DETERMINATION OF THRESHOLD PRESSURE FOR INFILTRATION OF LIQUID ALUMINIUM INTO SHORT ALUMINA FIBER PREFORM①

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ABSTRACT The statics of infiltration of liquid metal into short fiber preform was theoretically analysed by treating the fiber preform as a porous body. Two representative fiber distribution models, of which one assumed a planar distribution while the other assumed a quasi-planar distribution, were proposed and equations for calculating the effective capillary tube radius of the preform and the threshold pressure for infiltration corresponding to either fiber distribution model were derived respectively. By liquid infiltration experiment, the threshold pressure for infiltration of an Al-1.5 Mg aluminium alloy / short alumina fiber preform system was measured and the theoretical analysis results were well verified.

Key words liquid infiltration effective capillary tube radius threshold infiltration pressure metal matrix composite

1 INTRODUCTION

Liquid infiltration is a remarkably convenient and economical route for fabricating metal matrix composites (MMC_S). The technical process by this route includes two basic steps: (a) to prepare a preform of the reinforcing fibers or particulates and (b) to drive the liquid matrix metal into the spaces left by the reinforcement in the preform. So far, it has been utilized in different ways to fabricate MMC_S and a variety of techniques, such as vacuum infiltration[1], variable pressure infiltration[2], liquid forging[3], and extrusion directly following infiltration[4], have been developed.

The infiltration of liquid metal into reinforcement preform is a rather complex physical process which influences the combination of the metal matrix with the reinforcement. For most MMC_S systems investigated currently, the wettability between the matrix and the reinforcement usually is not good enough for spontaneous infiltration to take place within the practical processing temperature range and thus an external pressure must be supplied. Generally, if the applied pressure is not adequate, the infiltration process may not be activated or the penetrating will be too slow for the liquid metal to penetrate any desired distance before the infiltration channels are blocked up due to simultaneous solidification of the liquid metal. On the other hand, if very high pressure is exerted, then localized turbulent flow of the penetrating liquid metal which usually leads to involvement or trapping of gases in the preform will probably occur during infiltration. Besides, the preform is apt to deform under high pressure. Therefore, rationalizing the applied pressure is one of the key means to obtain good infiltration result.

It is necessary for the rational selection of the applied pressure to take into account the threshold pressure for infiltration, that is, the minimum external pressure required to activate infiltration. The present paper reports theoreti-

① Supported by the National Natural Science Foundation of China
Received Dec. 7, 1995; accepted Mar. 22, 1996

cal analysis and experimental investigation of the threshold pressure for infiltration of an aluminium/alumina system.

2 THEORETICAL ANALYSIS

If we treat a short fiber preform as porous body and take consideration of the problem according to statics, whether the infiltration process can take place spontaneously depends on the value of the capillary pressure drop given by the following Yong-Kelvin equation:

$$p_C = 2\gamma_{LV}\cos\theta / r \qquad (1)$$

where p_C is the capillary pressure drop at the infiltration front, γ_{LV} is the surface tension of the liquid metal, θ is the contact angle between the liquid metal and the preform material, and r is the effective capillary tube radius of the fiber preform.

For $\theta < \pi/2$ (wetting system), infiltration can take place spontaneously; for $\theta > \pi/2$ (non-wetting system), spontaneous infiltration is impossible and an external pressure is needed to overcome the capillary pressure drop so that infiltration can take place. As far as the non-wetting system shown in Fig. 1 is concerned, the threshold pressure for infiltration can be expressed as

$$p_{th} = p_V - \frac{2\gamma_{LV}\cos\theta}{r} - \rho g h_0 \qquad (2)$$

where P_{th} is the threshold infiltration pressure, P_V is the gas pressure in the preform, ρ is the density of the liquid metal and h_0 is the initial height of the liquid metal. Usually, the value of the term $\rho g h_0$ is very small and can be neglected. For infiltration under vacuum condition, $p_V = 0$; for infiltration under atmosphere, $p_V \approx 0.1$ MPa.

