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Sustainable injection moulding: The impact of materials selection and gate location on part warpage and injection pressure

Marton Huszar *, Fawzi Belblidia, Helen M. Davies, Cris Arnold, David Bould, Johann Sienz

College of Engineering, Swansea University, Singleton Park, Swansea SA2 8PP, UK

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ABSTRACT

This paper presents an approach of how warpage (i.e. part deflection) and injection pressure of an intricate geometry could be minimised by selecting an optimal thermoplastic material and injection gate location (through which the molten plastic flows into the cavity). The numerical analyses for mould filling considered four gate locations along with a PP (polypropylene), PS (polystyrene) and a fibre-filled PP material (each had different shrinkage characteristics, mechanical property and viscosity). Results of the cavity filling simulations indicated that (on average) the largest and smallest warpage was predicted with the PP and PS respectively. The warpage of the fibre-filled PP showed the most gate location dependent behaviour. In addition, the lowest injection pressure was associated with the fibre-filled PP. For reduced pressure, the best and second best solutions for gate location were the top and middle ones. In addition, specific attention was paid to differential fibre orientation, as one of the most important factors responsible for part warpage. In an attempt to maximise the part stiffness, the fibre-filled PP was selected. It became clear that the gate location affected the melt flow evolution and therefore the fibre orientation. Simulation results showed that bidirectional flow and asymmetrical fibre distribution was achieved with the gate positioned at the mid-section of the part. Unidirectional flow and therefore symmetrical fibre distribution could be achieved by placing the gate at the top section of the part. The injection moulding experimental utilised the fibre-filled PP along with the two aforementioned gate locations. It was discovered that warpage was present when the middle gate was applied, but it was successfully eliminated using the top gate location. It can be stated that differential fibre orientation did not cause warpage, but the asymmetrical distribution of fibre orientation did. The information discussed in the paper may be particularly useful in the early mould/part design stages when any modification can still be easily and cost-effectively implemented. An important finding is that the final gate location should only be chosen after the thermoplastic material properties and melt flow direction have been taken into account. The successful reduction of warpage and injection pressure may help to reduce the amount of production waste and energy consumption, ensuring defect-free sustainable manufacturing.

1. Introduction and literature review

Thermoplastics injection moulding is regarded as one of the most important processes that can be used to produce plastic products [1]. It commences with feeding solid plastic material (usually granules) through the hopper to the heated injection barrel. In the plastication stage, the injection screw rotates and transports molten material to the screw chamber in front of the screw tip. When sufficient amount of molten material is prepared, the plastication stops [2].

During the filling stage, the part to be formed is achieved by injecting molten material into a mould cavity. The location of the injection gate is of great importance since it can influence the flow direction and melt solidification during and after filling [3]. When the cavity is nearly filled, the injection stage is followed by the packing stage, during which period additional pressure is applied to force more molten material into the cavity to compensate for material shrinkage [4]. Then, the cooling stage removes the remaining heat from the melt with the aid of cooling channels positioned inside the mould. The process ends with the opening of the mould half (or halves) and the solidified parts are removed by the means of ejector pins [5]. In Fig. 1 a schematic is presented, describing the steps involved in the moulding process.

This cyclic process has widely been regarded as a quick and efficient technology where the production of complex geometries with intricate features is achievable. The whole process is controlled by numerous physical parameters and it is recognised that there is correlation among the process parameters, materials, part geometry and the quality of the moulded parts [6].

In one study cavity balancing was emphasised as being an important criterion during filling analyses to improve the quality of the moulded

* Corresponding author.
E-mail address: m.huszar@swansea.ac.uk (M. Huszar).

