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A study on the manufacturing conditions of metal matrix composites by low pressure infiltration process

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Abstract

Metal fiber preform reinforced aluminum alloy composite as made by the infiltration of molten metal under low pressure casting process. The infiltration behavior of filling pattern and the velocity profile with low-pressure casting process was investigated. The thermocouple was inserted into the preform in order to observe the infiltration behavior. The infiltration of applied pressure time, 1, 2 and 5 s under constant pressure of 0.4 MPa was completely filled during 0.4 s. In these conditions, molten aluminum alloy has successfully infiltrated to FeCrSi metal fiber preform by low-pressure casting process. It was observed the porosity of composites for reliability of composites. The automobile piston was developed with FeCrSi reinforced aluminum alloy that is 0% porosity by the optimal applied pressure and applied pressure time.

Keywords: Low-pressure casting; Infiltration behaviour; Molten aluminum alloy; Preform

1. Introduction

Recently, technique is advancing in the aviation, space development, automobiles, and electronic technologies, Hence, development of thermal and wear resistant material are being demanded for lightweight. Compared to other types of materials, development of metals with good productivity, low cost, high durability, good heat resistance, and wear resistant have continuously been demanded. Therefore, metal matrix composites (MMC) and fiber reinforced metals (FRM) have been actively conducted to satisfy these characteristics. [1-4]

Especially light weight alloys such as aluminum alloys have good specific strength and specific stiffness. Therefore, aluminum alloy has been used as a favourable material for development of lightweight materials. [5-7]

Production method of MMC reinforced by whiskers or short fibers can be classified into solid phase method and liquid phase method. Solid phase method was proceeded by powder sintering and liquid phase method was proceeded by spark, solution method, agitation of melted aluminum, compo-casting and pressure infiltration. Powder sintering has a great advantage in which whiskers can be arrayed in uniform direction [8-9]. However, as production process is complicated, production cost is high. In the melt stirring method, this process is relatively simple

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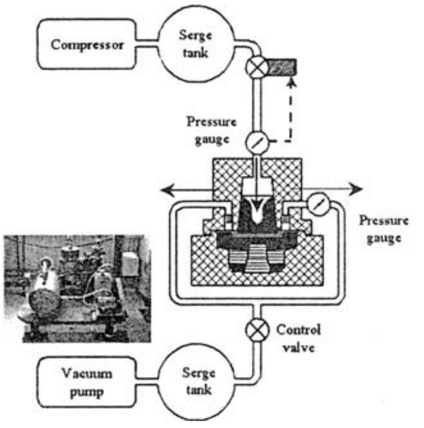
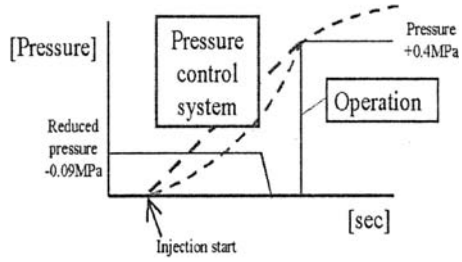


(a)



(b)

Fig. 1. (a) Equipment of low pressure casting and (b) process diagram of low pressure casting.

Table 1. Property of FeCrSi metal fiber.

Diameter (μm)	Density (Mg/m^3)	Thermal conductivity(W/m·K)	Thermal expansion (K^{-1})
40	7.32	11.8	11.5×10^{-4}

and high cost performance compared to the other methods. However, there are many problems in the reaction or wettability between the molten metal and reinforcement and dispersion of the reinforcement. Therefore, application of melt stirring method has been delayed. In pressure infiltration, the preform can be applied to make compounding part. The fact that it can modify and strengthen needed region in the product is a big difference of this method from the others. Also, the squeeze casting is simple to be applied with relatively low production cost. It can be considered to be the most suitable method for application compared to other methods. The studies on the operation of the pressure casting process are very few. The pressure required to fill a casting in low pressure can be separated in two stages to exert pressure to force the molten metal into the mold. The second stage is to add additional reduced pressure to air vent. Then a computer simulation for the pressure distribution with direct finite difference method (DFDM) had been developed. While the pressure distribution is calculated by numerically solving the equations, the pressure required at the gate can also be computed. Ultimately, an optimal pressure-porosity relation for the filling of low pressure casting under consideration can be obtained.

The purpose of this study was to fabricate the composite with porosity 0 % by low pressure casting. Ultimately, an optimal pressure-porosity relation, pressure-porosity curve, under low pressure casting can be obtained. So, in this study, pressure distribution in preform was calculated by DFDM based on Darcy's law.