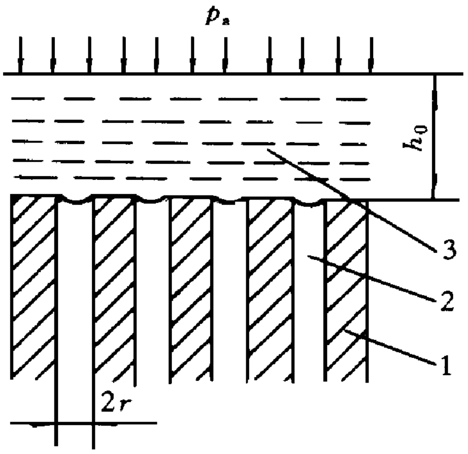

Fig. 1 Schematic illustration of liquid infiltration

1 —fiber preform; 2 —infiltration channel; 3 —liquid metal

Notice that the effective capillary tube radius in Eqn. (2) remains to be determined. The value of r often depends on such factors as fiber volume fraction, distribution and size characteristics. The following shows how it can be theoretically determined on the basis of two different kinds of approximation for fiber distribution.

The first fiber distribution model (Model Ⅰ) is shown in Fig. 2. It is a planar distribution model. In this case, we can obtain

$$\left.\begin{aligned} a &= \frac{\pi d_f}{4V_f} \\ r &\approx \frac{1}{2}(a - d_f) \\ &= \frac{(\pi - 4V_f)d_f}{8V_f} \end{aligned}\right\} \qquad (3)$$

where d_f is the fiber diameter and V_f the fiber volume fraction.

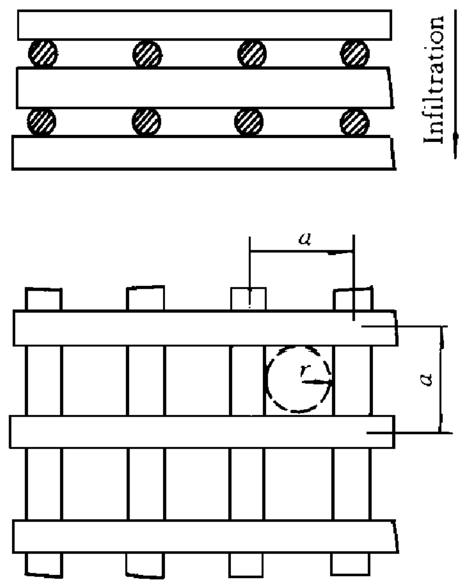

Fig. 2 Model Ⅰ demonstrating fiber distribution in fibrous preform

The secend fiber distribution model (Model Ⅱ) is shown in Fig. 3. It assumes a quasi-planar fiber distribution, with most fibers being distributed in parallel planes while a small fraction between the planes with an average inclination angle of α. When the fiber preform is prepared by unidirectional pressing, the practical distribution of the fibers is much similar to this model. Assuming that the volume fractions of the in-plane and the cross-plane fibers in the preform are V_{fp} and V_{fc} respectively and that f is the fraction of the cross-plane fibers to the overall fibers of the preform, we have

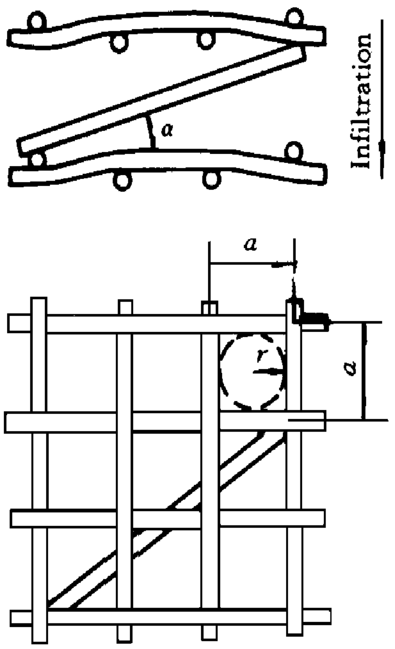

Fig. 3 Model II demonstrating fiber distribution in fibrous preform

$$\left.\begin{aligned} V_{fc} &= f \cdot V_f \\ V_{fp} &= (1-f)V_f \\ V_f &= V_{fc} + V_{fp} \end{aligned}\right\} \quad (4)$$

From Fig. 3, V_{fp} can be formulated as

$$\begin{aligned} V_{fp} &= \frac{\pi}{4} d_f^2 \cdot 2a/[a^2(L \cdot \sin\alpha + 2d_f)] \\ &= \pi d_f/[2a(\lambda \cdot \sin\alpha + 2)] \end{aligned} \quad (5)$$

where L and λ ($\lambda = L/d_f$) are the average fiber length and aspect ratio respectively. Substituting Eqn. (5) into Eqn. (4), we obtain

$$\left.\begin{aligned} a &= \pi d_f/[2V_f(1-f)(\lambda \cdot \sin\alpha + 2)] \\ r &\approx \frac{1}{2}(a - d_f) \\ &= \frac{d_f}{2}\left[\frac{\pi}{2V_f(1-f)(\lambda \cdot \sin\alpha + 2)} - 1\right] \end{aligned}\right\} \quad (6)$$

