UNDERSTANDING THE DEVELOPMENT OF FIBRE ORIENTATION DURING THE MELT EXTRUSION OF SHORT GLASS FIBRE REINFORCED POLYPROPYLENE

P.J.Hine*, S-W.Tsui#, P.D.Coates# I.M.Ward* and R.A.Duckett*

* - IRC in Polymer Science and Technology, University of Leeds, Leeds, UK
# - IRC in Polymer Science and Technology, University of Bradford, Bradford, UK

ABSTRACT

An IRC collaborative project has been undertaken to investigate and model the melt extrusion of short glass fibre reinforced polypropylene using a single screw extruder. Two die geometries, a conical die and a slit die, were used to examine the effects of die configuration on fibre orientation in the extrudate. Fibre orientation has been measured in detail using sophisticated image analysis facilities developed in-house. It has been found that the 'pseudo-affine' deformation model predicts the resulting fibre orientations very well for both die configurations. In addition, it is shown that a breaker plate in the barrel of the extruder, placed between the extruder screw and the convergent die, produces a very high degree of fibre alignment.

INTRODUCTION

Although it is well known that convergent flow can induce preferred fibre alignment in the extrusion and injection moulding of short fibre reinforced thermoplastics [1-3], little research has been undertaken to measure fully and model the development of fibre orientation in these situations. Recently [4] we reported a study of the injection moulding of circular dumbbells of short glass fibre reinforced polypropylene. It was shown changing from a larger diameter end section to a smaller diameter centre section produced a convergent flow region so that preferred fibre orientation was produced in the centre section during injection. Furthermore it was shown that the development of this fibre orientation could be predicted well by the 'pseudo affine' deformation scheme [5] proposed initially to predict the effects of an imposed deformation on the rotation of polymer crystals [6], and more recently used by us to predict accurately the rotation of fibres during the solid state extrusion of short glass fibre reinforced polyoxymethylene [7]. Because in both of these cases the deformation was uniaxial, one of the aspects of the current study was to establish whether this model could predict the effects of other imposed deformation fields.

In this publication the extension of the previous studies are described, using a single screw extruder and two die geometries: a conical die, where the deformation is uniaxial; and a slit die which produces a reduction in thickness at constant width. We have also investigated the effect of the breaker plate, normally present in the extruder barrel, on extrudate fibre orientation and shown that it has a beneficial effect.

EXPERIMENTAL

General Details

A commercial grade of glass fibre filled polypropylene, G3N01 manufactured by Hoechst AG, Frankfurt was used: the material had a fibre weight fraction of 30% (fibre volume fraction of 11%). The average fibre length was measured to be 425μm in the starting pellets, falling to 330 μm after extrusion.

Rod and sheet samples of short glass fibre reinforced polypropylene were produced using a Betol single screw extruder with a single 37mm diameter general purpose screw and a 2:1 compression ratio. There were six zones of temperature control, four along the extruder barrel and two around the die. The barrel zones were set to 180, 190, 200 and 200°C (working from the inlet hopper to the end of the screw), while the two die zones were set to 200°C. A pressure transducer was located within the die region to monitor melt pressure. All the tests used a screw speed of 20rpm. After the material left the die, it was passed though a water bath and then through driven haul-off rollers, producing material at approximately 1 m/min.

A breaker plate is normally present in the extruder at the end of the screw to help translate helical motion to axial motion. However the breaker plate causes complicated fibre orientation structures to be developed downstream, making modelling the effect of the convergent dies more difficult: Therefore for the modelling studies the breaker plate was removed. Two die geometries were used for the experiments without the breaker plate, a conical die with a 9mm diameter exit and a slit die with an exit cross section of 27mm by 3mm: both dies had a semi-angle of 15° and a 25mm land after the end of the convergence region. Experiments were also carried out with the breaker plate in place, using the slit die. Figure 1 shows a diagram of the breaker plate. The plate contained 66 holes, 3.2mm in diameter giving a total hole/extruder barrel ratio of 49%. The ratio of the hole size to fibre length was approximately 10.

