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Control of the degree of pore-opening for porous metals

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A mechanism-based analytical model for calculating the Degree of Pore-Opening (DPO) of porous metals processed via negative pressure infiltration method is developed. The emphasis is placed on predicting the dependence of DPO on the infiltration pressure difference, particle size, surface tension, and wetting angle between liquid metal and particles. Experimental measurements are subsequently performed to check the accuracy of model predictions, and it is shown that the proposed model can be used to quantitatively control the microstructure of porous metals during infiltration processing. © *2001 Kluwer Academic Publishers*

1. Introduction

The microstructure of an infiltration-processed porous metal with open cells is characterized by a variety of parameters, including the pore size, porosity, and the Degree of Pore-Opening (DPO). Amongst these, DPO is perhaps the key parameter controlling the permeability of the material, and hence strongly influences such material properties as sound absorption [1], heat transfer [2, 3] and filtration. However, except for some preliminary studies [3], it appears that no existing method can be used to quantitatively control the DPO of porous metals during the infiltration process.

In the present study, a mechanism-based model is developed to predict the DPO as a function of process parameters such as the infiltration pressure ΔP, radius of spherical particles R, surface tension of liquid metal σ, and wetting angle between liquid metal and particles θ. Experimental measurements on porous aluminium alloys are subsequently carried out to check the accuracy of analytical predictions.

2. Principles of the infiltration preparation of porous metals

Porous aluminium alloys were processed by the method of negative pressure infiltration. Here, liquid metal is infiltrated under negative pressure around preheated spherical particles packed in a mould to form a metal/particle composite; after cooling down to room temperature, the water-soluble particles are then removed under water jet, resulting in a porous metal skeleton consisting of interconnecting pores. Fig. 1 depicts two rigid spherical particles O_1 and O_2, having identical radius R and contacting at point O, with liquid metal trying to enter the interstices of the particles under infiltration pressure ΔP. In the X-Y plane of interest, let the contacting between melt surface and particles O_1, O_2 be denoted by A' and A, and let the contacting point between melt surface and the Y axis be represented by D. Note that the surface of the melt trapped between the particles is formed by rotating the curve ADA' around the X axis. Because the particles are normally not wetted by the melt, i.e., the wetting angle θ between the melt and particles is greater than 90°, the surface tension σ of the melt will prevent the melt from penetrating to the point O if the pressure is not sufficiently high. Consequently, a passage connecting the neighboring pores after the removal of particles exists. With the assumption that the radius of the passage is δ which equals the length of OD, the ratio δ/R is defined here as the Degree of Pore-Opening (DPO). The existence of DPO ensures the successful removal of spherical particles after infiltration and, to a certain extent, controls the structure of the pores. Fig. 2 shows a typical cross-section of a porous aluminium specimen where the pore-openings can be easily identified—the small, dark circular dots underneath individual pores.

According to the above infiltration mechanism of porous metals, it can be expected that DPO is strongly influenced by the parameters ΔP, R, δ and θ. The main purpose of this work is to determine the functional dependence of DPO on these parameters.

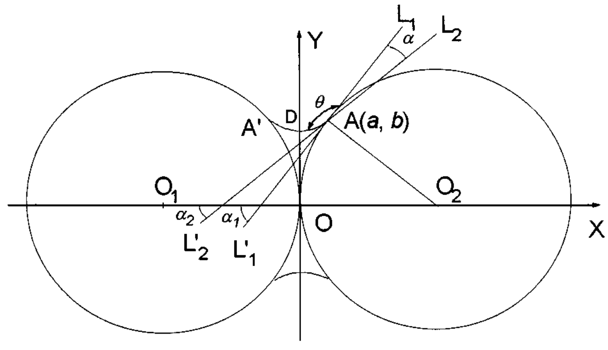

Figure 1 Schematic illustration of infiltration process.