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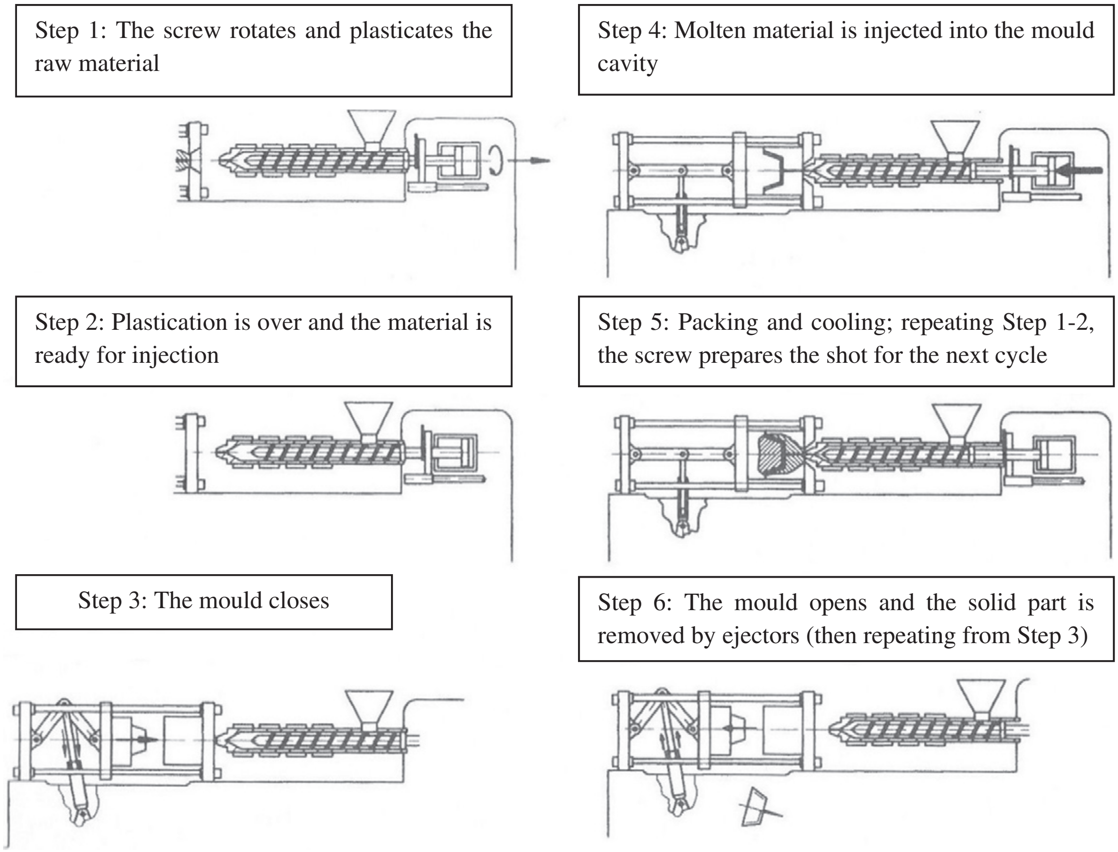

Fig. 1. The representation of the complete injection moulding cycle [2].

parts. If an unbalanced flow pattern existed, that would lead to (over-)packing difficulties and part warpage [7]. Also, the appropriate selection of gate position would help to reduce the filling time and balance the moulded parts' temperature distribution [8]. The incorrect selection of process conditions may result in undesirable shrinkage, warpage [9], unbalanced fill or deterioration of mechanical or optical properties [10].

Among the aforementioned moulding problems, the present paper focuses on part warpage and injection pressure. Prior to discussing warpage, it is necessary to describe the principle difference of shrinkage characteristics of thermoplastic materials. The Pressure–Volume–Temperature (PVT) diagrams provide information with respect to change in specific volume as a function of melt processing temperature and pressure applied on the melt. For amorphous and crystalline materials the specific volume in the melt range varies linearly with the temperature. When pressure is applied on the melt, the specific volume decreases, hence its reciprocal value, the density increases. Upon reaching the transition temperature below which the material is considered solid, amorphous and crystalline materials differ in shrinkage characteristics. Amorphous materials exhibit a linear variation, while crystalline grades show an exponential dependence of specific volume on temperature just below the transition temperature. Owing to the fact the crystalline grades consist of crystalline and amorphous phases, the crystallization phenomenon during solidification causes an orderly, consequently more densely packed microstructure. The formation of the crystalline phase results in greater density and therefore greater shrinkage, compared to amorphous grades [2].

It should be pointed out that uniform shrinkage will not cause warpage, however the variation in shrinkage will [9]. For warpage, the following major factors or the combination of these can contribute towards this quality problem.

Differential shrinkage can be caused by variations in part wall thickness. Upon solidification the larger thickness undergoes higher shrinkage. If the part is ejected before thicker region has cooled, there will be an increased variation in shrinkage between thick and thin regions [9]. In direct relation to this, variation in melt cooling rates (deviations in part temperature distribution) can cause variation in crystalline content increasing the likelihood of warpage.

Moulding process conditions may also induce variations in shrinkage. To control the formation of frozen layer and warpage, the appropriate selection of injection time, melt temperature [11], packing pressure [12] and packing time would be necessary [13]. Not only have the processing conditions played an important role in reduction of warpage but also part design as well. The warpage might be improved by introducing ribs which were to enhance the part's structural integrity [14]. Moreover, selecting a material that has low stiffness may cause greater warpage as it will have less resistance to distortion, while greater stiffness may help to improve the overall warpage [9]. For fibre-filled materials, greater warpage might be expected to occur with increased fibre volume fraction [15].

Also, differential mould cooling conditions can cause temperature deviation between the mould core and cavity surfaces. The melt suffers greater shrinkage at higher temperature areas, while lower shrinkage is observed at areas where the temperature is lower [16]. Here, the bending moment created by thermally-induced residual stress will cause the part to warp towards the hotter areas [9]. To override this problem the careful selection of cooling time and/or melt temperature would be necessary [17]. Further difficulties may arise if injection moulding is coupled with the in-mould roller (surface decoration) technique. For that, the thermal (e.g. heat retardation) effect of the film can also be a critical parameter than can affect the mould temperature distribution and final part warpage [18].