The different configurations used in these experiments are shown schematically in Figure 1

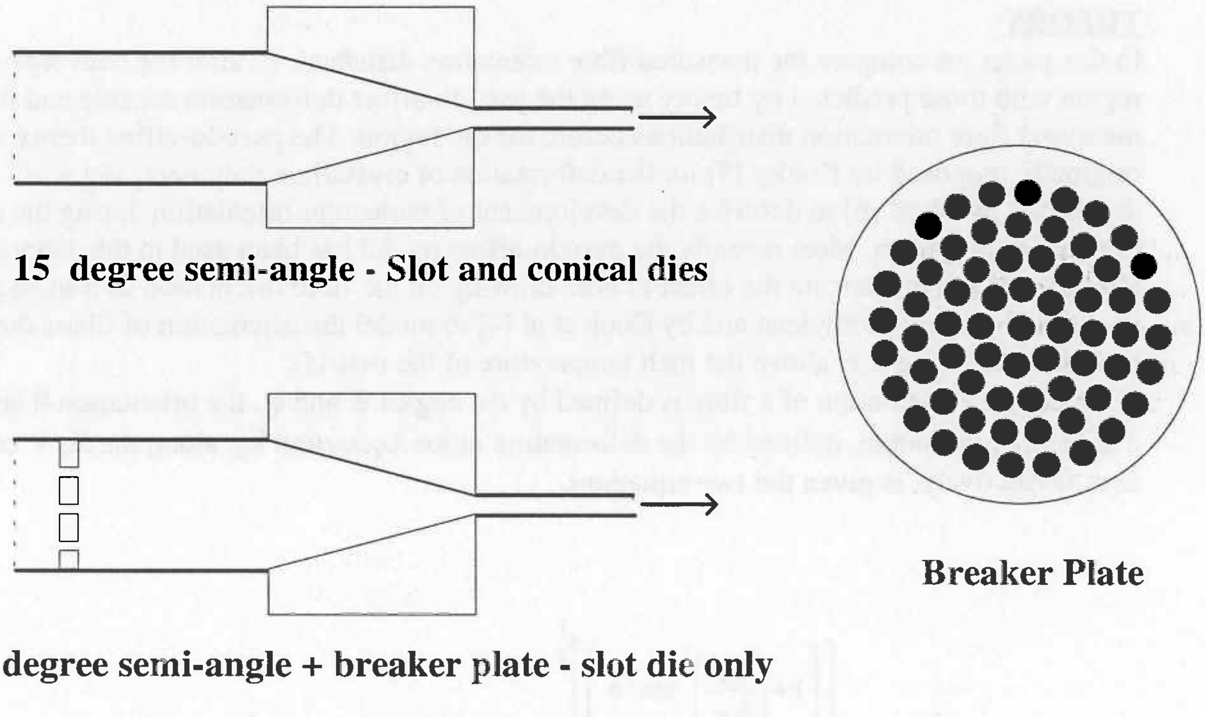

Figure 1: Experimental configurations and the breaker plate geometry.

Fibre orientation measurement

Samples from the die zones were examined after cooling and removing from the extruder when sample manufacture had been completed. The fibre orientation before and after the die was measured from sections taken from frozen die zones. Fibre orientation was measured using a transputer controlled image analysis system developed at Leeds University [7,8]. Images were produced directly from a polished composite section, where each fibre appears as an ellipse. Measuring the ellipticity and orientation of each fibre image enables the two angles θ and ϕ, which specify the orientation of the fibres, to be determined.

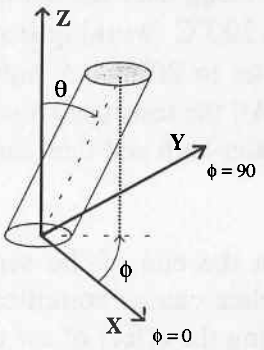

Figure 2a

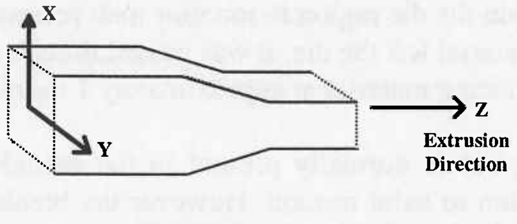

Figure 2b

Figure 2: Definition of the orientation angles θ and ϕ, and the sample axes.

θ is defined as the angle the fibre makes with the extrusion direction (Z axis), while ϕ is the angle between the X axis and the projection of the fibre axis on the XY plane, as shown in Figure 2a. The definition of the sample axes are shown in Figure 2b. Further details of the image analysis system and the measurement of fibre orientation can be found in [8].