The values of the effective capillary tube radius r and the threshold infiltration pressure corresponding to the above two fiber distribution models can now be theoretically calculated from Eqns. (3), (6) and (2). For the aluminium / alumina system investigated here, using $d_f = 5\ \mu m$ and $\lambda = 6$ from Ref. [5], $\theta = 132°$ and $\gamma_{LV} = 0.893\ Pa \cdot m$ from Ref. [6], letting $f = 0.3$ and $\alpha = 18(1 - V_f)(°)$, and ignoring the hydrostatic pressure $\rho g h_0$ caused by the self-weight of the liquid metal, the effective capillary tube radius r and the corresponding threshold pressure for infiltration were plotted as separate functions of the fiber volume fraction V_f, shown in Fig. 4. The effective capillary tube radius r decreased while the threshold pressure for infiltration p_{th} increased with the increase of the fiber volume fraction V_f. When the fiber volume fraction V_f was given, both the capillary tube r and the threshold pressure p_{th} depend only on the fiber distribution, with Model I which assumed a planar fiber distribution always giving a higher value of r and corresponding lower value of p_{th}.

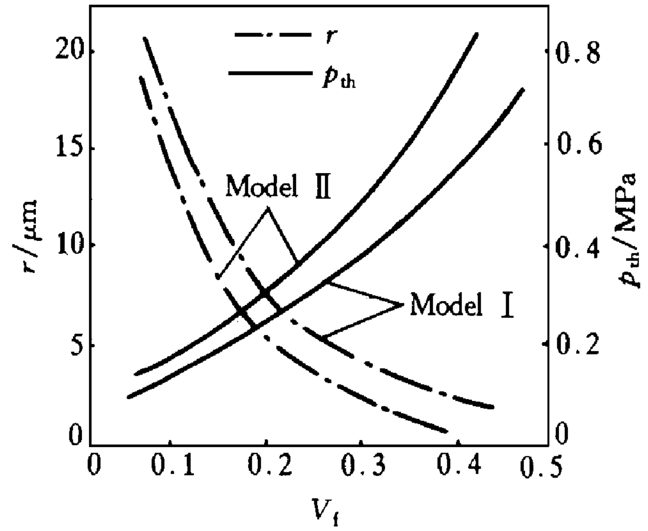

Fig. 4 Dependence of effective capillary tube radius and threshold infiltration pressure on fiber volume fraction

3 EXPERIMENT AND DISCUSSION

3.1 Experimental method

To verify the preceding theoretical analysis, liquid infiltration experiments were carried out with an apparatus shown in Fig. 5. The experimental procedure was as follows. First, a fiber preform was set into a cylindrical mould and heated along with it until some predetermined temperature was reached. Then, liquid matrix metal was poured into the mould cavity above the preform. Following that, pressure was applied as soon as possible by means of a punch, and the liquid metal was forced to infiltrate the preform. After infiltration, the specimen (that is, the infiltrated preform) was sectioned and the penetrated distance was measured.

Alumina short fibers, with their average diameter and aspect ratio being about 5 μm and 6 respectively, were used as the reinforcing material while an Al-1.5Mg alloy was used as the matrix metal. Two kinds of preforms, with the size of them scheduled to be d50 mm × 50 mm and the fiber volume fraction to be 0.1 and 0.2 respectively, were used for infiltration. They were prepared by tamping given quantities of loose fibers packed in a tube-shaped mould into cylindrical compacts with predetermined height.

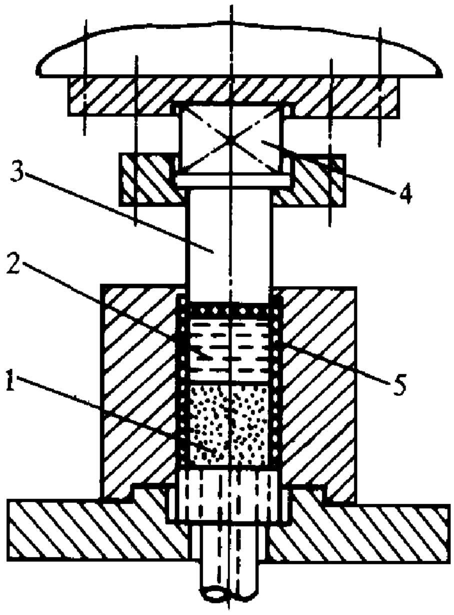

Fig. 5 Experimental apparatus for liquid infiltration

1 —fiber preform; 2 —liquid metal; 3 —punch; 4 —pressure regulating unit; 5 —heat insulator