2. Experimental method

2.1 Materials and experimental procedure

Fig. 1 shows schematic diagram of a typical low-pressure casting. Fig. 1(a) was low pressure casting machine including usually a pressurized mould, compressor, vacuum pump and air vent that is removing the air in the preform before applying pressure. Fig. 1(b) was process diagram of low pressure casting. For removing the air in the preform, it was carried to reduce pressure about -0.09 MPa at the air vent for 5 s after pouring molten aluminum alloy. Then the pressure of 0.4 MPa was applied from the top. The preheating temperature of the preform was 400℃. The preform was set in the metal mould. The temperature of this mould was about 200℃. The molten aluminum with 750℃ was poured into the mould. The filling velocity measurements were conducted by thermocouple with 1 mm diameter that was put in the preform of 8-piece hole.

Table 1 shows the property of FeCrSi metal fiber. AC8A (Al-11~13% Si-0.8~1.5% Ni-0.8~1.3% Cu-

0.7~1.3% Mg) aluminum alloy was used as a molten metal to infiltrate the preform.

2.2 Analysis of pressure distribution inside preform by medal

The distribution of pressure in preform should be found as the flow of molten alloy inside preform because infiltration occurred the pressure difference between applied pressure and air vent pressure. Fig. 2 shows schematic drawing of low pressure casting system used in this study for removing the air in the perform. It was carried to reduce pressure about -0.09 Mpa at the air vent. Therefore, the filling velocities by applied pressure time of 1 s, 2 s and 5 s are investigated under constant pressure of 0.4 Mpa. Thermocouple was used to measure the variation of temperature, which indicates the filling velocities when molten alloy was infiltrated in the preform. The molten alloy was infiltrated from the side and bottom of perform. The upper preform was not infiltrated.

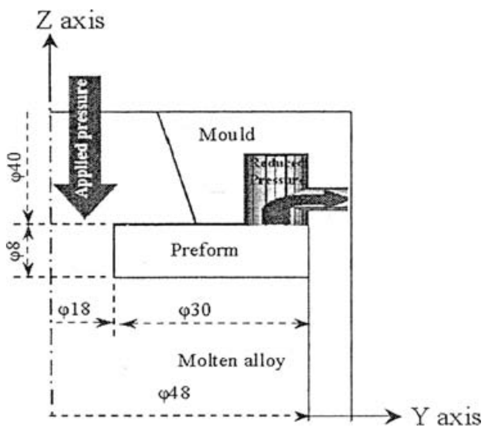


Fig. 2. Schematic drawing of low pressure casting system used in this study (Unit : mm).

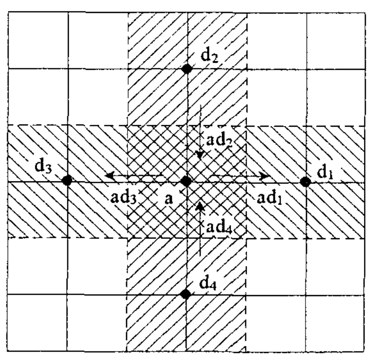


Fig. 3. Darcy's flow by DFDM.

There is plate on the preform. In previous study, the molten aluminum flowing from different directions impinges each other in the preform and then the turbulent flows are generated.

Fig. 3 shows Darcy's flow by direct finite difference method (DFDM). Eq. (1) described the viscosity of molten alloy and the gravity and the pressure difference between molten alloy and air vent. So, pressure distribution in preform was calculated by DFDM. When solving this Eq. (2), Eq. (3) can be obtained.

Therefore, Eq. (4) which can calculate the inner pressure distribution of the preform is determined by Eq. (2) and Eq. (3).

$$(P_d - P_a)S_{ad}\varepsilon = -\frac{\varepsilon}{K}\mu U_{a,d}d_{ad}S_{ad} - \rho g S_{ad}\varepsilon(Z_d - Z_a) \quad (1)$$

$$U_{a,d} = -\frac{K}{\mu d_{ad}}[P_d - P_a + \rho \ g(Z_d - Z_a)] \quad (2)$$

$$\sum_{j=1}^{n} U_{ij}S_{ij} = 0 \quad (3)$$

$$0=\frac{K}{\mu}\{S_{ad2}\frac{1}{d_{ad2}}[P_{d2}-P_a+\rho\ g(Z_{d2}-Z_a)]+S_{ad3}\frac{1}{d_{ad3}}[P_{d3}-P_a+\rho\ g(Z_{d3}-Z_a)]+S_{ad1}\frac{1}{d_{ad1}}[P_{d1}-P_a+\rho\ g(Z_{d1}-Z_a)]+S_{ad4}\frac{1}{d_{ad4}}[P_{d4}-P_a+\rho\ g(Z_{d4}-Z_a)] \quad (4)$$