<u>THEORY</u>

In this paper we compare the measured fibre orientation distributions after the convergent die region with those predicted by theory using the pseudo-affine deformation scheme and the measured fibre orientation distributions before the die region. The pseudo-affine theory was originally proposed by Kratky [5] for the deformation of crystalline polymers, and was developed by Ward [6] to describe the development of molecular orientation during the cold drawing of polymers. Most recently the pseudo-affine model has been used in this laboratory by Hine et al [7] to investigate the effect of cold drawing on the fibre orientation of a short glass fibre filled polyoxymethylene and by Cook et al [4] to model the orientation of fibres during injection moulding (i.e. above the melt temperature of the matrix).

If the original orientation of a fibre is defined by the angles θ' and ϕ', the orientation θ and ϕ after a general deformation, defined by the deformation ratios λ_X,λ_Y and λ_Z, along the X, Y and Z axes respectively, is given the two equations.

$$\tan\theta = \frac{\lambda_X}{\lambda_Z}\tan\theta'\left[\frac{\left(1+\left(\frac{\lambda_Y}{\lambda_X}\right)^2\tan^2\phi'\right)}{\left(1+\tan^2\phi'\right)}\right]^{\frac{1}{2}} \quad (1a) \qquad \tan\phi = \frac{\lambda_Y}{\lambda_X}\tan\phi' \quad (1b)$$

For the conical die the deformation is uniaxial and $\lambda_x = \lambda_y = \frac{1}{\sqrt{\lambda_z}}$, assuming constant volume during deformation. For the slit die the deformation has been approximated to constant width so that $\lambda_y = 1$ and $\lambda_x = \frac{1}{\lambda_z}$. The deformation ratios for the two dies, determined from the entrance and exit sizes, are shown below in Table 1.

	λ_x	λ_y	λ_z
Conical die	**0.317**	**0.317**	**9.95**
Slit die	**0.11**	**1.0**	~~9.92~~ 9.12

RESULTS

Modelling the effect of the convergence zone - No Breaker Plate

Figure 3 shows theta distributions taken from flow through the conical die (a) and the slit die (b).

