4·5	50·9	2·48	165	0·7
21	1·5	25·5	5·0	165	0·7
22	4·5	25·5	5·0	165	0·7
23	1·5	50·9	5·0	165	0·7
24	4·5	50·9	5·0	165	0·7
25	1·5	25·5	2·48	195	0·7
26	4·5	25·5	2·48	195	0·7
27	1·5	50·9	2·48	195	0·7
28	4·5	50·9	2·48	195	0·7
29	1·5	25·5	5·0	195	0·7
30	4·5	25·5	5·0	195	0·7
31	1·5	50·9	5·0	195	0·7
32	4·5	50·9	5·0	195	0·7

area and its shape to be characterised with regard to the slot dimensions, extrusion parameters and polymer rheology. This has allowed the development of an expert system, which predicts the area and shape of the filament for square die-slot structures.

Materials and methods

For the extrusion, two polymers were used. The first was a low density polyethylene (LDPE) with a MFI of 0·7 g min^{-1} at 190°C and the second was a high density polyethylene (HDPE) with a MFI of 0·035 g min^{-1} at 190°C. Both were extruded with a carbon black masterbatch such that the final extruded polymer contained 1% carbon black by weight.

Extrusion equipment

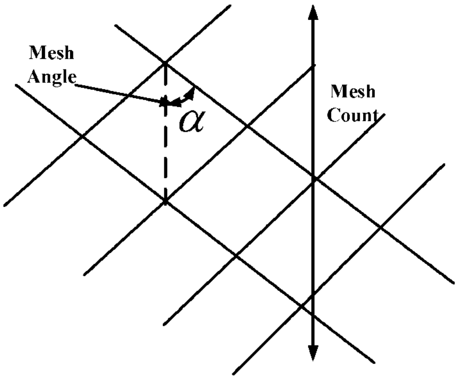
For the extrusion of the net structures, an extrusion system was used at Tensar International, this is a single screw melt extruder with 80 mm diameter screw. A series of static die extrusions were also carried out within the authors' own laboratories at Bolton Institute. These were produced using a melt extruder with a screw length to diameter ratio (*L*/*D*) of 21 : 1.

Extrusion matrix

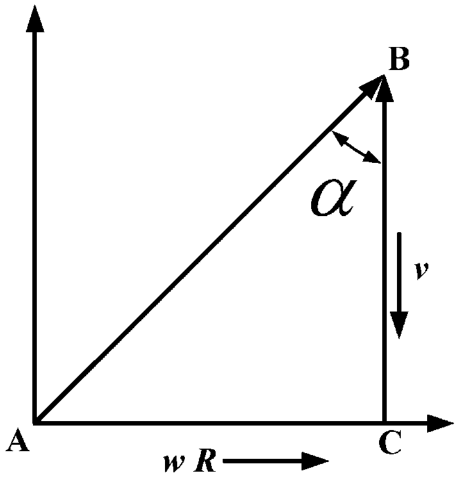
The experimental matrices were defined using MaxSuite (software) based on Taguchi's technique[5] using a two-level full factorial design. Table 1 shows the matrix for the net extrusions in which the five main process

Table 2 Experimental design for static dies

Sample number	Extruder speed, rpm	Take-up speed, m min^{-1}	Temperature, °C	MFI, g min^{-1}
1	17·42	5	195	0·035
2	34·84	5	195	0·035
3	17·42	10	195	0·035
4	34·84	10	195	0·035
5	17·42	5	225	0·035
6	34·84	5	225	0·035
7	17·42	10	225	0·035
8	34·84	10	225	0·035
9	17·42	5	165	0·7
10	34·84	5	165	0·7
11	17·42	10	165	0·7
12	34·84	10	165	0·7
13	17·42	5	195	0·7
14	34·84	5	195	0·7
15	17·42	10	195	0·7
16	34·84	10	195	0·7



1 Mesh angle and mesh count defined in a net structure



2 Velocity vector diagram

parameters, i.e. melt flow index (MFI), temperature, die speed, extruder speed and take-up speed, are considered. For the static die extrusion, a series of sixteen samples were produced based on a static single-square slot die (2 mm deep and 2 mm wide) using four main process parameters, namely, MFI, temperature, extruder speed and take-up speed in order to investigate the effect of die rotation on the filament shape within the net structure. This experimental matrix is shown in Table 2.

