



Adhesion tension force between mould and pattern wax in investment castings



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ABSTRACT

The adhesion tension of commercial filled and unfilled waxes in contact with a representative ceramic shell system used in investment casting was determined by the Wilhelmy plate method. The average adhesion tension force off our filled waxes reduced at a rate of approximately $6.0 \times 10^{-8} \text{ Nmm}^{-1} \text{ }^{\circ}\text{C}^{-1}$ and the unfilled wax at a rate of $3.4 \times 10^{-8} \text{ Nmm}^{-1} \text{ }^{\circ}\text{C}^{-1}$. Adhesion tension measured by Wilhelmy plate method was compared to the surface tension of wax measured by the Du-Nuoy ring method. It is suggested that Du-Nuoy ring method is the simplest practical experiment to obtain the characteristics of wax-shell interaction for modelling applications.

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1. Introduction

A key step in the investment casting process is the removal of the wax from the mould. During the de-waxing process, the heating rate is rapid; so that bulk expansion of the wax does not occur before a proportion of the wax melts and flows from the mould or penetrates the shell. This is due to the wax having a lower thermal conductivity but a greater thermal expansion coefficient than the shell. This difference of thermal expansion would otherwise cause the shell to crack. Peter Wang (2012) has described the way stresses can be relieved, by;

- Propagating an existing crack or defect (fracture toughness).
- Absorbing the force exerted by wax on the shell (strength).
- Allowing the wax to flow through the shell (permeability).
- Removal of wax before critical stress values are reached.

It is believed that permeability and strength of the ceramic shell are the two most critical properties to prevent shell cracking. Surface tension (γ) is an important parameter that influences the penetration of wax into the porous shell and the flow of molten wax out of the mould. It is however, not understood if the inter-

action of the investment casting ceramic's surface energy with the wax in terms of contact angle is significant. Gebelin et al. (2004) used computer modelling to understand the wax penetration into shell and made the assumption that the contact angle of wax and ceramic was zero.:

In this paper, the adhesion tension, $\gamma \cos(\theta)$ where θ is the contact angle is determined using the Wilhelmy method and compared to surface tension measured by Du-Nuoy ring to establish an estimate of ceramic-wax interaction.

The flow of liquid (wax) into porous materials is governed by the Washburn equation (Washburn, 1921).

$$\frac{dl}{dt} = \frac{r}{\mu} \frac{\gamma}{4l} \cos\theta \quad (1)$$

where r is radius of pores (m), μ is the viscosity of permeate (Pa s) and l is the depth of penetration (m)

The equation is derived from the Poiseuille's law where volumetric flow rate is replaced with length of fluid flow over time. Hagen-Poiseuille equation is used to describe flow of liquids passing through tubes (horizontal capillaries) and neglecting the effect of gravity (Fig. 1). The length of penetration L_{lf} can be simply found by integrating the Washburn equation,

$$L_{lf} = \sqrt{\frac{\gamma D_e \cos(\theta)}{4\mu} t} \quad (2)$$

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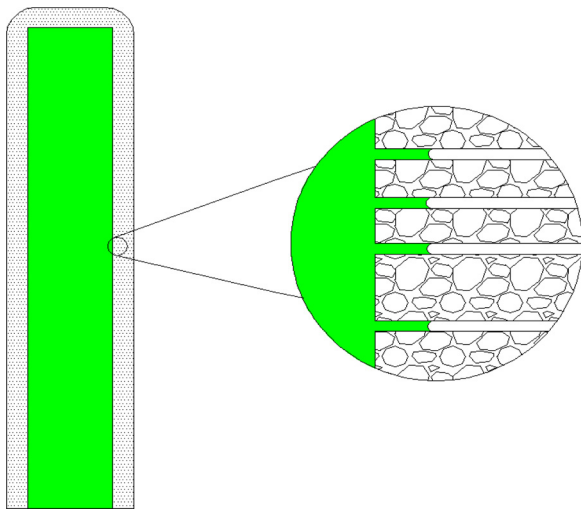


Fig. 1. Schematic representation of the initial de-wax process where wax is forced into the porous ceramic shell. In the models where Poiseuille is assumed, the pores are represented as horizontal tubes.

where D_e is diffusivity ($\text{m}^2 \text{s}^{-1}$), μ is viscosity ($\text{kg m}^{-1} \text{s}^{-1}$), t is time (s).

Masoodi and Pillai (2010) showed how Darcy's law can be integrated with the continuity equation (volume-averaged liquid velocity in all directions is equal to zero) to give Eq. (4) in which the surface tension effect is taken into account. Darcy (1856) had showed flow rate of permeates can be described as,

$$Q = \frac{-kA (P_b - P_a)}{\mu l} \quad (3)$$

where Q is the flowrate of permeate ($\text{m}^3 \text{s}^{-1}$), A is the surface area pores (m^2) and $(P_b - P_a)$ is the pressure difference across the porous media (Pa).