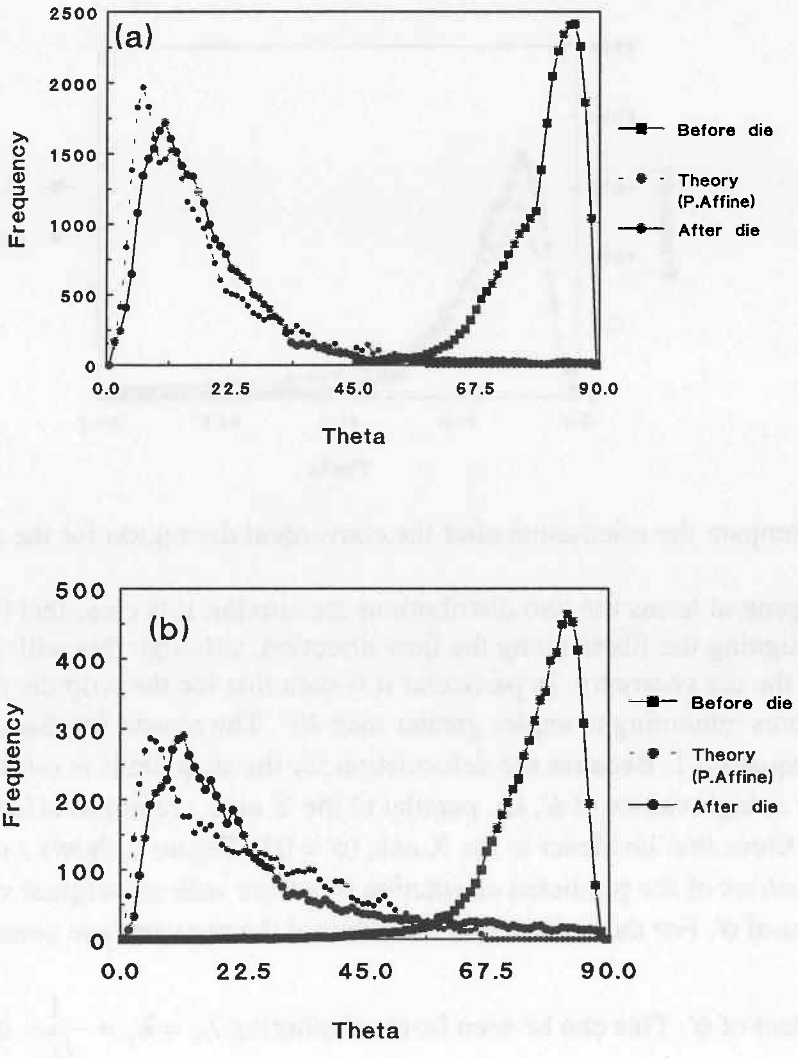

Figure 3: Theta distributions for a) the conical die and b) the slit die

The two figures show a comparison between the fibre orientation before the convergent die region, after the convergent die region, and the theoretical prediction of the fibre orientation after the die region based on the fibre orientation before the die and the pseudo-affine deformation scheme. The fibre orientation distribution in the barrel before the melt reached the convergent dies was built up from a number of image scans (taken in the XY plane) approximately 5mm square. It was found that whereas the theta distributions for each scan area were similar, the phi distributions were different for each scan area. In general it was found that the fibres in this area lay predominantly in the XY plane (θ=90°) and were aligned predominantly circumferentially due to the helicity of the flow. Although for the best comparison between theory and experiment it would be necessary to scan the complete barrel diameter, the size of this area meant that this was not practical. Instead, four image scans were taken at different positions across the barrel diameter, and therefore different local values of ϕ, to attempt to produce as representative a sample as possible: area scans were taken for local average values of ϕ = 0, 45, -45 and 90°. The results in Figure 3 show that the two die geometries are very effective in aligning the fibres along the flow direction, and that this alignment is predicted very well by the pseudo-affine theory for both die shapes. Figure 4 shows a comparison of the fibre orientation after the die for the two die geometries. The orientation average $\langle\cos^2\theta_z\rangle$ for these two distributions was measured to be 0.82 for the slit die and 0.90 for the circular die ($\langle\cos^2\theta_z\rangle = 1$ for perfect alignment).

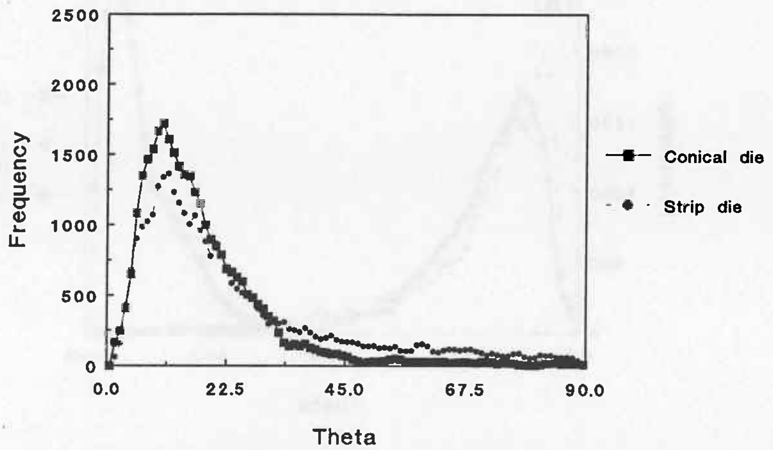

Figure 4: Compare the orientation after the convergent die region for the conical and strip dies

Although in general terms the two distributions are similar, it is clear that the conical die is more effective in aligning the fibres along the flow direction, although this will of course depend on the details of the die geometry. In particular it is seen that for the strip die there are a significant number of fibres remaining at angles greater than 40°. The reason for this can be seen by considering equation 1. Because the deformation for the strip die is at constant width ($\lambda_y = 1$), fibres that lie at high values of ϕ', i.e. parallel to the Y axis, are not as effectively rotated towards the Z axis as fibres that lie closer to the X axis ($\phi' = 0°$). Figure 5 shows a comparison for the two die geometries of the predicted orientation of a fibre with an original value of $\theta' = 85°$ for various values of ϕ'. For the conical die, the effect of the convergence zone on the final value of

θ is independent of ϕ'. This can be seen from substituting $\lambda_x = \lambda_y = \frac{1}{\sqrt{\lambda_z}}$ into equation 1, where

then $\tan\theta = \lambda^{-\frac{3}{2}} \tan\theta'$.

