Modelling of fibre damage in single screw processing

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ABSTRACT: In injection moulding, long glass fibre reinforced thermoplastics (LGFT) are an attractive way to produce large parts at low cost. However the strength of the part depends chiefly on the average fibre length, fibres which are subjected to considerable attrition during processing in conventional three stage screws.

In this study, two models of fibre breakage are considered: The first mechanism is specific to plastication during which a fibre anchored at one end in the solid bed is submitted at the other end to the intense shear existing in the molten film, close to the barrel. The thickness of the molten film and the shear stress applied to the fibre vary with polymer viscosity, fibre strength and dimensions, and process parameters. As the melting of the solid bed progresses, more fibres are unlayered and submitted to bending. When the bending stress applied exceeds the fibre strength, the fibre breaks. This results in bimodal fibre length distributions. The sensibility of the model to main processing parameters such as screw rotation, initial fibre length, viscosity, barrel temperature and screw geometry is also investigated. The second mechanism addresses the fibre breakage occurring at a later stage in the process, when the screw channel is completely filled with melt. The basis for this is to look at the fibre as an array of bonded spheres. The flexibility of the fibre model is altered by changing the bending, stretching and twisting strength of the bond connecting adjacent spheres. The motion of the fibre in the flow field is determined by solving the translational and rotational motion equations for individual spheres under hydrodynamic forces and torques exerted on them. Again, the fibre fractures at the bond at which the applied stress exceeds the fibre strength.

KEYWORDS: fibre breakage, plastication, injection moulding, extrusion, single screw, viscous fluid flow

1 INTRODUCTION

In injection moulding, long glass fibre reinforced thermoplastics (LGFT) are an attractive way to produce large parts at low cost. However the strength of the part depends chiefly on the average fibre length, fibres which are subjected to considerable attrition during processing in conventional screws. While there is a number of studies on the effect of fibre attrition on the mechanical strength of the part, little has been done on giving a physical mechanism of fibre breakage, let alone confronting its predictions to experiments. It is known that most of the fibre attrition occurs during screw processing [4], while the solid polymer is melted. This step, known as plastication, implies the continuous rubbing of a solid bed made of compacted polymer pellets, against a hot metallic barrel and the screw channel flights. As the solid bed progresses along the screw, more fibres are unlayered and submitted to intense shear and bending. This can cause the failure of the fibre when the bending stress exceeds the fibre strength. In this case the fibre attrition is very much linked to the plastication process and fibre length distribution depends chiefly on melt film thickness and plastication length. At the end of the plastication process, the polymer is completely melted and fibres are submitted to hydrodynamical interactions. The way the fibres react to this flow field depends on the type of the flow field (shear or elongation), the level of rate of strain imposed compared to the bending modulus and strength and the fibre length. For instance, very rigid fibres could sustain an intense shear while very flexible would just deform at will. Both would avoid breaking. In between, fibres can break because of buckling for example. When a fibre breaks, the resulting pieces are themselves submitted to the flow field and can be further damaged. These two processes create a fibre length distribution. A study of fibre fracture during processing contributes to an understanding in how the process can be changed to maintain longer fibres.

2 FIBRE DAMAGE DURING PLASTICATION

2.1 Modelling

Pellets are fed to the screw and move forward in the screw channel, forming a more or less compact solid bed. It is reasonable to consider that at the beginning fibres are protected by the polymer matrix well enough. As the heat coming from the barrel and from the friction melts the protective polymer, fibres begin to be exposed, with one end in a molten film, submitted to the intense shear and the other end firmly anchored in the solid bed, as shown on Figure 1.

