

Test equipment

Prototype and methodology for the characterization of the polymer-calibrator interface heat transfer coefficient



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ARTICLE INFO

Article history:

Received 27 May 2013

Accepted 8 July 2013

Keywords:

Interface heat transfer coefficient

Contact resistance

Extrusion

Calibration

Cooling

ABSTRACT

The extrusion of technical thermoplastics profiles generally uses a dry calibration/cooling system, composed by one or several calibrators in series. One of the major difficulties to be faced when modelling this important stage is an adequate prescription of the heat transfer coefficient, $h_{interface}$, between the plastic profile surface and the cooling medium, which must include the effect of the interface contact resistance. This is the motivation that led the present research team to develop a prototype calibration system and respective methodology for the characterization of $h_{interface}$ values which is able to consider a variety of conditions that can be found in extrusion practice. A modular construction was adopted for the calibration system, which allows studying easily the effect of several process parameters. In this work, the developed prototype system is described and its use is illustrated in the determination of $h_{interface}$ for the production of a polystyrene tape, under specific processing conditions.

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1. Introduction

The extrusion of thermoplastic polymer systems is a continuous process used in the production of constant cross-section products, namely rods, sheet, films, pipes and profiles. Independently of the technical particularities demanded for the manufacturing of different types of products, in general, an extrusion process encompasses three main stages (see Fig. 1): i) the plastication stage, where the polymer is melted, homogenized and pumped into the extrusion die; ii) the forming stage, where the melt is shaped by an extrusion die; iii) the calibration/cooling stage, where the extrudate is cooled down and, eventually, calibrated, until a sufficiently low average temperature is reached that guarantees its shape downstream of the extrusion line. This stage is followed by a pulling device (or haul-off), which is responsible for the maintenance of a

constant extrusion linear velocity, and a saw or winding device, to store the extrudate.

Thermoplastics have very low thermal diffusivity, of the order of 10^{-7} m.s^{-2} , which can bring some advantages in specific applications but makes all the processing stages involving heat exchanges with the polymer (heating or melting and, specially, cooling) critical. In fact, in continuous processes, such as extrusion, the cooling stage is usually responsible for limiting the maximum velocity of production, whereas in cyclic processes, such as injection moulding, thermoforming and blow-moulding it determines a significant part of the total cycle time (that can be of the order of 80%). Low thermal diffusivity is also responsible for the development of considerable thermal gradients during the cooling stage [1–4] and, consequently, for the development of stresses [5–13] that can be frozen in the product (generally referred as residual thermal stresses) that will affect negatively the mechanical performance of the product in use [14–18].

Unlike the other above mentioned types of extruded products, technical thermoplastic profiles may have a great

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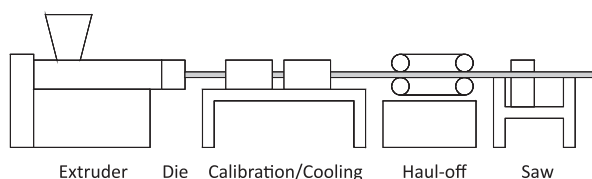


Fig. 1. Typical extrusion line for the production of pipes/profiles.

variety of shapes, uneven thickness and complexity, having varied and demanding applications such as window and door frames, decks for exteriors, blinds and electrical rails, for example. Therefore, these are the most challenging products in terms of the design of the corresponding forming/cooling tools, since each specific profile demands design of a tailored calibration system. A calibrator for extruded profiles comprises the forming cavity, a cooling system and a vacuum system as can be seen in Fig. 2.