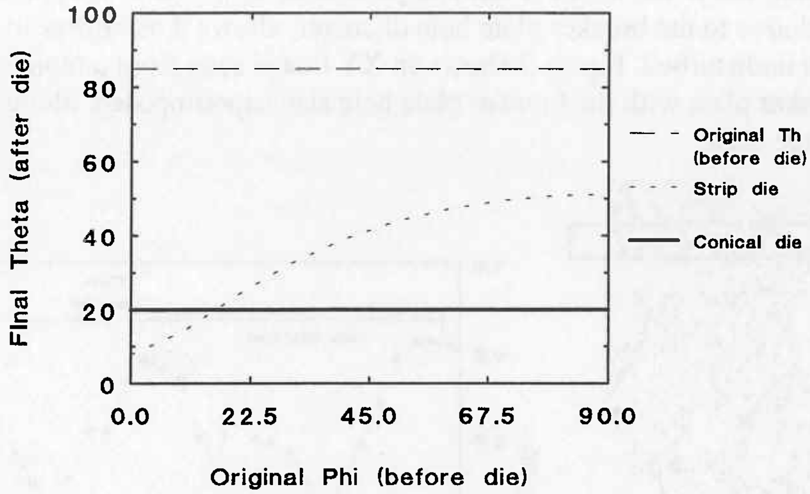

Figure 5: The effect of the die geometry and ϕ' on the final value of θ

For the conical die shape used in this work, a fibre which has a value of θ' of 85° before the die, will be predicted to have a constant value of θ of 20° after the die.
In comparison, for the strip die the final value of θ depends on both θ' and ϕ'. For an original value of θ of 85° (the most probable value as shown from Figures 3a and 3b) and ϕ' greater than 20° (or less than -20° because the relationship is symmetrical around ϕ' = 0), the strip die is less effective than the conical die in aligning the fibre along the flow direction. If ϕ' is less than 20° the strip die is more effective than the conical die.

The effect of using the breaker plate
Figure 6 shows the effect of the breaker plate on the θ distribution just before the convergence zone using the slit die.

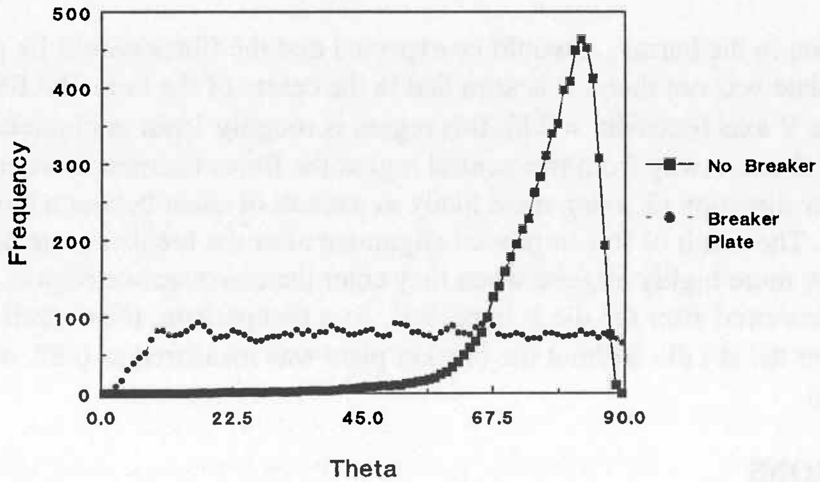

Figure 6: The effect of the breaker plate on the fibre orientation before the die.

It is clear that the breaker plate has a profound effect on the fibre orientation distribution. As described above, without the breaker plate the fibres lie predominantly perpendicular to the flow direction. With the breaker plate the fibre[illegible]anged in a very inhomogeneous manner, with a large number of fibres now more aligned in the extrusion direction, although there are roughly circular regions where the fibres remain perpendicular to the flow. It appears that the short length of the fibres, relative to the breaker plate hole diameter, allows those fibres in the centre of the holes to flow through undisturbed. Figure 7 shows an XY image scan from a representative area measured after the breaker plate with the breaker plate hole size superimposed, along with a strip analysis from the image scan.