3. Results and discussion

3.1 Porosity

The infiltration time at pressure accelerating times of 1 sec, 2 sec and 5 sec was investigated under a constant pressure of 0.4 MPa. Porosity of the completed composite was evaluated by low-pressure casting testing according to infiltration times. Porosity was evaluated by scanning electron micrograph (SEM) and the optical microscope. The composite has some pores caused by solidification and imperfect infiltration. Fig. 4 shows relationship between porosity by solidification and applied pressure acceleration speed. Porosity is caused by solidification of molten alloy around the reinforcement. It can be seen that there are numerous pores at the beginning of infiltration in the preform that evaluated the effect of reducing pressure. Molten alloy was infiltrated by reducing pressure for 1.35 sec. Then the reducing pressure revived to 0.1MPa, and infiltrated molten alloy was infiltrated again after 5 sec by applying pressure. Porosity occurred this part, which happened

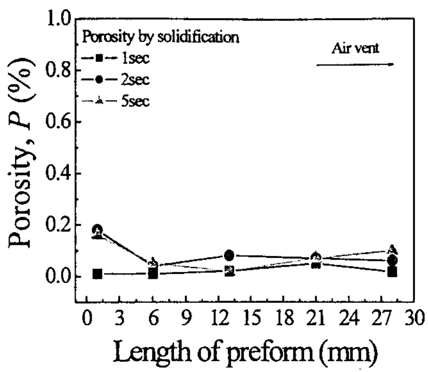


Fig. 4. Relationship between porosity by solidification and applied pressure acceleration speed.

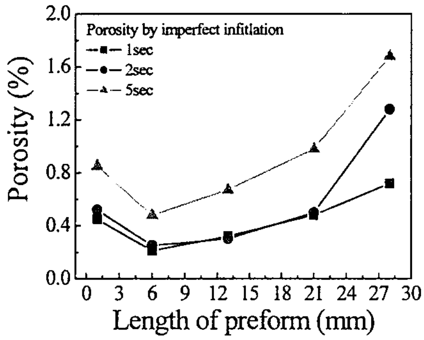


Fig. 5. Relationship between porosity by infiltration and applied pressure

solidification around fiber by re-infiltrated molten alloy. Porosity by solidification was decreased the accelerating times 1sec compared with 2sec and 5 sec. Fig. 5 shows relationship between porosity by imperfect infiltration and applied pressure acceleration speed. Numerous porosities were observed at the side of the mould compared with the beginning of infiltration inside the preform. Moreover, the applied pressure was not sufficient to the air vent part. However, in the case of the pressure accelerating times of 1 sec, a small porosity was observed compared with those in the cases of 2 sec and 5 sec. Furthermore, the pressure accelerating times of 1sec induce high pressure compared to 2 sec and 5 sec.

Fig. 6 shows the results of porosity in the composite fabricated under applied pressure of 0.4 MPa to 0.8 MPa. Pressure accelerating time is fixed by 1 sec. in the case of an applied pressure of 0.8 MPa, there was no porosity in the composite compared to other applying pressures. Fig. 7 shows optical micrographs of porosity in composites fabricated by low pressure. Fig. 7 shows optical

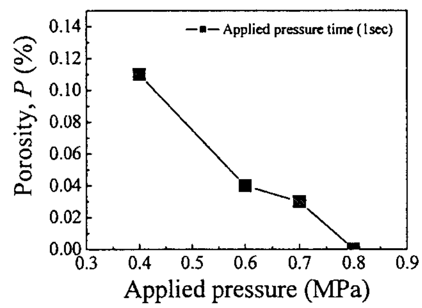


Fig. 6. Relationship between porosity and applied pressure.

