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Two-phase Flow Characteristics in Hollow Shape Fabrication Process of Metal Matrix Composites by Thixoforging

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Among advanced manufacturing processes of metal matrix composite parts, thixoforging is one of the most effective forming processes. The investigation of this research article is to provide the proper conditions such as the die shape, the forging velocity, the forging time, the forging pressure, and reinforcement content in the thixoforming process for fabricating hollow shape parts. To investigate the effect of injection velocity and pressure on various defects in thixoforged cylinder liners, filling tests were performed by MAGMA S/W. In order to evaluate the effectiveness of calculated conditions, which are given by computer-aided engineering, A380 and SiCp/A380 cylinder liners were fabricated under the calculated conditions. SiCp/A380 composite billets were fabricated by both the mechanical stirring and electro-magnetic stirring processes. In the case of SiCp/A380 composite cylinder liners, the effect of reinforcement (SiCp) distribution, content (10-20 vol.%) and size (5.5-14 μm) on the mechanical properties was investigated.

Keywords die design, homogeneous distribution, metal matrix composites, thixoforging process, two-phase flow

1. Introduction

Lightweight materials can be of significance for automobiles to achieve weight reduction of parts to enhance the fuel efficiency. In automobiles, substitution of aluminum alloy cylinder liners for the cast-iron cylinder liners used up to now has been attempted. The liner inserted into the engine must have wear resistance, which is the main property for designing a cylinder liner. But existing materials have not been satisfying this property and hence the need for materials which meet both mechanical and thermal expansion coefficient properties that are similar to aluminum and castiron respectively. MMCs that simultaneously satisfy high tensile strength, fatigue strength, elastic modulus, and wear resistance with low density are suitable for making cylinder liners for the substitution of aluminum and cast iron (Ref 1, 2). Especially, if the thixoforming process is applied with secondary forming processes, parts can be manufactured with high interfacial bond strength. Therefore, investigations on thixoforming process have been actively performed (Ref 3-6).

In the case of particulate-reinforced metal-matrix composites (PMMCs), silicon carbide particles (SiCps) in the matrix in the liquid state are apt to come up to the surface of the liquid or settle by density difference between SiCps and matrix. Hence, after thixoforging it is difficult for the distribution of SiCps in the matrix to be homogeneous and for machining of part to be performed. In this study, the problems to confront in fabricating cylinder liner and how to settle the matters in thixoforming will be presented.

When the cylinder liner was thixoforged with process of PMMCs (Ref 7, 8) billet fabricated by combined stirring method by simultaneous application of electromagnetic stirring, the effects of solid fraction, holding time, die temperature, thixoforging pressure, and thixoforging velocity on part formability were investigated. Using the billet with desired solid fraction, the method to thixoforge cylinder liners by thixoforming process will be presented.

Moreover, to evaluate the feasibility for the application of the composites cylinder liner to automobile components, mechanical properties of fabricated composite cylinder liner were investigated and compared with those of commercial composites cylinder liner fabricated by Duralcan.

2. Thixoforging of Cylinder Liner

The die based on predictions of filling behavior and defects obtained from filling and solidification simulations by MAGMA S/W was designed (Ref 9). MAGMA S/W is a computational fluid dynamics software. The height of the billet considering the volume of the gate part was 60 mm, and the billet was reheated to a semisolid state with the original shape pressured. A high-speed 2MN hydraulic press was used to thixoforge the part.

Thixoforging process enables thermal fatigue of the die to be reduced and die life to be longer. The time to the desired temperature by induction heating is much shorter than that by electric furnace. Also, the control of temperature is relatively

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easy with induction heating in semisolid state. Therefore, induction heating is required for the billet to be reheated in thixoforming process (Ref 10). In this study, a 3-step reheating condition studied by the authors to reduce the temperature difference in the billet is used (Ref 11, 12). It is necessary for reheating temperature, which corresponds to certain solid fraction in the PMMCs, to be chosen (Ref 12). Thixoforming process was initially performed by using A380 alloy to obtain the desired part without defect. A380 and SiCp/A380 PMMC cylinder liners using the results mentioned above were fabricated. Here, the particle distributions with particle sizes of 14 and 5.5 μm were compared.

2.1 Thixoforging Condition Calculated by Computer-aided Engineering (CAE)

The 3-D solid modeling of the cylinder liner and die was carried out by CAE package of CATIA. Several simulations with MAGMA S/W were executed under the conditions with pressure of 80 MPa and punch velocity of 200, 250, and 300 mm/s.