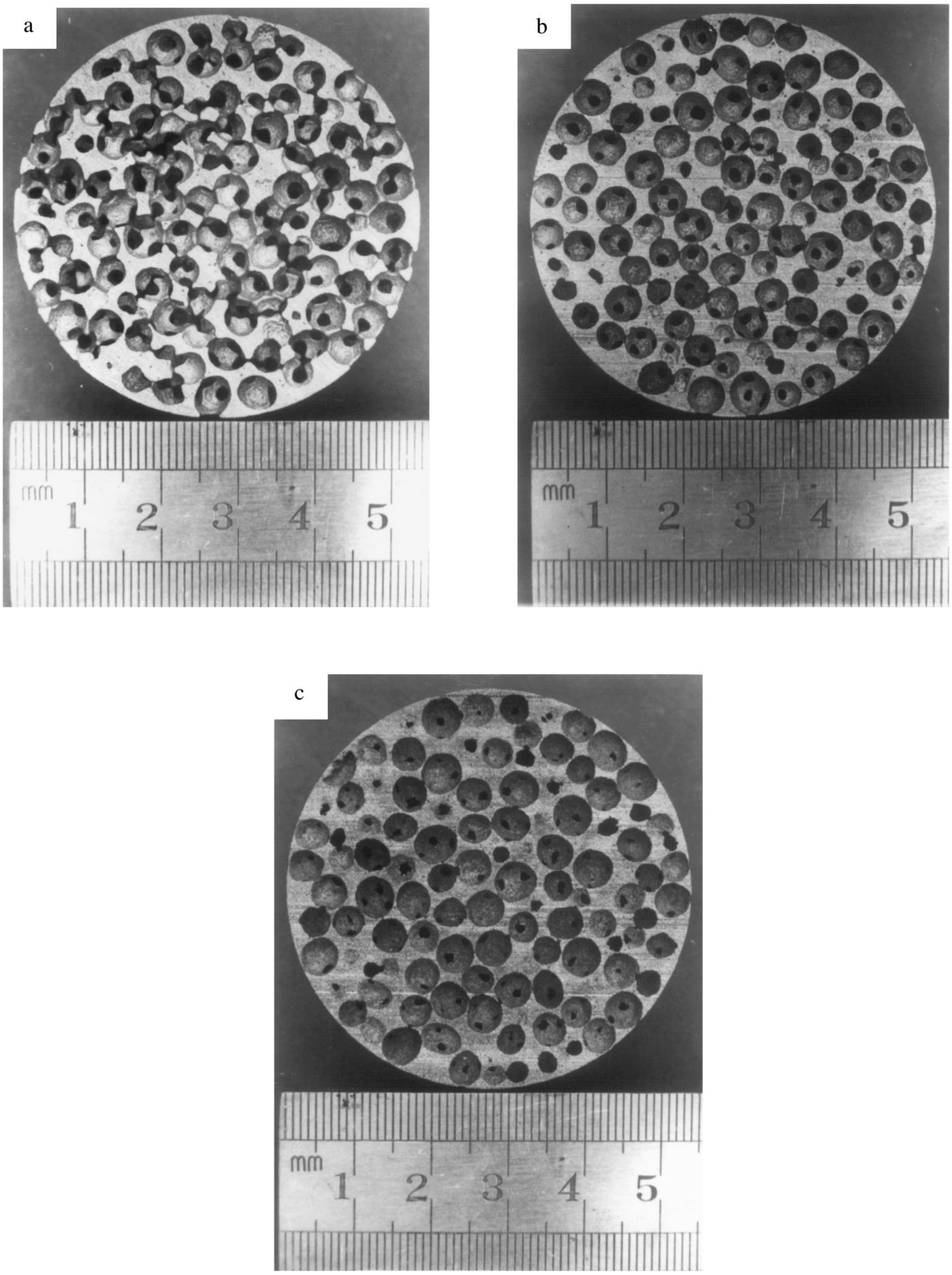

Figure 2 Typical cross-section of porous alluminium with open cells: (a) $\Delta P = 4.00$ kPa, DPO = 0.33; (b) $\Delta P = 9.33$ kPa, DPO = 0.27; (c) $\Delta P = 29.3$ kPa, DPO = 0.16.