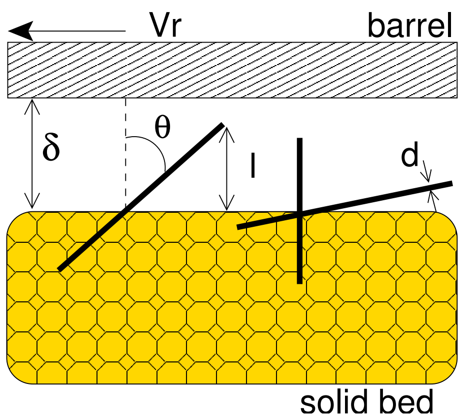

Figure 1: Fibre breakage

The model determines the bending moments experienced by a single fibre due to shear flow past it and bring out the effects of molten film thickness, screw velocity, viscosity of the molten polymer and fibre orientation relative to the flow direction. Fibre fracture results if the bending moment is sufficient to cause flexural failure of the fibre. The maximum stress applied to the fibre has to be then compared to the breaking stress of the fibre itself, to know whether the fibre will break or not. Originally Mittal et al. [3] considered a Newtonian fluid, we extended his calculation to a power-law fluid equations:

$$\sigma_{\text{applied}} = \frac{128\delta^{3-n}KV_r^n}{d^3}\frac{A^{n-1}}{(\exp(A)-1)^n}F \quad (1)$$

$$F = \int_0^{\frac{l}{h}} \frac{(1-\exp(-Ax))x}{\log(\frac{7.4}{R_e})}dx \quad (2)$$

$$A = \frac{\alpha(T_b - T_m)}{n} \quad (3)$$

where σ_{applied} is the applied stress, h is the film thickness, V_r the relative velocity of the barrel to the solid bed, d the fibre diameter and R_e the Reynolds number, K , n and α are the consistency factor, power-law index and Arrhenius factor of the power law of viscosity. T_b and T_m are the barrel and melting temperature.

When a fibre does break, the remaining part of it still inside the solid bed is considered for breakage at a later characteristic time built on the melting velocity computed from the plasticising model. Thus, at the end of the melting process, typical fibre length distributions are obtained. However, this model involves several assumptions. Each fibre faces individually the shear flow and fibre/fibre interaction effects are not taken into account as well as concentration effects.

2.2 Results

Screw extraction and fibre length measurement were conducted by Gupta [2] on a 38mm single screw with long glass fibre reinforced polypropylene. Comparisons have been made between experimental and computed length distribution as in Figure 2. The comparison of average length is good, particularly when submillimetre fibres are concerned.

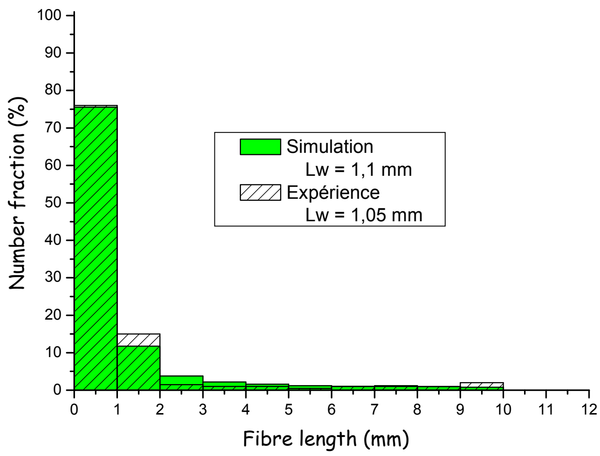

Figure 2: Number averaged fibre length

2.3 *Sensitivity to process parameters*

Increasing barrel temperature results in less fibre breakage because it diminishes the polymer viscosity (although it increases film thickness). Increasing screw rotation increases shear stress applied on the fibres but also diminishes film thickness, a counter acting influence as far as fibre breakage is concerned. Employing a less shear thinning polymer results in larger fibre breakage because the stress applied to the fibre is larger.

3 FLOW-INDUCED FIBRE DAMAGE

Forgacs and Mason [1] studied the behaviour of a fibre in viscous fluid submitted to a laminar shear flow and developed the theory of fibre fracture in an infinitely dilute system. Using slender body theory they derived a critical shear stress value above which buckling of a straight fibre occurs. Yamamoto and Matsuoka proposed a dynamic simulation of flow-induced fibre fracture [6]. The basis for it is to look a the fibre as an array spheres bonded together by flexible joints Figure 3. The motion of the fibre in the flow field is determined by solving the translational and rotational motion equations for individual spheres under hydrodynamic forces and torques exerted on them.