From the results, optimal die concept and thixoforging conditions such as velocity and pressure were obtained and these conditions were applied to the thixoforming process. The results of filling simulation indicated that the effect of thixoforging velocity on filling and solidification phenomena was not significant because shrinkage defects were concentrated on the gate position (Ref 13).

The product, die, and core are modeled by CATIA. The scheme of gate was set up by MAGMAsoft. Figure 1 shows the result of STL file which recognizes cylinder liner model with CATIA. From STL file, preprocess of MAGMAsoft generated the material database.

Preprocess modeler of MAGMAsoft generated the fixed die and moving die. The flow characteristic of overflow part was applied to die design for outflow of the gas in forming process. In the reheating processing, the oxidized layer was formed on the billet face. This oxidized layer is included in the liner material, and the mechanical properties of the liner are deteriorated. Therefore, the shape and size of the gate were important to control the oxidized layer in the forming process. In this study, the design criterion was decided by the gate diameter 35 and 45 mm, with and without overflow shown in Fig. 2.

The number of elements in rectangular coordinates was 393,040 and the number of metal cell element in product region was 28,392. Table 1 shows the matrix alloy and die of physical properties used in the thixo simulations. Table 2 shows the property values used to thixoforging simulation. Table 3 shows the number of control volume and the number of metal cell element in product region. Filling analysis by MAGMA S/W was performed by using material properties such as heat conductivity, solid fraction, viscosity, and Ostwald-de Waele coefficient and exponent, which was provided by MAGMA S/W (Ref 13). However, those properties provided by MAGMA S/W can not be used to simulate composites processing. Therefore, material properties derived using mixture of rule presented in Eq. 1 were used in calculation. The thermal property of the metal matrix material was calculated by Eq. 1.

$$P_{th}^{c} = P_{th}^{m}(1 - V_f) + P_{th}^{f} V_f \quad \text{(Eq 1)}$$

where V_f: Volume fraction of reinforced material; P_{th}^{m}: Thermal mechanical property of experimental machine; P_{th}^{f}: Thermal property of reinforced material; P_{th}^{c}: Thermal property of metal matrix material.

Figure 3 shows the simulation results for gate diameter variation. The velocity profile in Fig. 3 shows that the velocity at the gate diameter of 35 mm is faster than that of 45 mm. The velocity of a molten metal increases at small gate diameter. Because fast velocity prevents the solidification of a molten metal in die cavity, better mechanical properties are achieved at the small gate diameter. Orifice shape of gate was manufactured to prevent oxidation film from incoming into die cavity. Gate