Analysis technique for area and shape of the filament

In order to analyse the extruded samples, a methodology was required which would allow filament cross-sections to be obtained without damage. Previous work at Bolton[6] demonstrated the usefulness of embedding samples in resin to minimise sample damage during sectioning before analysis and a similar technique has been followed here. The resin used was Araldite CY212 which is a typical resin used in the sectioning of samples before microscopy. The plasticity of the resin was modified using dibutyl phthalate to allow a clear section to be obtained. Images of the sections were obtained using a low magnification optical microscope with a CCD camera attached. The signal from the CCD was fed into a computer and the resultant image saved as a bitmap. Analysis of the images was carried out using the University of Texas Health Science Center, San Antonio (UTHSCSA) Image Tool program[7] providing data for both the area and shape of the filaments, which could then be compared with the respective die slot dimensions and shape. The shape of the filaments was specifically defined using the in-built functions of Image Tool program such as background separation and filtration. These functions separate the background from the filament image and, apparently, identify the exact shape of the filament. The data for the area was analysed statistically using MaxSuite to provide empirical models for the area of the filaments. Visual observations were also made for the shape of the filaments.

Results and discussion

Geometry of net structures

Within a melt extrusion net production, the die head consists of a disk and an annulus, which will usually be counter rotating. Both components have slots cut on the bearing surface and each slot results in the formation of a filament. Because of the rotation of the die, the slots in the disk and the annulus will meet and, at this point, the two molten polymer streams form a single stream thus forming a joint. The resultant structure will be a cylindrical net.

The geometry of the net structure can be expressed by mesh angle and mesh count. Mesh angle is defined as the half of the angle formed between the filaments in the vertical direction and mesh count is defined as the number of joints formed within the net structure in the machine direction in a specified distance, as shown in Fig. 1.

Consider a single filament emerging from a die of radius R with a rotational velocity w and a linear velocity or take-up speed v, which forms a helix with angle α (i.e. mesh angle) due to the rotational effect and the vectorial representation of a typical filament is shown in Fig. 2. From this representation, α is expressed as

$$\tan\alpha = \frac{wR}{v} \tag{1}$$

Assuming that the inner and outer parts of the die are counter rotating with angular velocities (rpm) w_i and w_o, respectively, then the relative angular velocity w_r of the inner part to the outer is

$$w_r = (w_i - (-w_o)) = (w_i + w_o) \tag{2}$$

If there are n_i and n_o slots on the inner and outer parts of the die, respectively, then, for a single slot on the inner die, the number of joints made per minute by slots on the outer die passing the slots on the inner die j_i can be represented by

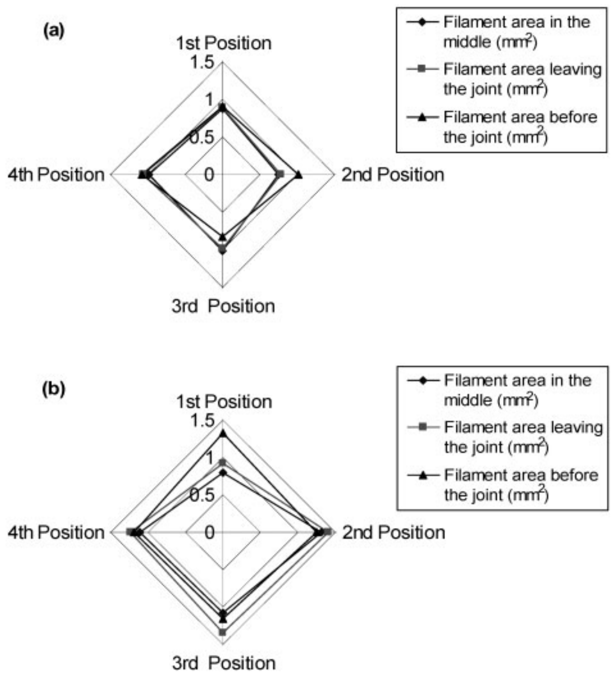
$$j_i = (w_i + w_o)n_o \tag{3}$$

Similarly, for a single slot on the outer die, the number of joints made per minute by slots on the inner die passing the slots on the outer die j_o can be represented by