3. Theoretical model

3.1. The model

Let L_1L_1' be the tangent of the circle O_2 at point A, which forms an angle α_1 with the X axis, and let L_2L_2' be the tangent of the curve ADA' at point A, which forms an angle α_2 with the X axis. The angle between L_1L_1' and L_2L_2' is denoted by α, so $\theta = 180 - \alpha$ is the wetting angle between liquid metal and spherical particles. Since $\alpha = \alpha_1 - \alpha_2$, it follows that

$$\theta = 180 - \alpha = 180 - (\alpha_1 - \alpha_2) \quad (1)$$

Under the present experimental conditions, the wetting angle satisfies the condition $90^\circ < \theta \leq 180^\circ$. Let the pressure difference above and below the melt surface ADA' be denoted by ΔP. Applying the Lapalace equation at point D on the curve ADA', we have

$$\Delta P = \sigma(1/r_1 + 1/r_2) \quad (2)$$

where r_1 is the radius of curvature of surface ADA' at point D, and r_2 is the radius of surface ADA' at point D formed by revolving ADA' around the X axis (the sign of r_2 is taken to be negative here). Note that r_2 equals the radius of the pore-opening OD, i.e., $r_2 = -\delta$. For simplicity, it is assumed that the shape of curve ADA' is parabolic, described by

$$Y = kX^2 + \delta \quad (3)$$

where the coefficient k is to be determined. It follows from (3) that the radius of curvature of the parabola at point D is $r_1 = 1/2k$. Upon substitution of the value of r_1, r_2 into Equation 2, one obtains

$$\Delta P = \sigma(2k - 1/\delta) \quad (4)$$

On the other hand, the equation of circle O_2 is

$$(X - R)^2 + Y^2 = R^2 \quad (5)$$

Let (a, b) denote the coordinates of point A, which is the contacting point of the parabola with circle O_2. Then from (3) and (5), one has

$$b = ka^2 + \delta \quad (6)$$

$$(a - R)^2 + b^2 = R^2 \quad (7)$$

Furthermore, from Equation 1, one has

$$\begin{aligned} \mathrm{tg}\,\alpha &= \mathrm{tg}(\alpha_1 - \alpha_2) \\ &= (\mathrm{tg}\,\alpha_1 - \mathrm{tg}\,\alpha_2)/(1 - \mathrm{tg}\,\alpha_1 - \mathrm{tg}\,\alpha_2) \quad (8) \end{aligned}$$

It is clear from Fig. 1 that tg α_2 is the slope of L_2L_2' which, from Equation 3, is given by

$$\mathrm{tg}\,\alpha_2 = 2ka \quad (9)$$

Similarly, because tg α_1 is the slope of L_1L_1', it can be calculated from Equation 5, as

$$\mathrm{tg}\,\alpha_1 = (R - a)/b \quad (10)$$

Substituting the expression of tg α_1, tg α_2 into Equation 8, one obtains

$$\mathrm{tg}\,\alpha = (R - a - 2kab)/[b + 2ka(R - a)] \quad (11)$$

The parameters ΔP, R, δ and α (a supplementary angle of θ) are determined by the processing conditions and the characteristics of the materials involved. From Equations 4, 6, 7 and 11, the unknown parameters a, b, k and δ can be obtained numerically [4]. The predicted dependence of DPO on ΔP, R, δ and θ is presented in Figs 3–5.

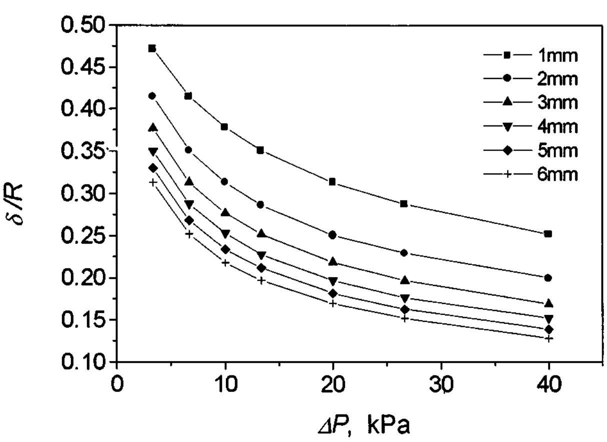

Figure 3 ΔP, R vs δ/R.

