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Phenomenological study and modelling of wick debinding

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ABSTRACT

Wick debinding employs capillary suction (via a surrounding wicking powder) to remove the liquid binder phase from powder injection moulded parts (known as a compact). Experimental measurements of binder distribution within the compact during debinding highlight flaws in previous wick debinding models. The spatially uniform distribution of binder observed consistently during debinding indicates that it is removed in order of pore size regardless of location in the compact. A model is proposed which gives good agreement with 1-D experimental data of binder distribution. Key parameters of the model are the permeability of the wicking powder and the relationship between the capillary pressure, saturation and relative permeability of the compact.

1. Introduction

Powder injection moulding (PIM) is used to manufacture precision high density items using extrusion (Mutsuddy and Ford, 1995). The injected material is a paste formed by mixing a powder with a binder phase: the latter is typically solid at ambient conditions but is liquid at elevated temperature. The paste is injection moulded above the binder melt temperature to form the green product, the resultant item removed from the mould and cooled. Before the powder can be sintered to form the final product, the binder phase must be removed without deforming the item.

This stage of the PIM process, known as debinding, can take place over several days in order for the binder to be removed in a controlled manner. There are several debinding methods (Lewis, 1997), the most common being to burn off the binder, leaving the solid powder. This can be performed in a single operation using a controlled temperature-time ramp. Solvent extraction is also used, where a large part of the binder is removed by dissolution in a suitable solvent, with the remaining binder subsequently removed by burn-out.

A third method is wick debinding, where the green compact item is placed in contact with wicking powder and the temperature increased so that the binder melts. The wicking powder then extracts the liquid binder by capillary action as a result of the larger capillary suction pressures of the pores in the wicking powder compared to the compact. As well as removing the binder in a potentially more controlled manner than burning out, the wicking powder is often used to embed the item, allowing extraction of binder from all directions as well as affording the item significant structural support (German, 1987). These effects combine to improve the product quality. Defects can still occur, however, especially in parts with complex shape.

The understanding of the fundamental mechanisms of wick debinding is not well developed, and much of the published work in the literature builds on the model published by German (1987) with later evidence (Vetter et al., 1994a) indicating its limitations. Here we report an experimental investigation of wick debinding to elucidate the governing mechanisms and thereby develop a numerical predictive model of the process. The study employs both a commercial paste and wick debinding powder; the results are thus expected to apply to many industrial systems.

2. Background—modelling of wick debinding

German (1987) suggested that wick debinding follows one of two modes, namely compact-controlled and wick-controlled debinding. The former was preferable as the latter was considered to be inefficient due to the restriction of the wicking powder on debinding times. For the compact-controlled case to occur, the permeability of the wicking powder, K_w, should be higher than that of the compact, K_c. However, German also stated that for the wicking powder to provide capillary suction, its pores should be smaller than those in the compact. Where the surface energies of the two powders are similar, this ordinarily leads to $K_c > K_w$, thereby contradicting the first condition.

German nevertheless proposed a quantitative model of wick debinding where a compact is in contact with wicking powder as shown

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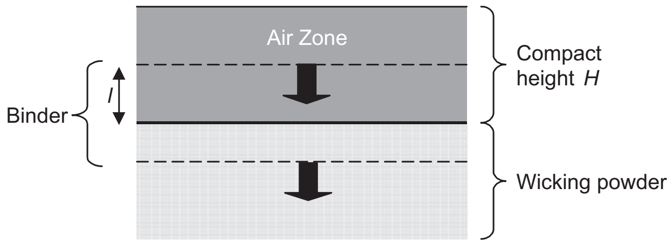

Fig. 1. Schematic of wick debinding mechanism proposed by German (1987).

schematically in Fig. 1. Debinding was modelled as the binder moving as a continuous body of liquid from its original location within the compact into the wicking powder, leaving the atmosphere to occupy the vacated pore space in the compact. The rate of removal was modelled as flow through a porous medium following Darcy's law, where the driving force is the difference in capillary pressures $(P_C - P_W)$, *viz.*

$$u = -\frac{K_C(P_C - P_W)}{\mu L} \tag{1}$$

where u is the superficial velocity of the binder, μ its viscosity, and L is the height (or length) of binder in the compact. The capillary pressure is determined by the surface tension, γ, the contact angle θ and the pore neck diameter d_p as presented in Liu et al. (1986):

$$P = \frac{10\gamma\cos\theta}{d_p} \tag{2}$$

while the permeability is based on the following approximation for packed beds of voidage ε; (German, 1987)

$$K_C = \frac{\varepsilon_C^3 d_C^2}{90(1-\varepsilon_C)^2} \tag{3}$$

A volume balance gives

$$-\varepsilon_C\frac{dL}{dt} = u = -\frac{K_C(P_C - P_W)}{\mu L} = \frac{\varepsilon_C^4\gamma d_C(d_C - d_W)}{9\mu d_W(1-\varepsilon_C)^2 L} \tag{4}$$

The time required to remove all the binder from the compact, t_D, is given by

$$\int_0^H L\,dL = -\frac{\varepsilon_C^3\gamma d_C(d_C - d_W)}{9\mu d_W(1-\varepsilon_C)^2}\int_{t_D}^0 dt \tag{5}$$

which yields

$$t_D = 4.5\frac{(1-\varepsilon_C)^2\mu H^2 d_W}{\varepsilon_C^3\gamma d_C(d_C - d_W)} \tag{6}$$

where H is the compact height.