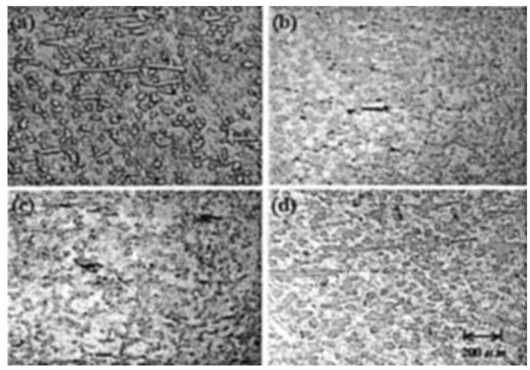


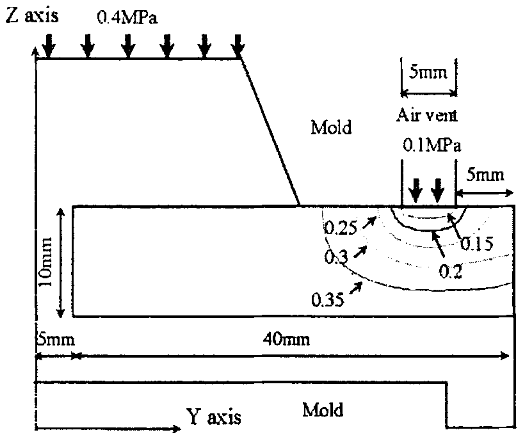
Fig. 7. Optical micrographs of porosity in composites fabricated by low pressure casting with (a) 0.4MPa, (b) 0.6MPa, (c) 0.7MPa and (d) 0.8MPa.

micrographs of porosity in composites fabricated by low pressure casting with (a) 0.4 MPa, (b) 0.6 Mpa, (c) 0.7 Mpa and (d) 0.8 Mpa. In the photograph of optical microscopy there is no porosity at the applied pressure of 0.8MPa. Under these conditions, FeCrSi fibers preform have been successfully infiltrated by A3660.0 molten alloy using the low-pressure casting process.

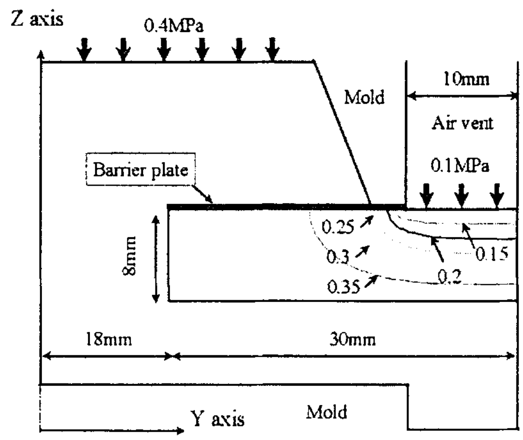
3.2 Pressure distribution in preform

The distribution of pressure in preform should be found as the flow of molten alloy inside preform because infiltration induced the pressure difference between applied pressure and air vent pressure. Fig. 8 shows pressure distribution, which is calculated by DFDM inside the preform.

This result shows pressure distribution contours in the y-z section of preform at steady state for the constant pressure, 0.4 MPa. Fig. 8(a) shows the results of pressure distribution contours without barrier plate and air vent, which was located 5 cm away from right mold. Air vent dimension is 5 cm. In



(a)



(b)

Fig. 8. Pressure distribution inside preform at state steady for constant pressure, 0.4MPa. (a) without barrier plate and air vent size, 5mm (b) with barrier plate and air vent size, 10mm.

the case of air vent, which is located 5cm away from right mold, pressure distribution contours was indicated the elliptical shape as the center of air vent. Fig. 8(b) shows the pressure distribution contours with barrier plate on preform and air vent, which was close at the right mold. Air vent dimension is 10 cm. In the case of air vent close at the right mold, pressure distribution contours indicated linear shape as the center of air vent.

3.3 Relationship between pressure distribution and porosity

Fig. 9 shows the relationship between the pressure distribution inside the preform calculated by DFDM and local pressure inside preform. FeCrSi metal fiber

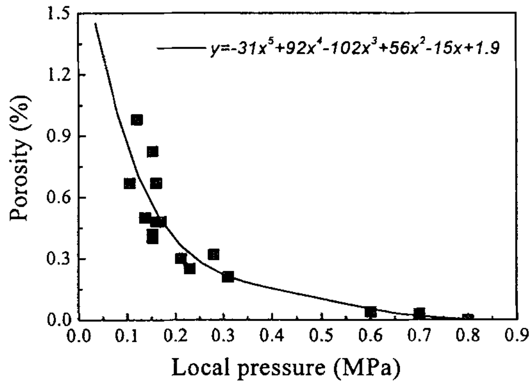


Fig. 9. Relationship between porosity and local pressure inside perform.