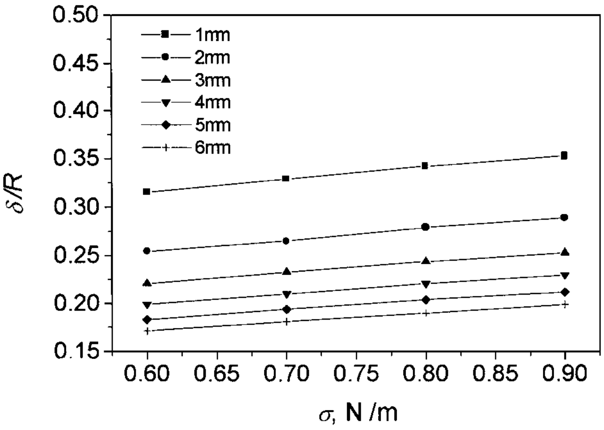

Figure 4 σ vs δ/R.

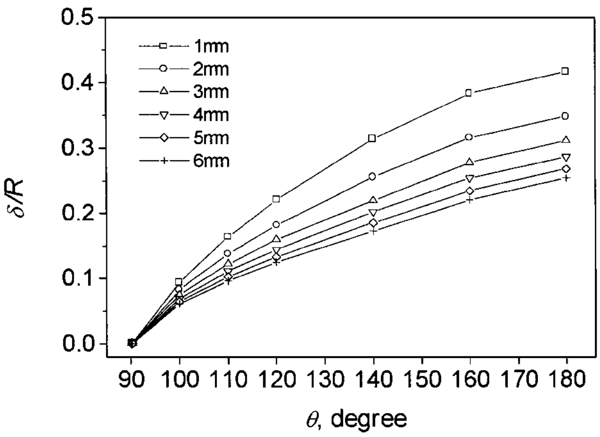

Figure 5 θ vs δ/R.

3.2. Parameter studies

3.2.1. The influence of ΔP and R

Assume the melt is pure aluminium at 720° (thus $\sigma_{\mathrm{Al}} = 0.893$ N/m [5]) and $\theta = 150°$. For particle sizes of $2R = 1$–6 mm and infiltration pressure difference of $\Delta P = 3.33$–39.99 kPa (25–300 mmHg), it is found that DPO decreases gradually with increasing ΔP for a constant R; however, for a constant ΔP, DPO increases with decreasing particle size (Fig. 3).

3.2.2. The influence of σ

Assume $\theta = 150°$ and $\Delta P = 13.33$ kPa (100 mmHg) for the Al-1%Pb aluminium alloy. At 720°, $\sigma_{\mathrm{A1}} = 0.893$ N/m and $\sigma_{\mathrm{A1-1\%Pb}} = 0.674$ N/m (Pb can effectively decrease the surface tension of the aluminium alloy melt) [6]. Within the variation range of $\sigma = 0.674$–0.893 N/m, DPO decreases slowly with the decrease of σ (Fig. 4).

3.2.3. The influence of θ

Assume $\sigma_{\mathrm{Al}} = 0.893$ N/m and $\Delta P = 13.33$ kPa (100 mmHg) for pure alluminium. It is found that DPO reaches its maximum value for $\theta = 180°$. With the decrease of θ, DPO decreases significantly and finally approaches zero when θ approaches 90° (Fig. 5).

3.3. Discussion

According to the above results, it is found that, to obtain a certain DPO, θ must be greater than 90°, and a large θ and a small R would have a bigger potential in adjusting DPO because changing ΔP is relatively easy during the infiltration processing of porous metals. σ has a weak influence on DPO, because it has a very limited adjustment range in practice. To obtain good properties of sound absorption, filtration and heat transfer (under forced convective conditions) for porous metals, these results suggest that it would be beneficial if smaller particles are chosen as the fillers so that DPO can be easily adjusted by varying ΔP during processing.