Since the threshold pressure was the only concern of the present work, the experiments were conducted primarily to investigate the dependence of the infiltration distance on the applied pressure. Therefore, the main experimental parameters except pressure were kept invariable for all experimental runs. The pre-heating temperature of fiber preform and the pouring temperature of liquid aluminium alloy were chosen as 450 ℃ and 740 ℃ respectively. The infiltration time was controlled to be 15 s. The infiltration pressure was used as the only experimental variable and selected for each separate experimental run within the range of 0.2~ 0.6 MPa.

3.2 Results and discussion

The infiltration distances obtained by experimental investigation were plotted in Fig. 6 as a function of the applied pressure, with each data point representing the result of a separate experimental run. The relationship between the applied pressure and the infiltration distance was found to be linear for this aluminium/alumina system. Such linear relationship seems to be typical for nonreactive systems, since a linear dependence of infiltration distance on applied pressure was also observed by Oh S Y *et al*[7] when they infiltrated liquid aluminium alloy into SiC praticulate compacts.

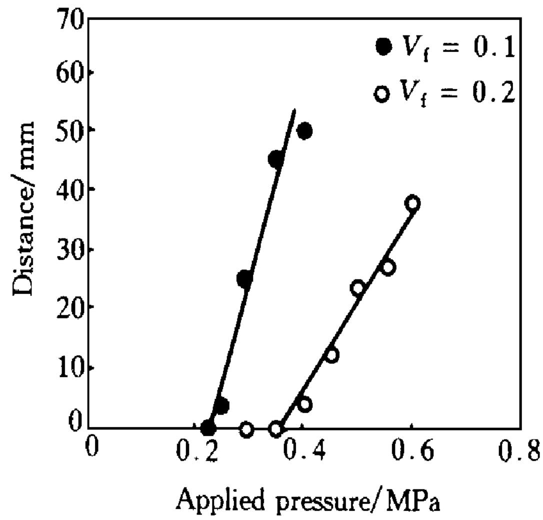

Fig. 6 Experimental relationship between applied pressure and infiltrated distance

As it was done in Refs. [6] and [7], the threshold pressure was obtained by extrapolating the relationship between the infiltration distance and the applied pressure back to zero penetration, shown in Fig. 6. From Fig. 6, it can be seen that the threshold pressure is dependent on the fiber volume fraction of the preform. For the two investigated fiber volume fractions of 0.1 and 0.2, the corresponding threshold pressures are about 0.22 MPa and 0.35 MPa respectively.

From Fig. 4 and Fig. 6, it can be seen that the theoretical values of the threshold pressure calculated from Eqns. (2) and (3) or Eqns. (2) and (6) are very close to the experimental results, though the latter is always a little higher. This means that the theoretical analysis is correct and reasonable. If a further comparison is given between the two models for fiber distribution, it can be found that the theoretical values calculated from Model II are closer to the experimental results. Therefore, this quasi-planar fiber distribution model is believed to be more reasonable. As for the phenomenon that the experimental results for the threshold pressure are a little higher than the theoretical values, it can be explained in the following aspects: (1) for infiltration under atmosphere, the gas pressure in the preform may be more than 0.1 MPa due to unfavorable ventilation; (2) the liquid aluminium at the infiltration front is apt to be oxidized by the air in the preform[8], which is unfavorable to infiltration; (3) between the mould and the punch of the experimental apparatus, there may exist friction which leads to pressure loss.

4 CONCLUSIONS

Two representative models for fiber distribution in fibrous preform used to fabricate metal matrix composite by liquid infiltration were proposed and equations for calculating the effective capillary tube radius of the preform and the threshold pressure for infiltration were derived respectively. The infiltration of the Al-1.5Mg aluminium alloy/short alumina fiber preform system was experimentally investigated. The threshold pressures for infiltrating the selected two kinds of preforms, of which the fiber volume fractions were 0.1 and 0.2 respectively, were obtained. By comparing the theoretical values of the threshold pressure with the experimental results, the theoretical analysis was proven to be effective and reasonable. Furthermore, although the experimental investigaton in the present paper was carried out in the light of the Al-1.5Mg/alumina system, the theoretical analysis was generally applicable since it was done without being limited to any specific composite system.

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(Edited by He Xuefeng)