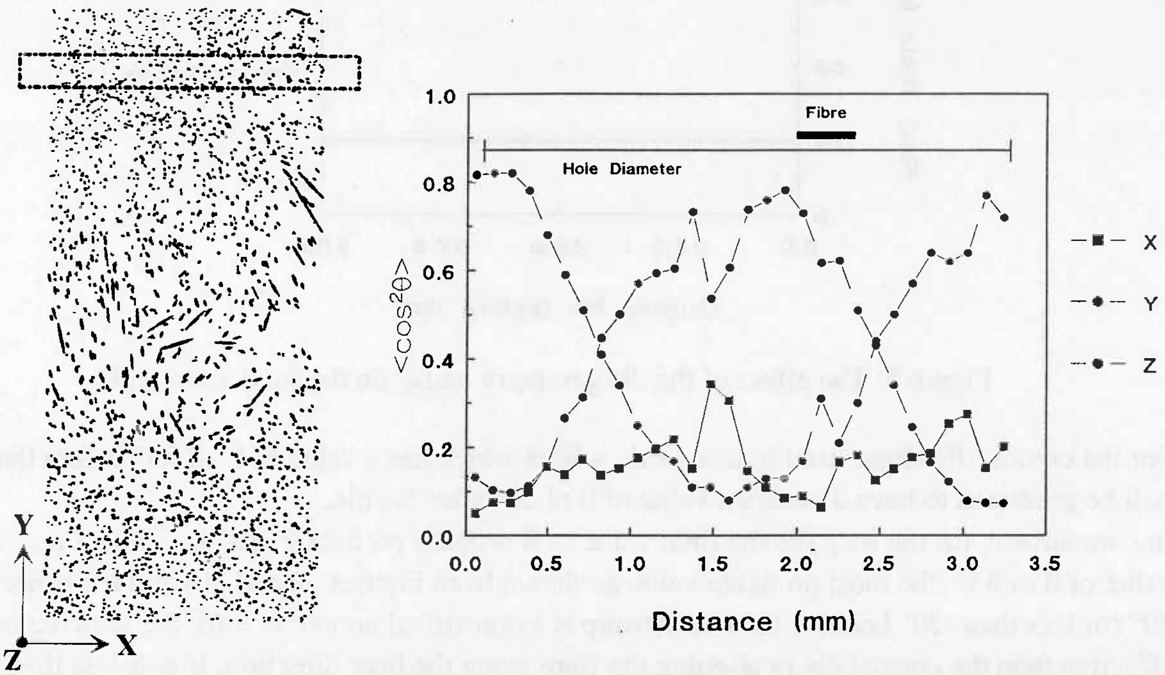

Figure 7: Image scan area after the breaker plate and associated strip analysis.

For the strip analysis it is possible to calculate the orientation averages $\langle\cos^2\theta_X\rangle$, $\langle\cos^2\theta_Y\rangle$ and $\langle\cos^2\theta_Z\rangle$, which indicates how the fibres are aligned with respect to the three principal axes, in a series of strips parallel to the X axis. For perfect alignment in a strip along a particular axis, the value of the orientation average would equal one, with the other two averages equal to zero. On the other hand for a random three dimensional arrangement of fibres all three averages would equal one third.

At this position in the barrel , it would be expected that the fibres would lie parallel to the Y axis if the breaker plate was not there. It is seen that in the centre of the hole, the fibres remain largely parallel to the Y axis ($\langle\cos^2\theta\rangle = 0.8$): this region is roughly 1mm in diameter compared to a hole diameter of 3.2mm. Away from this central region the fibres become more predominantly aligned along the flow direction (Z axis), most likely as a result of shear between the hole edges and the moving melt. The result of this improved alignment after the breaker plate has the result that the fibres are now more highly aligned when they enter the convergence region, such that the final orientation measured after the die is improved. As a comparison, the overall orientation average $\langle\cos^2\theta_Z\rangle$ after the slit die without the breaker plate was measured as 0.82, and with the breaker plate as 0.896.

CONCLUSIONS

It has been shown that melt extrusion through convergent dies can produce high degrees of fibre alignment. If a breaker plate is positioned between the extruder screw and the convergent die this increases the extrudate fibre orientation further. The degree of fibre alignment in the extrudate has been shown to be predicted well by the 'pseudo-affine' deformation theory, for both a conical die (uniaxial deformation) and a slit die (constant width deformation).

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