4. Experimental verification

To verify the analytical model, a series of experimental measurements were made by infiltrating liquid aluminium under different vacuum pressures into packed spherical particles of different sizes. A big container was used to keep the vacuum pressure relatively constant during the infiltration process. After the removal of the particles, the samples were sectioned using an electrodischarge machine, and the pore-openings of the pores (see Fig. 2) were measured with an optical testing apparatus having a precision of 0.01 mm. However, the measurement of pore openings is only approximate because the pore openings connecting the neighboring spherical pores appear at various positions on the surface of each pore, and at varying angles to the plane section. Here, the radius of those openings appearing normal to the observing direction of the optical microscope can be easily measure. For those openings inclined to the observing direction, the largest radius that can be measured with this method is used. For each section, the average of approximately 20–30 measurements is used below, and it is estimated that the measurement error is likely to be less than 10%. The measured DPO as a function of ΔP is shown in Fig. 6 (solid points).

The predicted relationship between DPO and ΔP is also shown in Fig. 6 (open points). The relevant parameters chosen are: R takes the average size of the particles having a size range of 0.9–1.6, 1.6–2.6, 2.6–3.0, 3.0–3.8, 3.8–5.8, 5.8–6.8 mm respectively; σ takes the value of pure aluminium melt at 660° (it starts to solidify at this temperature), i.e., $\sigma = 0.914$ N/m [5]; θ takes 152°, which was by analyzing the pore geometries with the optical microscope [4]. The theoretical relationships between DPO and ΔP agree closely with the experimental ones. Apart from experimental measurement errors, the slight discrepancy between theoretical and experimental results may be attributed to the fact that, in the theoretical model, only the average size of the particles practically having a size distribution was used.

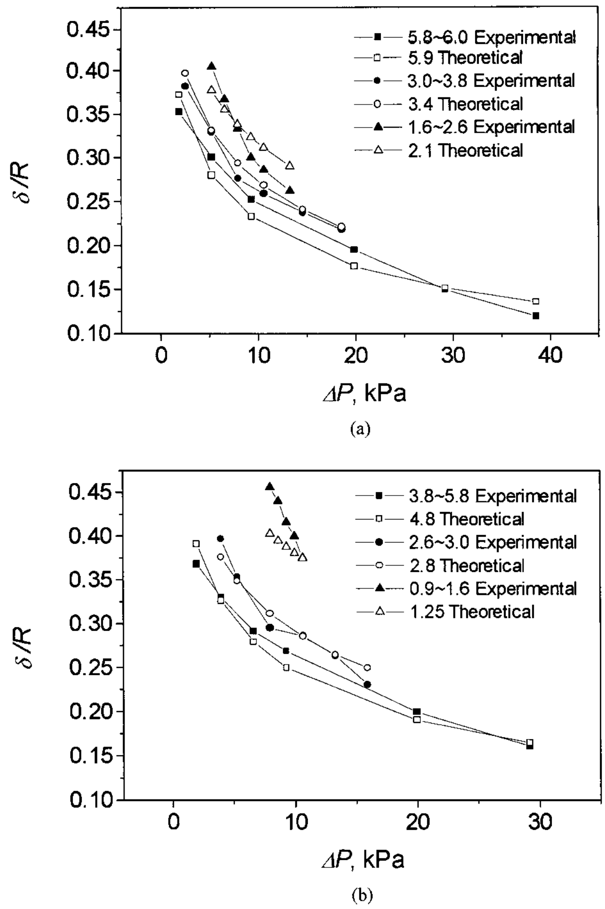

Figure 6 Contrast between theoretical and experimental results.

5. Conclusion

1. An analytical model for the Degree of Pore-Opening (DPO) of porous metals processed with infiltration method was developed. It was found that DPO decreases with increasing values of ΔP and R, whereas it increases with increasing θ. Surface tension only has a minor influence on DPO.
2. The predicted relationships between DPO and ΔP compares favorably with those measured.

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