German reported that this model gave good agreement with the experimental data of Waikar and Patterson (1986) which showed a linear relationship between the square of the total mass loss against time. However, he assumed the total debind time (as predicted by his model) could be equated to the time for partial debinding (as measured experimentally). German equated the mass loss with H, which was subsequently critiqued by Vetter et al. (1994a) since the mass of binder removed does not relate directly to H for partial debinding. Fig. 2 schematically illustrates this discrepancy between German's model and typical experimental results, such as those of Patterson and Aria (1989) and Waikar and Patterson (1986), in terms of x verses debind time, where x is the fraction of binder removed from the compact.

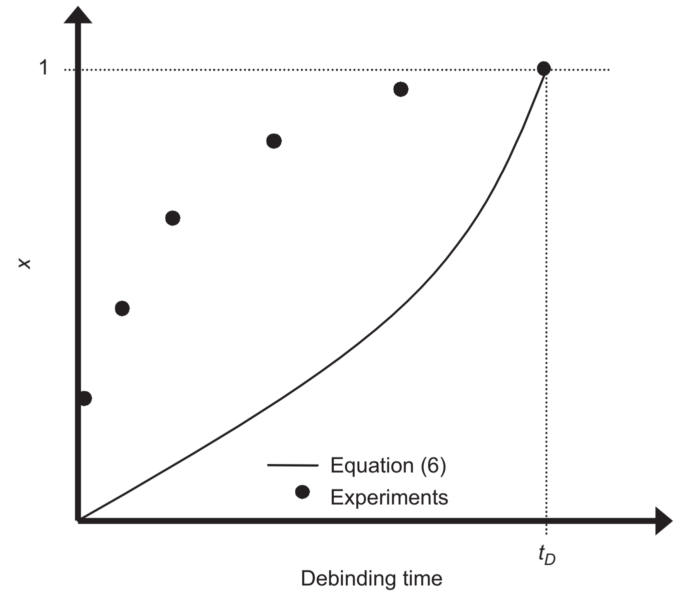

Fig. 2. Comparison of Eq. (6) with typical experimental results (such as those reported by Patterson and Aria, 1989; Waikar and Patterson, 1986).

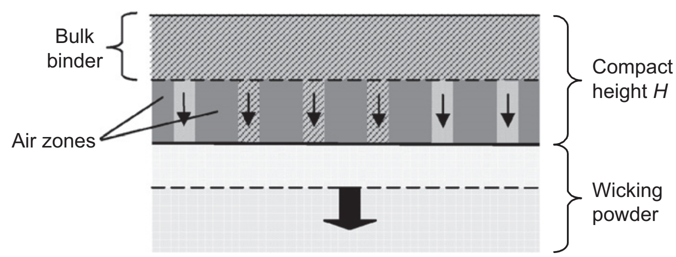

Fig. 3. Schematic of wick debinding mechanism proposed by Vetter et al. (1994b).

Although Lograsso and German (1990) claimed to confirm Eq. (6) experimentally, Vetter et al. (1994a) found that this model underestimated the debinding time by two to three orders of magnitude. Furthermore, German's model prediction of t_D is of limited use as complete removal of binder from a compact is unlikely because there often exists a minimum x in the form of an irreducible liquid binder saturation. It is impossible to remove all the binder from a porous network due to: (i) small pores retaining binder that have a higher capillary suction pressure than the wicking powder and (ii) snap-off where ganglia form in the porous network (Dullien, 1972), creating small pores which cannot be drained due to the surrounding larger pores having been completely drained; there is thus no route for binder transport to the surface.

Despite these criticisms, German's model is frequently used as the basis for research in wick debinding. Chen and Hourng (1999) conducted finite element numerical simulations based on Eq. (6) that agreed with the theory as expected. Their 2D simulations showed binder moving from a compact into wicking powder with both leading and trailing fronts as in Fig. 1. However, their results were not validated experimentally. Lin and Hourng (2005) simulated the movement of binder from a compact into wicking powder by German's binder removal mechanism using a pore network approach. They compared the predicted location of the binder front with corresponding experimental observation of the front in the wicking powder. Although their results demonstrated reasonably good agreement, they again assumed a trailing binder front leaving the compact on completion of debinding.