Having in mind the above, the research team of the current work developed and validated an algorithm for the thermal design of calibrators for thermoplastic profiles, encompassing a non-isothermal 3D code based on the finite volume method (FVM) to model the thermal interchanges during the extrusion calibration/cooling stages, geometry and mesh generators, and an optimization routine aiming at determining the optimal cooling conditions [15–18]. A major difficulty to be faced in the use of the referred modelling code is an adequate prescription of the heat transfer coefficient, h , between the plastic profile surface and the cooling medium, i.e., calibrator internal walls, water or air, which must include the effect of the contact resistance. In fact, in a previous work [15] it was demonstrated that, despite the huge numbers of parameters influencing the performance of calibration systems (such as geometry of the cross section of the extrudate, polymer used, extrusion temperature, extrusion velocity, layout and diameter of the cooling channels, cooling water temperature, use of one or more calibrators in series, length of calibrators, distance between consecutive calibrators, material of construction of the calibrator, among others), the value adopted for the convection heat transfer coefficient, h , at the polymer-calibrator interface is one of the most influential parameters affecting the plastic profile cooling rate. The selection of the most appropriate value for h is still an unsolved problem, since it depends on many factors (surface finish of the

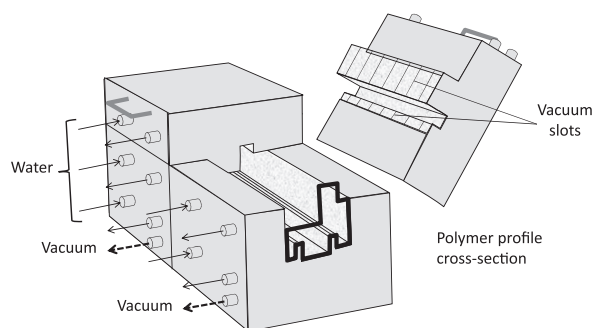


Fig. 2. Typical thermoplastic profile calibrator.

calibrating cavity, level of vacuum used, difference of temperature between the surfaces of the polymer and the calibrating cavity, length of calibrator, cooling fluid used, etc.), is difficult to determine and, therefore, often appears in the literature with values ranging several decades (between 10 and 10 000 W.m⁻².K⁻¹) [19].

If the contact between two bodies is not perfect, a discontinuity in the temperature profile at their interface may occur (see Fig. 3(a)), its magnitude being proportional to the heat contact resistance that characterizes their interface. As described in [15], at the polymer-metal interface the heat flux is equal in both domains, its magnitude being a function of the temperature difference, thus governed by the following equations:

$$\begin{aligned} k_c \left(\frac{\partial T_c}{\partial n} \right)_{\text{interface}} &= -k_p \left(\frac{\partial T_p}{\partial n} \right)_{\text{interface}} \\ &= h_{\text{interface}} (T_p - T_c)_{\text{interface}} \end{aligned} \quad (1)$$

where T is the medium temperature, k is the thermal conductivity, $h_{\text{interface}}$ is the interface heat transfer coefficient and n is the normal vector of the surface. The subscripts p and c denote polymer and calibrator, respectively.

Therefore, the determination of the local heat contact resistance at the interface, or its inverse (corresponding value of the heat transfer coefficient), would require the measurement of the temperature of each surface at the interface. In extrusion calibration, this means that one would need to measure the temperature of the surface of the calibrator that is in contact with the polymer extrudate, and that of the polymer contact surface at the same location. This is not feasible since it would affect the heat transfer that takes place at the interface. Some alternative procedures have been developed to bypass this problem [20,21], which are described in the few published works related to the determination of convection heat transfer coefficients in polymer extrusion. One of the most complete studies is that carried out by Pittman and Whithan [20]. They studied the cooling of thick pipes, resorting to a special thermocouple unit encompassing four thermocouples that are pressed onto the pipe wall and inserted at different depths along the thickness of the thick pipe, which is carried down the length of the cooling stage. After the extrusion run, the precise location of the thermocouples was determined by X-ray. The process gave rise to the detailed evolution of the temperature of the pipe along the extrusion line (at different depths along its thickness) and enabled determination of the heat transfer coefficients corresponding to the different water tanks and in the annealing zones between them, after performing computer simulations of the experimental run. This solution proved to be quite useful for thick pipe extrusion where the cooling is performed by immersion in water, but could not be used in profile cooling, where the physical structure that supports the thermocouples (which is carried by the extrudate) would be in contact with the internal surface of the calibrator, affecting the heat transfer at the polymer-calibrator interface and bringing problems related to friction. Recently, a study on heat transfer during the cooling of profiles, using calibration, was published by Mousseau et al. [21]. These researchers developed a special instrumented calibration device which, together with a 2D

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