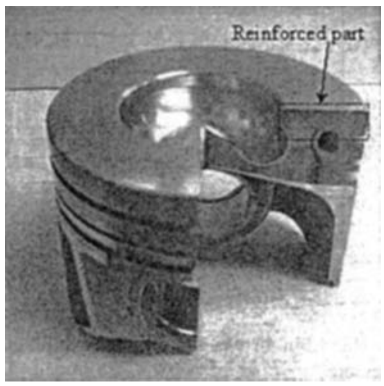


Fig. 10. Piston of automobile by fabricated FeCrSi/AC8A alloy composites by low pressure casting.

reinforced MMC piston with porosity of 0% was obtained by low-pressure casting method. From this result, pore inside preform was decreasing as increasing pressure. It was found that pore occurrence depends on pressure [10]. This shows that some breakage penetrates reinforced material in the compound material but most of breakage develop avoiding the reinforce material. As a result, it infers that the excellent wettability of reinforced material and matrix interfere the process of breakage. This is the cause of increasing the fatigue strength life. The fatigue life of head part in compound piston will be improved compared to A366.0 alloy by increasing the fatigue life and generating power of the piston. There was perfect infiltration in the preform. Furthermore, composite with 0% porosity could be fabricated under the conditions of optimal applied pressure of 0.8 MPa and pressure accelerating times of 1 sec.

Fig. 10 shows the engine piston with FeCrSi reinforced aluminum alloy composite. The dark region in the piston, which is in the upper edge of the piston, is the composite part. High fatigue strength and a good wear resistance at high temperature is required for this part. Usually, the mechanical properties and reliability of composites are related to porosity. Accordingly, in this study, automobile piston reinforced FeCrSi fiber can have 0% porosity under the optimum fabrication condition.

4. Conclusion

The aim of this paper is to establish the optimum fabrication condition by the low-pressure infiltration and analyze the infiltration behavior theoretically. From this result, FeCrSi/AC8A composite piston with porosity of 0 % was fabricated by low pressure casting. The present work has made the framework of simulation of low pressure infiltration of molten aluminum alloy to porous preform. The primary results are summarized and further analyzed as follows.

(1) Two types of pores are observed, that is porosity due to solidification and imperfect infiltration. The porosity of solidification was less than 0.1 %, which is independent to the pressure accelerating times (1 sec, 2 sec and 5 sec). The porosity of imperfect infiltration was the smallest at the pressure accelerating times. Pressure distribution inside the preform with barrier plate and without barrier plate was calculated by DFDM. There is no difference between pressure distribution with and without barrier plates. Furthermore, the effect of air vent location was evaluated.

(2) The inner pressure of the perform was calculated by DFDM using Darcy's equation, and the pressure gap appeared more by reducing the pressure.

(3) In this study, the developed automobile piston with FeCrSi metal fiber reinforced aluminum alloy composite can have 0 % porosity under the condition of optimal applied pressure of 0.8 MPa and applied accelerating time of 1sec.

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References

[1] H. Westengen and O. Holta, Low pressure permanent mould casting of magnesium-recent developments, *Founder Trade Journal.* 163 (1989) 738-742.

[2] S. Morimoto, N. Ohnishi and S. Okada, Development of a low-pressure die casting process for improved soundness of aluminum castings, *AFS Trans.* 21 (1987) 39-46.

[3] N. Onishi, T. Aizawa and S. Okada, Development of inert gas low-pressure die casting process, JACT News. 355 (1986) 283-298.

[4] S. Morimoto, N. Ohnishi and S. Okada, Development of a low-pressure die casting process for improved soundness of aluminum castings, *AFS Trans.* 21 (1987) 39-46.

[5] A. Mortensen and L. J. Masur, Infiltration of fibrous prefroms by a pure metal, *Met. Trans. A.* 20 (1989) 2535-2557.

[6] E. Lacoste, M. Danis, F. Girot and J. M. Quenisset, Numerical simulation of the injection moulding of thin parts by liquid metal infiltration of fibrous preform, *Mater Sci. Eng.* 135 (1991) 45-49.

[7] J. H. Kuo, F. L. Hsu and W. S Hwang, Development of an interactive simulation system for the determination of the pressure-time relationship during the filling in a low pressure casting process, *Sci. and Tech. of Advan. Mat.* 2 (2001) 131-145.

[8] J. Segurado, C. Gonzalez and J. Llorca, A numerical investigation of the effect of particle clustering on the mechanical properties of composites, *Acta. Mater.* 51 (2003) 2355-2369.

[9] W. J. Fleming and J. M. Temis, Numerical simulation of cyclic plasticity and damage of an aluminum metal matrix composite with particulate SiC inclusions, *Int. J of Fatigue.* 24 (2002) 1079-1088.

[10] C. Y. Choi, G. Sasaki, K. Matsugi, N. Sorida, S. kondoh, T. Fujii and O. Yanagisawa, Development of FeCrSi/AC8A composite by low pressure casting and application of piston, 2005 Spring Annual Meeting Program JSME, (2005) 9-12.