Powder Technology 305 (2017) 405–410

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

# Interface development and numerical simulation of powder co-injection moulding. Part. I. Experimental results on the flow behaviour and die filling process

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ARTICLE INFO

*Article history:*
Received 18 July 2016
Received in revised form 28 September 2016
Accepted 8 October 2016
Available online 11 October 2016

*Keywords:*
Powder co-injection moulding
Feedstock
Injection parameters
Interface morphology
Rheological theory

ABSTRACT

Powder co-injection moulding (PCM) was carried out by using two feedstocks, 316L(60%) and 316L(40%), as core and skin feedstocks, respectively. The effects of processing parameters such as the pre-filling volume of skin feedstock, the injection temperature of core feedstock and the injection rate of skin feedstock on the profiles of the two feedstock layers were studied. It was found that the interface between core and skin feedstocks exhibited an arched shape in the transverse plane and a V shape in the longitudinal plane. There is a “maximum thickness” of core feedstock in the longitudinal direction. The penetration length and maximum thickness depended on the injection parameters. The formation mechanism of the interface was studied on the basis of rheological theory. This research provided an experimental base for the simulation work of PCM processes.

## 1. Introduction

Powder co-injection moulding is a novel technology which combines the advantages of polymer co-injection moulding and powder injection moulding [1–6]. It allows the fabrication of parts consisting of two layers with different properties. During processing, skin and core feedstocks are injected sequentially in one moulding machine through a single injection route. The first melt is injected, solidifying against the mould walls and creating a skin region. Then, the second melt is injected and solidifies between the top and bottom skin layers, forming a core region encapsulated by the skin layer. As a result, a skin-core-skin morphology through the thickness of the moulded part can be obtained. Subsequent co-debinding and co-sintering are carried out to produce the final parts.

Recently, the amount of reports and patents concerning PCM have increased [7]. PCM significantly reduces the manufacturing steps required by conventional coating or other surface treatment methods, and enables the production of parts consisting of two ceramic and/or metal materials with different mechanical, electrical or thermal properties. Compared to a coating process, which is an additional processing stage, PCM is more suitable to produce samples with small complex geometries and relatively thick surface layers [3]. Moreover, PCM can reduce the processing cost by using cheap core materials and eliminating finishing steps of the final product. Our previous work has reported a PCM gear consisting of an outer layer fabricated from Fe-2Ni-1Cr low alloy steel, which exhibits high abrasive properties, and an inner layer fabricated with Fe-2Ni steel, which exhibits excellent ductility [8].

Nevertheless, the limited reports of PCM also outline several critical issues of this method. First, the breakthrough phenomenon, which is said to happen when the core material feedstock appears at the surface of the fabricated part, is the most prominent moulding defect in PCM and polymer co-injection moulding processes [9]. The breakthrough of core material makes the part unusable and must be avoided. This phenomenon has been investigated systematically in polymer co-injection moulding but is of limited concern in PCM [9]. In PCM, the probability of breakthrough is less due to higher strength of the feedstock, but cannot be ignored.

Apart from breakthrough of core material, most problems are related to the interface between the core feedstock and skin feedstock, namely the profile of the two feedstocks and the homogeneity of the distribution of the skin feedstock. The thickness and homogeneity of the skin feedstock play a critical role in the properties and cost of the final part. From previous research on polymer co-injection moulding, it is known that the morphology of the interface is influenced by the incompatibility of the injection parameters of the two feedstock, which requires an overall study involving several moulding factors such as

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http://dx.doi.org/10.1016/j.powtec.2016.10.015
0032-5910/

viscosity ratio, injection speed, injection timing of the core material, skin/core volume ratio and mould temperature [10–12]. Up to now, research on PCM is limited, and most of it focuses on the co-sintering behaviour and properties of the final product [13–18]. Research on the co-injection step, especially the flow behaviour and core/skin feedstock interface development, has not been addressed. However, the profiles of the skin/core feedstock is essential for achieving defect-free parts after subsequent co-debinding and co-sinter procedures [1]. The two materials need to follow a similar shrinkage pathway in the subsequent processes to avoid development of mismatch stresses at the interface, which may lead to cracking, warpage, or distortion [13,19,20].

In this work, the flow behaviour and the interface evolution of skin and core feedstock layers used in PCM were investigated. The effects of processing parameters such as pre-filling volume of skin feedstock, injection temperature, injection rate and injection time on the PCM process were studied. The flow and formation mechanism of the core/skin feedstock morphology and the distribution of the two feedstocks are discussed in detail using a model. This model can provide an alternative solution for understanding die filling and extend the knowledge of interface development of PCM.

## 2. Experimental procedures

### 2.1. Injection parameters

A thin square plate mould was used for the simulation process. The injection gate was located in the bottom centre. The geometry of the mould is shown in Fig. 1.

The gas-atomised 316L stainless steel powder (provided by Osprey Metals Ltd., $d_{50} = 12$ μm) and a multicomponent binder system composed of 55 wt.% paraffin wax, 35 wt.% polypropylene, and 10 wt.% stearic acid were used. Feedstock with 40% powder loading was used as core feedstock, and with a loading of 60% was used as skin feedstock. In order to distinguish the two feedstocks, graphite powder (mass ratio = 1/150) was added to the core feedstock. The powder and binder were initially blended in a three-dimensional shaker for 30 min at room temperature, and then compounded in an XSM1/20-80 rubber mixer at 165 °C for 2 h. The apparent viscosity and specific heat of the binder were measured using a Rheo5000 capillary rheometer at temperatures ranging from 152 to 170 °C. The determination of the rheological properties of the feedstock was described in previous work [21].