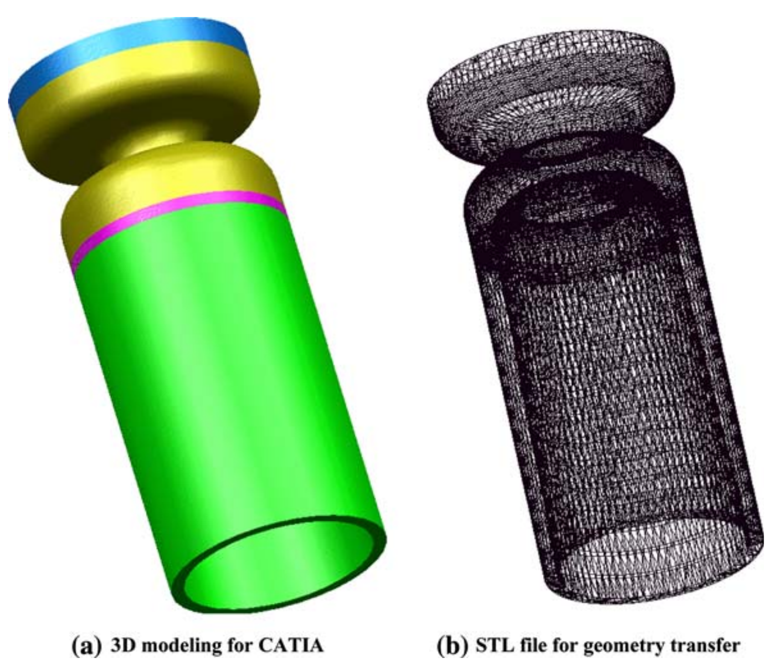

Fig. 1 The geometry modeling of designed gating system

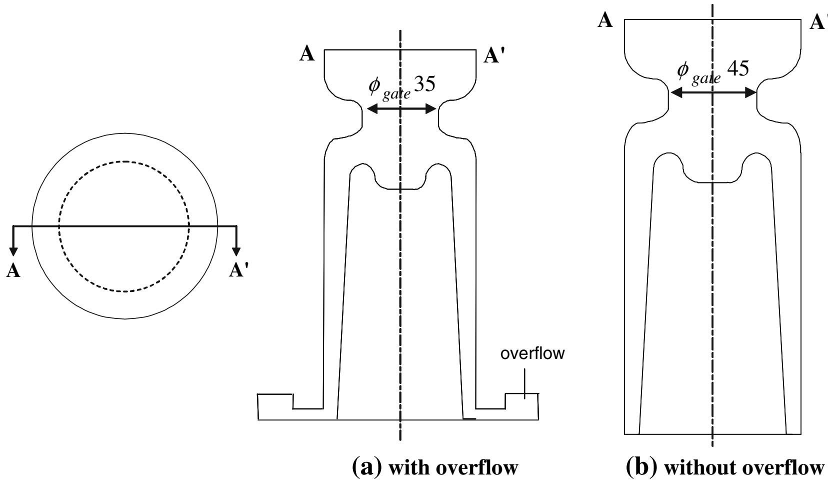

Fig. 2 The designed various gating system with gate dimension $\phi_{gate} = 35$ mm and $\phi_{gate} = 45$ mm

Table 1 Matrix alloy and die of physical properties used in the thixo simulations

	Material	Initial temp. (°C)	Latent heat (KJ/kg)
Cast	A380	575	430.5
Mold	SKD61	250	278.43
Core	SKD61	250	278.43

Table 2 Property values used to thixoforming simulation

Parameters	Symbol	Unit	Values
Solidus temperature	T_{sol}	°C	547
Liquidus temperature	T_{liq}	°C	617
Punch speed	V_{punch}	mm/s	250
Pressurize parameter	P	MPa	80 (20 s)
Boundary condition	K	W/m^2 K	500 (mold&mold)
Heat transfer coefficient	K	W/m^2 K	1000 (cast&mold)

Table 3 Result of mesh generation

Case	Control volume	Metal cell	Remark
(a)	393,040	28,392	With overflow
(b)	250,992	25,123	Without overflow
(c)	250,992	25,123	$\Phi_{gate} = 35$
(d)	251,352	25,435	$\Phi_{gate} = 45$

diameter was selected to be 35 mm rather than 45 mm so that the cylinder liner with 160 mm length could be manufactured when the molten metal passed the gate.

Figure 4 shows that thixoforging with overflow has higher pressure than thixoforging without overflow. The results presented in Fig. 3 and 4 show that thixoforging with overflow has better result than that without overflow. Because higher pressure distribution can be expected with existence of overflow than the case without overflow, the die whose gate was designed to be 35 mm diameter was manufactured with overflow placed at the final filling position.

Figure 5(a) shows the result of thixoforging with overflow and Fig. 5(b) shows the result of thixoforging without overflow. Figure 4 and 5 correspond to 100% and 70% fill states, respectively. Figure 5 shows that the temperature distribution was uniform and extrinsic to overflow part.

Forming by thixoforging is preceded by reheating process. But oxidized layer formed on billet face during reheating. To prevent the oxidized layer from being entrapped in the products, the gate is designed to a bottleneck shape. In view of the above results, the gate diameter of 35 mm is adopted and the die with overflow is fabricated in this study in terms of pressure and velocity distribution and oxidation layer control obtained by simulation results.

2.2 Thixoforging Experiments

Die shape and working principle for forging of the cylinder liner are as shown in Fig. 6. Figure 6(a) and (b) show the external shape of the die in the case of separation and union of the right and left dies. Figure 6(c) and (d) show pressing state of the punch during thixoforging and ejecting the part from the fixed die, respectively. To preheat the die, 10 cartridge heaters with a capacity of 1 KW and with a diameter of 16 mm were used on the sleeve. To control the temperature of the materials in semisolid state, K-type CA thermocouples of diameter 1.8 mm were inserted into the die. To reduce the friction between the composite billet and die, graphite was sprayed and the die was preheated up to required temperature. Reheated PMMC billet was inserted into the die sleeve and thixoforged by using 2MN hydraulic press machine. After thixoforging, the part was ejected and water-quenched. Filling states and microstructure were investigated under the various factors like thixoforging time, pressure, and velocity.

Figure 7(a) shows the die set for right die and left die to be conjoined to each other. Fig. 7(b) shows the appearance of thixoforged cylinder liner. The inner and outer diameters of this part are 76 and 84 mm, respectively. The length of part including the gate height is 160 mm in consideration with the volume of the gate part.

