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A matricial approach of fibre breakage in twin-screw extrusion of glass fibres reinforced thermoplastics

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A B S T R A C T

Limiting fibre breakage during composite processing is a crucial issue. The purpose of this paper is to predict the evolution of the fibre-length distribution along a twin-screw extruder. This approach relies on using a fragmentation matrix to describe changes in the fibre-length distribution. The flow parameters in the screw elements are obtained using the simulation software Ludovic®. Evolution of an initial fibre-length distribution for several processing conditions was computed and the results were compared with experimental values. The computation gives satisfying results, even though more comparisons with experiments would be necessary.

1. Introduction

A classical use for glass fibres in industry is thermoplastic polymers reinforcement, mostly for injected parts. Long-fibre composites are known to offer better mechanical properties than short-fibre ones. Consequently, an important point is to preserve as much as possible long fibres during compounding, despite strong flow conditions, eventually leading to severe break-up.

Fibre orientation for long-fibre thermoplastics in moulding process has already been studied and modelled [1–4] and a quantitative model predicting changes in fibre-length distribution during mould filling has been recently developed by Tucker et al. [5]. However, prior to injection moulding, other processes are used to compound glass fibres into polymer matrices. An important issue is thus to control fibre lengths in these processes to subsequently inject compounds exhibiting a suitable final length distribution. The most common of these processes is twin-screw extrusion, in which considerable fibre length degradation occurs [6–8]. Shon et al. [9] have been the firsts to develop an empirical model describing the average fibre length evolution in different continuous processes, including twin-screw extrusion. More recently, this approach was improved to calculate average fibre length evolution during twin screw extrusion and Buss kneader compounding [10–11]. However, these methods do not provide information on the whole fibre-length distribution. Therefore, the aim of the present paper is to propose a computational method to predict changes in the fibre-length distribution along a twin-screw extruder.

2. Theoretical model

2.1. Forgacs and Mason model

Our model is based on the assumption that fibre breakage is only due to flow-induced buckling, as described by Forgacs and Mason [12]. According to this model, a rotating rigid fibre in a shear flow may break when oriented in the direction of compressive forces. Beyond a critical force, which depends on its mechanical properties and length, the fibre buckles and then breaks-up (Fig. 1). Breakage occurs because of the severe tensile stress σ_s induced on the external surface of the fibre when it is bending. This stress depends on the fibre radius b, its Young modulus E and the local radius of curvature R:

$$\sigma_s(x) = -\frac{Eb}{R(x)} \qquad (1)$$

where x is the abscissa along the fibre principal axis. When the stress σ_s on the surface reaches the tensile strength value of the fibre σ_c, the fibre breaks-up. As the radius of curvature of the fibre is linked to the fibre deformation, the breakage phenomenon directly depends on this deformation. In this work, it was assumed that, when buckling occurs, the fibre systematically breaks-up because

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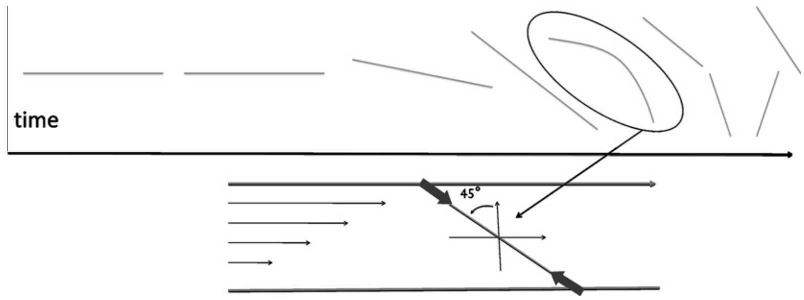

Fig. 1. Rotating fibre in a shear flow. Break-up occurs when the maximum flow-induced compressive force is high enough.

of the resulting huge deformation. This assumption is validated in Section 2.3.