Injection was conducted on a HTF90W2 polymer co-injection machine. Several groups of PCM experiments were conducted, and their parameters are summarized in Table 1. The influence of the skin feedstock volume, injection rate, injection temperature and injection time of the two feedstocks was investigated. The injection pressure for both types of feedstock was 70 MPa, and the mould temperature was 35 °C.

### 2.2. Morphology of the PCM parts and its measurement method

The green parts were polished from the transverse or longitudinal direction to observe the morphology. Fig. 2 shows the pictures of the mid-cross section of the sample polished from the transverse direction (the injection gate is located on the top side). Fig. 2(a) shows that the core feedstock region is arched-shaped. The width of the core feedstock region (shown as dark grey area) gradually decreases from the top (13.4 cm) to the centre (13.1 cm) of the sample, followed by a rapid decrease to 11.4 cm and then to 0. While, Fig. 2 (b) shows a near-ladder shape. The width of the core feedstock region decreases slowly till the bottom end of the grey area and that bottom end is almost parallel to the square plate's bottom edge, which is the characteristic of breakthrough.

Fig. 3 shows the pictures of the samples polished from the mid-cross section of the longitudinal direction (the injection gate is located on the right side). Fig. 3 (a) shows evidence of breakthrough (a reverse hook shape morphology), in which the thickness of the core layer increases from the centre to the left side, and the core feedstock appears on the top and bottom side. Fig. 3(b)–(d) show a V-type morphology, where the thickness of the core layer decreases gradually with the penetration length.

In order to determine the profiles of the two feedstocks, the penetration length and thickness of the core feedstock in the longitudinal direction were measured. The thickness was measured for every 10 mm penetration length. The core layer friction, i.e. the ratio of core layer thickness to the whole thickness, was used to represent the interface

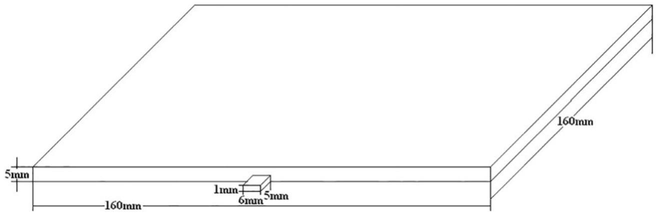

**Fig. 1.** Schematic of the mould used for simulation and verification work.

**Table 1**
Co-injection moulding parameters of PCM experiments.

| No. | Injection rate (core/skin)/mm·s$^{-1}$ | Injection temperature (core/skin)/°C | Pre-filling volume of skin feedstock | Injection time (core/skin)/s |
|---|---|---|---|---|
| 1-1 | 40/40 | 170/160 | 40% | 3.0/3.0 |
| 1-2 | 40/40 | 170/160 | 50% | 3.0/3.0 |
| 1-3 | 40/40 | 170/160 | 60% | 3.0/3.0 |
| 1-4 | 40/40 | 170/160 | 70% | 3.0/3.0 |
| 1-5 | 40/40 | 170/160 | 80% | 3.0/3.0 |
| 2-1 | 80/80 | 135/165 | 60% | 3.0/3.0 |
| 2-2 | 80/80 | 145/165 | 60% | 3.0/3.0 |
| 2-3 | 80/80 | 155/165 | 60% | 3.0/3.0 |
| 2-4 | 80/80 | 165/165 | 60% | 3.0/3.0 |
| 2-5 | 80/80 | 175/165 | 60% | 3.0/3.0 |
| 3-1 | 60/15 | 170/160 | 60% | 3.0/3.0 |
| 3-2 | 60/20 | 170/160 | 60% | 3.0/3.0 |
| 3-3 | 60/30 | 170/160 | 60% | 3.0/3.0 |
| 3-4 | 60/60 | 170/160 | 60% | 3.0/3.0 |
| 3-5 | 60/90 | 170/160 | 60% | 3.0/3.0 |
| 4-1 | 40/40 | 170/160 | 60% | 0.5/3.0 |
| 4-2 | 40/40 | 170/160 | 60% | 0.6/3.0 |
| 4-3 | 40/40 | 170/160 | 60% | 0.7/3.0 |
| 4-4 | 40/40 | 170/160 | 60% | 0.8/3.0 |
| 4-5 | 40/40 | 170/160 | 60% | 0.9/3.0 |
| 4-6 | 40/40 | 170/160 | 60% | 1.0/3.0 |
| 4-7 | 40/40 | 170/160 | 60% | 1.2/3.0 |
| 4-8 | 40/40 | 170/160 | 60% | 1.5/3.0 |
| 4-9 | 40/40 | 170/160 | 60% | 2.0/3.0 |
| 4-10 | 40/40 | 170/160 | 60% | 2.5/3.0 |

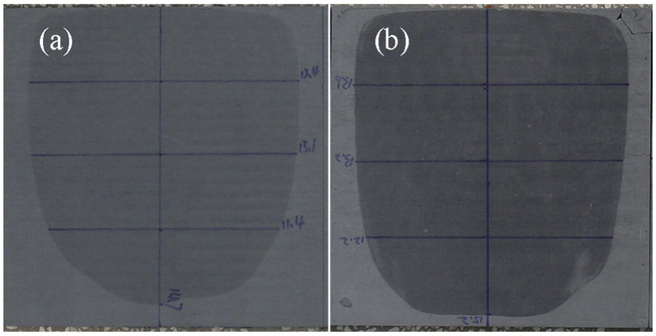

**Fig. 2.** Pictures of the mid-cross section of the sample polished from the transverse plane: (a) green part without breakthrough phenomenon; and (b) green part with breakthrough phenomenon. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)