In this article, metal-matrix composites were produced by horizontal continuous casting process with an electromagnetic stirring system (Ref 14). The mechanical properties of fabricated composite billet, dispersion state of reinforcement and continuous fabrication process are given in more detail in Ref 14.

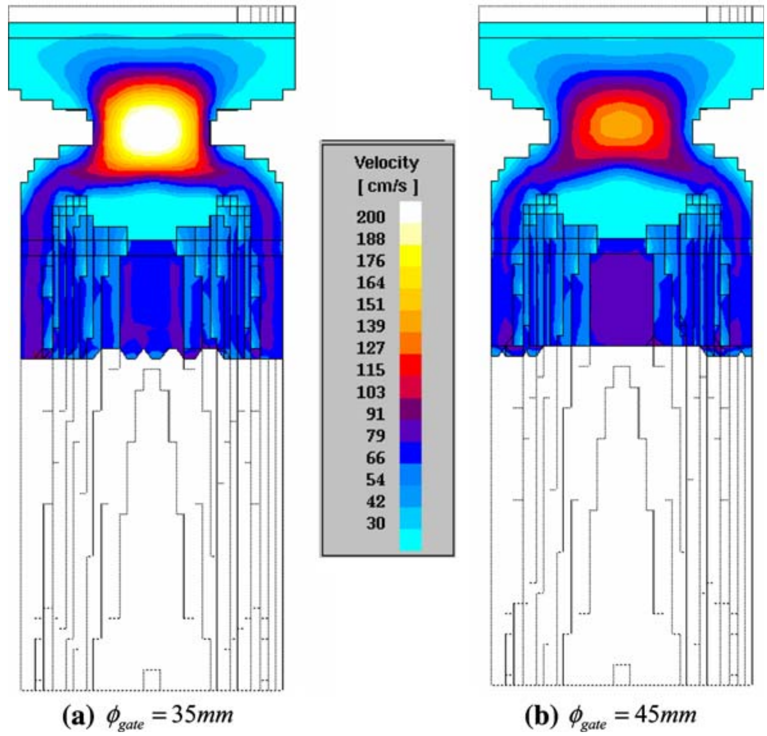

Fig. 3 The velocity distribution at 70% fill state (80 MPa, 250 mm/s)

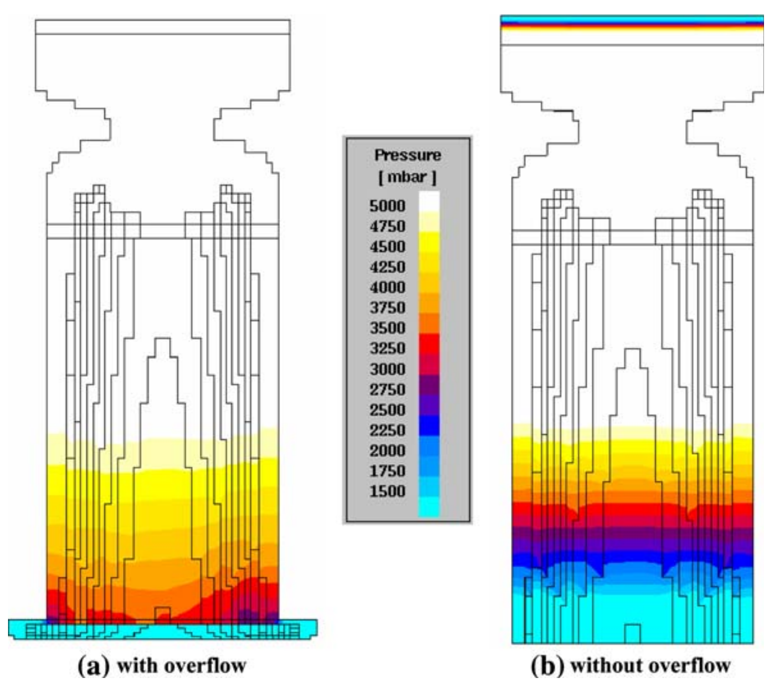

Fig. 4 The pressure distribution at 100% fill state (80 MPa, 250 mm/s)

3. The Experimental Results and Discussion

The samples of thixoforged MMCs with variations in the die temperature under the condition of pressure of 80 MPa, velocity of 250 mm/s, and volume fraction of 10% are as shown in the Fig. 8(a)-(c). The particulate volume fraction was calculated by image analysis in an electron-microscope. The defects such as contact traces with the die and rough surface on the liner were exhibited and a separation phenomena of the part at the gate position was observed. These defects occurred due