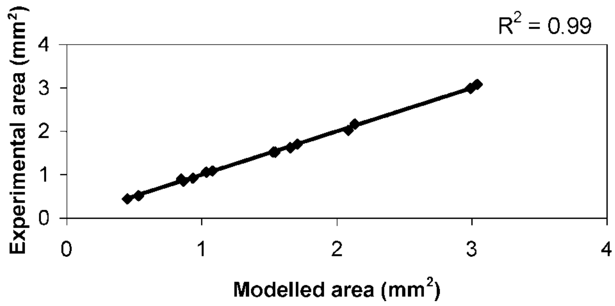
$$j_o = (w_i + w_o)\,n_i \tag{4}$$

Therefore, mesh count in the machine direction (i.e. AB as shown in Fig. 2) per unit length j_{imd} formed during each revolution of inner or outer die can be expressed by either

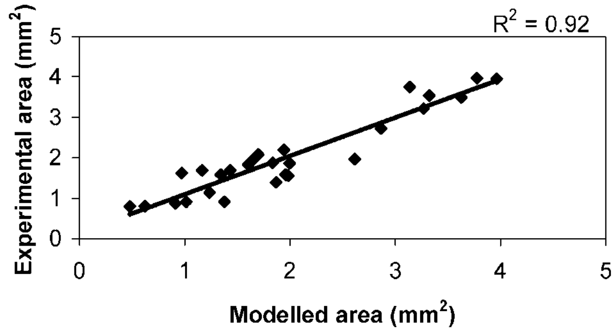
$$j_{imd} = (w_i + w_0)\,n_o/(v\sec\alpha) \tag{5}$$



3 Filament section *a* parallel to the machine direction *b* perpendicular to the machine direction



4 Area model for static square die slot



5 Area model for rotating square die slot

or

$$j_{\mathrm{imd}} = (w_{\mathrm{i}} + w_0)n_{\mathrm{i}}/(v \sec \alpha) \quad (6)$$

Analysis of cross-sectional area of the filaments

Area measurements were carried out for both the rotating and static die extrusions. In the case of rotating dies, the filament sectioning was carried out at four distinct positions by dividing the circumference of the net into four equal parts. Furthermore, in order to examine the effect of direction of sectioning, the net structures were sectioned either parallel or perpendicular to the machine directions. The sectioning was carried out before the joint, after the joint and at the midpoint of the filaments between the joints. It was expected that the filament sections obtained before and after the joint should have greater cross-sectional area, as shown in Fig. 3a and b. Since the two streams of the polymer emerging from the die slot attempt to form a single stream during the process, they leave the trailing and leading edges before and after the joints, respectively.[8] The average area for the three views was found to be more uniform by cutting the cross-section parallel to the machine direction, as shown in Fig. 3a. Therefore, in the current research work, the sections of the filaments at the midpoint between the two joints were obtained at four positions in the machine direction.

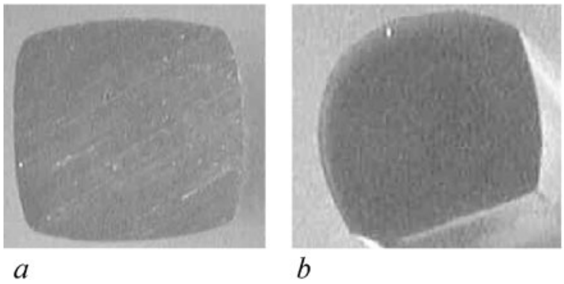
Use of multivariate linear regression has allowed a statistical analysis of the data to be carried out using MaxStat (a commercial software package). A comparison between the modelled area and experimental observations from static and rotating die slots are shown in Figs. 4 and 5, respectively, and gives excellent correlations. Therefore, in order to ensure that these results have real significance, the t-test was performed on cross-sectional area values. The t-test (as shown in Table 3) for area values has revealed that the correlation coefficients based upon theoretical models and experimental data are extremely high and found to be significant at the 0·1% level. Hence, the models can be used in developing the expert system. Moreover, Table 4 shows the comparison of percentage contribution of the