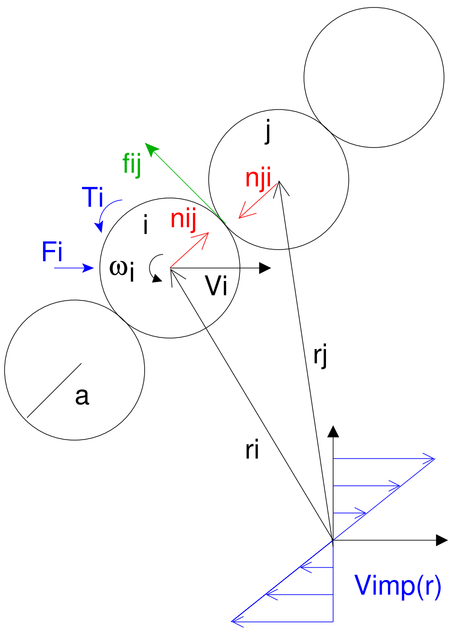

Figure 3: Fibre Model

The flexibility of the array of spheres is taken into account basically by considering the Young modulus E and stretching, bending constants of the bonds linking adjacent spheres i and j, and deriving the correspondent forces and torques applicable to neighbouring spheres.

$$\underline{F}^{ij}_{\text{stretch}} = -\frac{\pi a E}{2}(\underline{r}^i - \underline{r}^j) \quad (4)$$

$$\underline{T}^{ij}_{\text{bending}} = \frac{\pi a^3 E}{8}(\theta^{ij}_b - \pi)\underline{n}_b \quad (5)$$

The hydrodynamical resistance for spheres is simply a translational and rotational friction force and torque expressed as :

$$\underline{F}^i_{\text{hydro}} = -6\pi a \eta_0 \left(\underline{V}^i - \vec{V}_{\text{imp}}(\underline{r}^i)\right) \quad (6)$$

$$\underline{T}^i_{\text{hydro}} = -8\pi a^3 \eta_0 \left(\underline{\omega}^i - \underline{\omega}_{\text{imp}}(\underline{r}^i)\right) \quad (7)$$

Where $\underline{V}^i$, $\underline{\omega}^i$ are the translational and rotational velocities of sphere i, $\underline{r}^i$ is its position and the unit vector $\underline{n}^{ij}$ between sphere i and j is defined as in Figure 3. The subscript ”imp” is related to the superimposed flow field. The cohesion of the fibre is assured by considering the non-slip velocity condition between two neighbouring spheres i and j :

$$\underline{V}^i + a\underline{\omega}^i \wedge \underline{n}_{ij} = \underline{V}^j + a\underline{\omega}^j \wedge \underline{n}_{ji} \quad (8)$$

and by considering the friction force f_{ij} that sphere j exerts on sphere i. Thus the equations of translational motion and rotational motions are written as :

$$m\frac{d^2\underline{r}^i}{dt^2} = \underline{F}^i_{\text{hydro}} + \sum \underline{F}^i_{\text{stretch}} + \sum \underline{f}^{ij} \quad (9)$$

$$\frac{2ma^2}{5}\frac{d^2\underline{\theta}^i}{dt^2} = \underline{T}^i_{\text{hydro}} + \sum \underline{T}^i_{\text{bend}} + a\sum \underline{n}^{ij}_{\wedge}\underline{f}^{ij} \quad (10)$$

3.1 *Results*

The model has been programmed with a few differences from Yamamoto and Matsuoka's original ideas. Most importantly the cohesion between adjacent spheres is insured by calculating the translation velocity of each spheres using equation 8 and removing it from the set of unknowns, instead of adjusting the spheres position at each time-step as done earlier by [5]. This allows for a standard Runge-Kutta routine from an open-source mathematical package (Octave) to be used for solving the differential equations equation (9,10).

Preliminary results on a very flexible fibre initially lying flat in a shear flow, show the typical coiling and rotation in the flow Figure 4. The relative strength of the fibre against the flow induced stress can be simply measured by the ratio $E/\eta\dot{\gamma}$. When the fibre has a higher elastic modulus the motion is different, still showing large deformation in the flow Figure 5.