2.2. Jeffery equation

To determine when buckling (and then breakage) occurs, forces applied on the fibre as well as fibre orientation must be computed. Classically, the orientation **P** of a single ellipsoidal fibre of length $2a$ and radius b in a shear flow is obtained by solving Jeffery equation [13]:

$$\dot{\mathbf{P}} = \boldsymbol{\Omega} \cdot \mathbf{P} + \lambda[\dot{\boldsymbol{\varepsilon}} : \mathbf{P} - (\dot{\boldsymbol{\varepsilon}} : \mathbf{P} \otimes \mathbf{P})\mathbf{P}] \quad (2)$$

where **P** is the orientation vector of the fibre principal axis, $\boldsymbol{\Omega}$ the vorticity tensor, $\dot{\boldsymbol{\varepsilon}}$ the strain rate tensor, and λ a parameter related to the aspect ratio $\beta = a/b$:

$$\lambda = \frac{\beta^2 - 1}{\beta^2} \quad (3)$$

The orientation vector **P** describes the fibre orientation in the reference frame. In the case of simple shear flow, this frame is defined as depicted in Fig. 2. This orientation can also be described by the angles θ and ϕ (which can be determined from **P**). As glass fibres are cylindrical, the ellipsoid aspect ratio β should be replaced in Eq. (3) with an equivalent aspect ratio β_e for cylinders, theoretically determined by Burgers [14]:

$$\beta_e = 0.74\beta \quad (4)$$

The orientation vector was then used in the forces computation. The shear induced force F_B, integrated on a half-fibre, was given by Burgers [14], without further indication on the forces distribution f along the fibre:

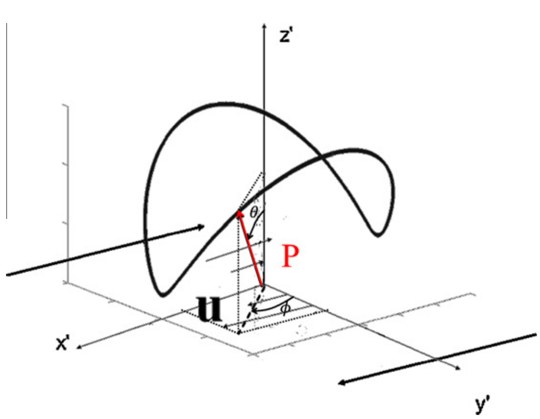

Fig. 2. Fibre end orbit in a simple shear flow. The shear plan frame (x', y', z') is translating with the fibre. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$F_B = -\int_a^0 f(x)\,dx = \frac{M\pi\eta\dot{\gamma}a^2}{\ln(2\beta) - 1.75} \quad (5)$$

where η is the viscosity and $\dot{\gamma}$ the shear rate. M is defined as:

$$M = \sin^2\theta \sin\phi\cos\phi \quad (6)$$

where θ and ϕ were obtained from the orientation vector **P**. In a more convenient form, Eq. (5) can be written in terms of stress:

$$\sigma_B = \eta\dot{\gamma}M\frac{\beta^2}{\ln(2\beta) - 1.75} \quad (7)$$

In order to determine when buckling occurred, forces were assumed to be punctually applied at fibre ends. Then, it was possible to obtain the buckling threshold by applying Euler buckling method.

2.3. Euler buckling method

In order to confirm that perfect (without any defect) rigid fibres cannot break-up when simply bending below the buckling threshold (in the case of small deformations) and also always break-up when buckling, the tensile stress σ_s applied on the external surface of the fibre when it bends (below the buckling threshold: small deformation) and when it buckles (over the buckling threshold: large deformation) must be computed. In this way, the tensile stress σ_s can be compared to the tensile strength σ_c in order to check if the fibre does break. Compressive forces were supposed to be only applied at fibre ends and along its principal direction. The bending momentum balance for a non-deformed configuration gives:

$$M_0(x) = F_B y(x) \quad (8)$$

where $M_0(x)$ is the bending momentum and $y(x)$ the fibre deflection at point x. From this equation, the deformation below the buckling threshold (assuming that there exists an initial deflection at rest) and beyond the buckling threshold can be obtained. First, the buckling threshold was calculated under the assumption of "small" deformations (Euler buckling method), in which the bending momentum M_0 is approximated by:

$$M_0 = \frac{EI}{R} \approx EIy'' \quad (9)$$

where I is the moment of inertia and R the radius of curvature. Combining Eqs. (8) and (9) leads to the differential equation:

$$y'' + k^2 y = 0 \quad (10)$$

with $k^2 = -\frac{4}{b^2}\frac{\sigma_B}{E}$. The only possible non trivial solution satisfying the homogenous boundary conditions ($y(a) = 0$ and $y'(0) = 0$) is:

$$y = A\cos(kx) \quad (11)$$

with $k = p\frac{\pi}{2}a$ and p is a strictly positive integer. Considering that the fibre is brittle, and assuming that it breaks when it reaches its