Table 3 Significance of correlation coefficient

Property	Area of the filament in rotating square die slot, mm^2	Area of the filament in static single square die slot, mm^2
Degree of freedom	30	14
Correlation coefficient	0·96	0·99
Expected t-value for 0·1% significance level	3·9	4·1
Calculated t-value	18·59	37·04

Table 4 Comparison of percentage contribution of each process parameter in rotating and static square die slots

Process parameter	Rotating square die-slot, %	Static square die-slot, %
Die speed	0·7	–
Extruder speed	35·8	32·0
Take-up speed	42	44·5
Temperature	0·2	0·0
MFI	6·7	17·1
Die speed and extruder speed	0·1	–
Die speed and take-up speed	0·1	–
Die speed and temperature	0·3	–
Die speed and MFI	0·4	–
Extruder speed and take-up speed	1·8	4·5
Extruder speed and temperature	0·4	0·0
Extruder speed and MFI	0·0	0·8
Take-up speed and temperature	2·1	0·0
Take-up speed and MFI	0·2	0·7
Temperature and MFI	0·0	0·1



6 **Shape of the filament produced from *a* static square die slot *b* rotating square die slot**

coefficients and the interaction coefficients to the area models. Here, it can be seen that the area is mainly dependent on two factors: extruder speed and take-up speed for both static and rotating dies. This may be expected as it can be assumed that the higher the extruder speed, the greater the throughput rate, resulting in an increase of the filament area. Similarly, increase in the take-up speed will result in greater attenuation of the filament, therefore, lowering the filament area. Whilst the MFI has a significant effect, as both the polymers have different swelling tendencies and the processing temperature and die speed has a negligible effect on the cross-sectional area of the filament.

Effect of die rotation on filament shape

For extrusion under static and rotating die conditions, the extruder was set up such that the polymer throughputs were matched. As the die slots for each had a similar dimension, the change in area should be similar. More importantly, the effect of die rotation on the filament shape may be compared by direct observation. Fig. 6 shows the comparison of filament shapes produced from square die slots, using static and rotating dies whilst keeping all other parameters constant. This has revealed the effect of die rotation on the filament geometry. In general, the polymer emerging from the die slot tends to deviate from its corresponding die slot shape due to higher surface tension. However, the effect of surface tension can be modified by changing the shear rate of the polymer. For polyethylene, the apparent viscosity decreases by increasing the shear rate.[9] Therefore, filament approaching a circular shape can be produced from a square die slot by increasing the shear rate. Empirical observations have been made which show that these stresses vary depending on the speed of die rotation. Further theoretical modelling is underway to more clearly define this tangential stress effect and the results will be reported later.[10]

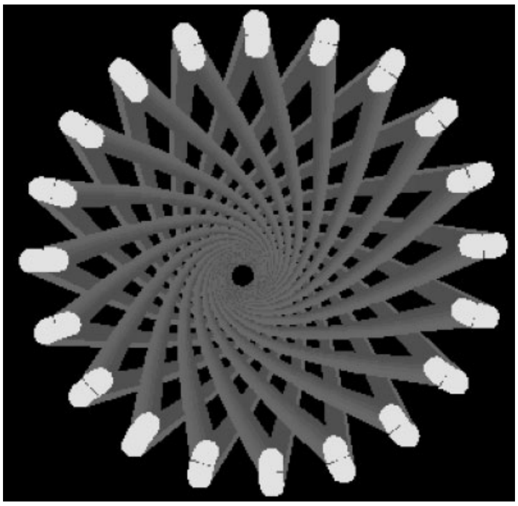
Computer simulation of filament shapes in melt extruded net structures

The empirical and theoretical models developed here have formed the basis of an expert system with the primary aim of defining an undrawn net structure from the process parameters. A computer model in the form of an expert system has been developed using Delphi[11] (a computer programming language). The basic form for data entry is shown in Fig. 7. It is intended that this will also provide the calculated data. In addition to providing the data in the form of expert system, it will also create an output text file. This text file is structured such that it can be read by a Virtual Reality Modelling Language (VRML) browser. From the text file created, a computer visualisation of the net structure may be observed and manipulated. These computer models are generated based upon analogies that have been used in previous models.[12] Here, a filament is created by sweeping a two-dimensional (2D) cross-sectional area along a three-dimensional (3D) path.[13] An example of the semi-circular cross-section net structure obtained from a square die slot is shown in Fig. 8.