The integration gives Eq. (4) which has similar form as Eq. (1). It can be seen that both equations require surface tension, contact angle, viscosity and either permeability or diffusivity

$$L_{if} = \sqrt{\frac{2Kp_c}{\epsilon_f \mu}} t^2 \quad (4)$$

where, K is permeability (m^2), ϵ_f is porosity, $P_c = 2\gamma \cos(\theta)/r$ and r is the radius of capillary.

The permeability of wax into the shell has been previously measured by Cendrowicz (2004). He forced molten low viscosity gate wax through the shell and measured the flow rate. A permeability of $1100 \pm 400 \text{ nm}^2$ was obtained for a standard ceramic shell used to cast steel. In some cases, permeability is measured using gas instead of wax. However, Hendricks et al. (2002) state that permeability measurement using gas is less indicative of the de-wax process. They found that this is due to the possibility of inherent variability in the permeability test where the gas flux takes into account the resistance time of gas flow through the shell. Ideally, the test should simulate the actual condition of the de-wax autoclave to obtain a similar pressure difference across the shell where the pressure of steam is pushing in the opposite direction to the wax flux. Henderson et al. (2005) and Civan (2001) predicted the permeability of porous media as a function of porosity. Henderson et al. (2005) claimed that the equations being used are suitable for heterogeneous porous media. Researchers have demonstrated the use of the Kozeny–Carman equation, which yields permeability as a function of porosity (Latief and Fauzi, 2012; Xu and Yu, 2008). However, Civan (2001) realised the Kozeny–Carman equation does not incorporate a gate effect term, which relates to the pores morphology on the shell surface, for porous media and showed that if this

Table 1
Standard steel primary slurry composition.

Initial formulation	Mass (%wt)
Filler (zircon flour)	79.83
Binder (silica)	17.00
Polymer	1.20
Wetting agent	0.06
Antifoam	0.10
Deionised water	1.81

were incorporated the permeability could be accurately predicted. Civan (2001) has validated his model using gypsum and quartz. This model could be applied to shell materials if the porosity was sufficiently well defined. The methods discussed above give a good approximation to obtain the permeability of shell to be substituted into Eq. (2) or Eq. (4).

Obtaining the depth of wax penetration into the shell using Eq. (2) or Eq. (4) and with a known shell surface area would allow the prediction of total volume of wax that penetrates the shell pores. This penetration potentially reduces the hoop stress in the shell. Two of the most common methods to measure surface tension are the Du-Nuoy ring and the Wilhelmy plate. Torres (2003) is one of the few researchers who have used the Du-Nuoy ring method to determine the surface tension, γ of wax. He found the surface tension of wax varies between 2 and $3 \times 10^{-5} \text{ N mm}^{-1}$ depending on temperature and wax type. In this paper, the Wilhelmy method which measures the adhesion tension, $\gamma \cos(\theta)$ was compared to the Du-Nuoy ring method to determine if the contact angle between the wax with the ceramic is an important factor. Most Du-Nuoy rings are made of platinum where the contact angle of most liquids on the surface of platinum can be assumed to be zero as platinum has high surface energy. If this method is used, it would not adequately represent the interaction between wax and ceramic. Adhesion tension is suggested as a complimentary measure to surface tension because other solids may have surface energies significantly different to platinum. If the Du-Nuoy ring method is used then the contact angle would have to be measured separately and at an elevated temperature this becomes an issue due to light diffraction and reflection and therefore, errors can be significant. Comparing adhesion and surface tension allows the contribution of contact angle to be established. The general equation to obtain the surface tension, γ using the Wilhelmy method is:

$$\gamma = \frac{W_g}{l \cos \theta} \quad (5)$$

where, W_g is the force observed (N), l is the perimeter of the rectangular plate (m) used in this test and θ is the contact angle of liquid with plate.

Harkins and Harkins (1929) show that the surface tension force from the Du-Nuoy ring method can be calculated using:

$$\gamma = \frac{W_g}{4\pi R} \times F \quad (6)$$

where, γ is the surface tension (Nm^{-1}), and R is the radius of the ring (m). F is correction factor.

2. Materials and methods

Primary slurry used for steel casting was slip cast into $20 \times 80 \text{ mm}$ rectangular bars. The formulation of primary slurry is shown in Table 1. These bars were then dried and sintered at 1650°C for 2 h, with a ramp rate of $10^\circ \text{C min}^{-1}$. X-ray diffraction (XRD) was carried out after the sintering process to confirm no dissociation of zircon had occurred (Fig. 2). Pavlik and Holland (2001) have shown that zircon converts to zirconia and silica at 1676°C . The high sintering temperature was selected to allow full densifi-

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