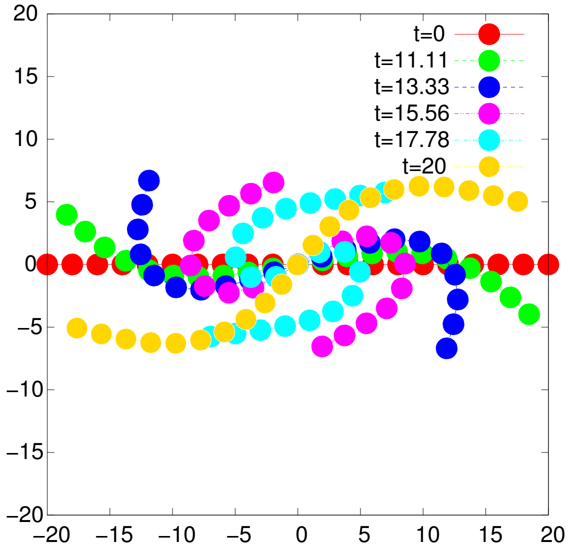

Figure 4: Flexible fibre in shear flow with $\frac{E}{\eta\dot{\gamma}} = 10^3$. Dimensionless time $1/\dot{\gamma}$

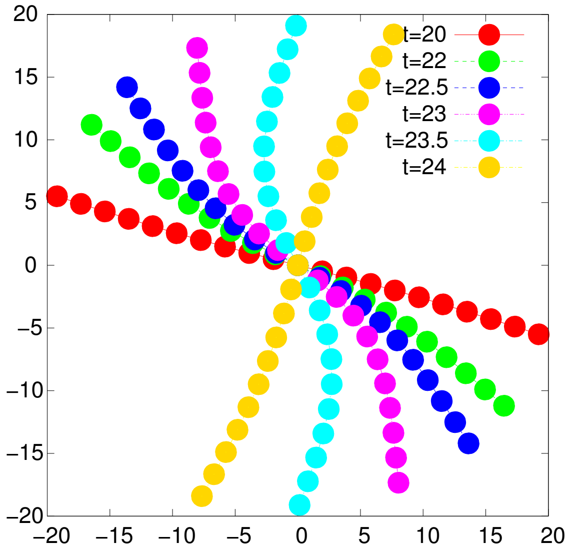

Figure 5: Flexible fibre in shear flow with $\frac{E}{\eta\dot{\gamma}} = 10^4$. Dimensionless time $1/\dot{\gamma}$

A simple test of the fibre elasticity is to check if an initially bended fibre will become straight again when released in an quiescent viscous fluid. Figure 6 shows the quick dampening of vibrations of the fibre.

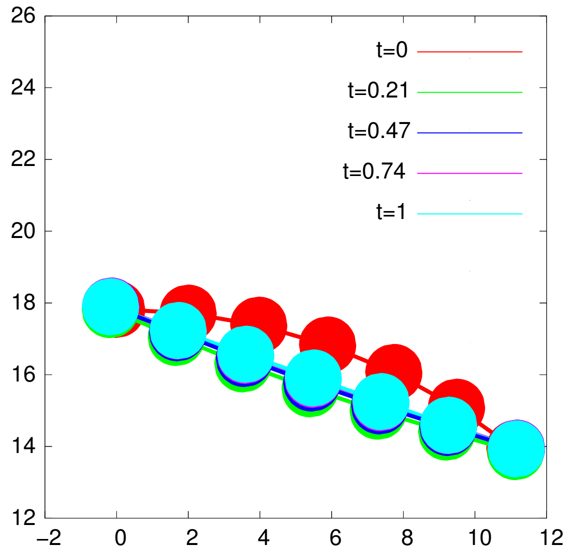

Figure 6: Flexible fibre in quiescent flow. Dimensionless time $1/\dot{\gamma}$

4 CONCLUSION

Two different mechanisms of fibre fracture during processing can be envisaged: the first one is specific to the plastication stage when fibres are still embedded in a bed of compacted polymer pellets. Fibre fracture occurs when applied shear stress exceeds bending strength. Typical bimodal distribution in length are obtained. The second mechanism is solely for fibres plunged in melt flow, where a complex load on a flexible fibre can be applied by the flow field.

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