Testing of expert system

The expert system developed was tested at the collaborating company. The eight randomly selected net structures, i.e. sample numbers 3, 4, 9, 12, 15, 19, 24 and 32 were produced from a square slot (1·78 mm wide, 1·78 mm deep and 5 mm land length), based upon the experimental design shown in Table 1. It was observed that the extent of circularity in the shape of the filament increases with the die rotational speed as shown in

7 **Data entry form for process parameters**

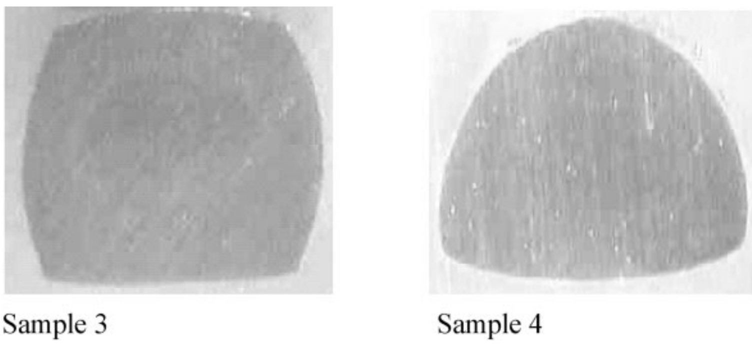


8 Semi-circular filament shape in a net structure

Fig. 9. Furthermore, the mesh count, mesh angle and the filament cross-sectional areas were also predicted and compared with the corresponding measured values. The predicted and measured values of filament cross-sectional area, mesh angle and mesh count are shown in Table 5. Furthermore, the t-test has shown that correlation coefficients based on expert system models and experimental data are significant at the 0·1% level as shown in Table 6. Thus, the expert system can be highly useful in predicting the filament and net geometries under a given set of process parameters, obtained from a square die slot.

Conclusions

A series of empirical models have been developed, which, in combination with theoretical geometrical data, allow the structure of an extruded net to be defined as a consequence of the process parameters. The empirical models for the cross-sectional area of the filaments have demonstrated that the structure is mainly dependent on two parameters: extruder speed and take-up speed. These empirical models of the filament cross-sectional area in combination with geometrical data have formed the basis of an expert system in the form of a computer model. The area models show good correlation with the measured area values. However, the shape of the filament in the net structure is complicated by the effect of the die rotation, resulting from a tangential shear on the polymer. It is accepted that controlling the filament cross-section in both area and shape will have a significant effect on the final properties of the net structure and is an important step in understanding the extrusion behaviour.



9 Effect of die rotation on the filament shape

Table 5 Testing of an expert system

	Mesh angle, degrees		Mesh count per 10 cm		Filament area, mm^2	
Sample number	Measured	Predicted	Measured	Predicted	Measured	Predicted
3	5·2	5·51	3·33	3·25	3·55	3·97
4	15·1	16·15	10·5	9·4	2·65	3·12
9	5·5	5·51	3	3·25	1·89	1·54
12	15·2	16·15	11	9·4	3·72	3·12
15	3·1	2·74	1·8	1·6	1·28	1·57
19	5·3	5·51	3·33	3·25	4·78	4·28
24	8·2	8·17	6·3	4·8	1·97	2·30
32	7·5	8·17	6·5	4·8	2·45	2·29

Table 6 Significance of correlation coefficient between measured and modelled filament area (expert system)

Property	Filament area, mm^2	Mesh angle, degrees	Mesh count per 10 cm
Degree of freedom	6	6	6
Correlation coefficient	0·93	0·99	0·99
Expected t-value for 0·1% significant level	5·21	5·21	5·21
Calculated t-value	6·19	17·19	17·19

Acknowledgements

The authors are highly thankful to Department of Trade & Industry (DTI) and Tensar International Ltd, U.K for their support provided to this research work.

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