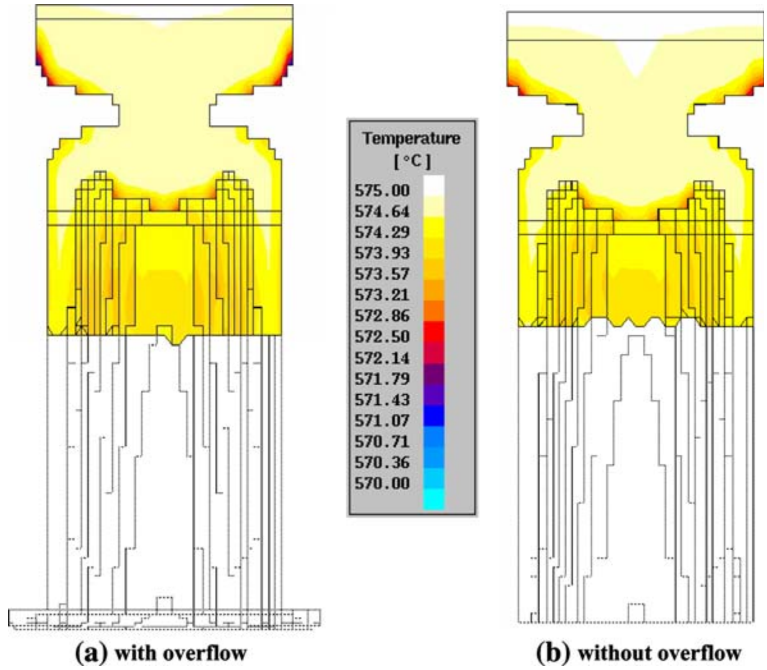

Fig. 5 The simulation result of temperature distribution at 70% fill state (80 MPa, 250 mm/s)

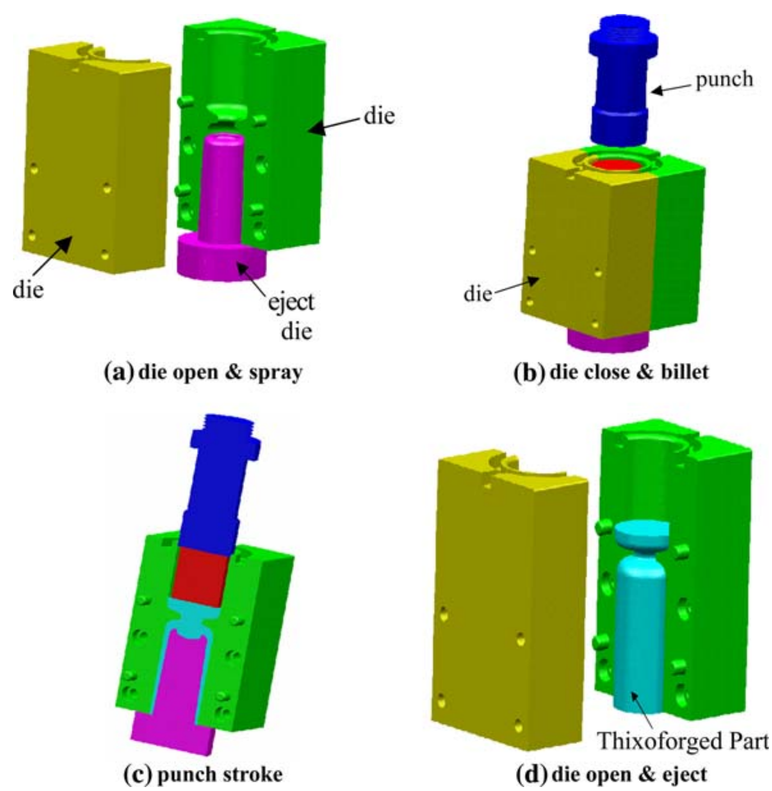

Fig. 6 Schematic diagram for thixoforging of cylinder liner

to the sticking phenomenon between the product and the die, when the dies were separated from each other. As shown in Fig. 8(e), filling was unsuccessful under the condition of 200 °C. Sticking was not observed at the temperature of 250 °C and 200 °C (Fig. 8(d) and (e)). But the solidification of reheated composite billet occurred during the thixoforging due to the low temperature of die and the amount of unfilled MMCs partly remained at the billet. However, relatively sound product was developed at the temperature of 250 °C with smooth surface and to prevent the seizing and incomplete filling phenomenon. Hence it was shown that the formability of the product strongly depends on the die temperature.

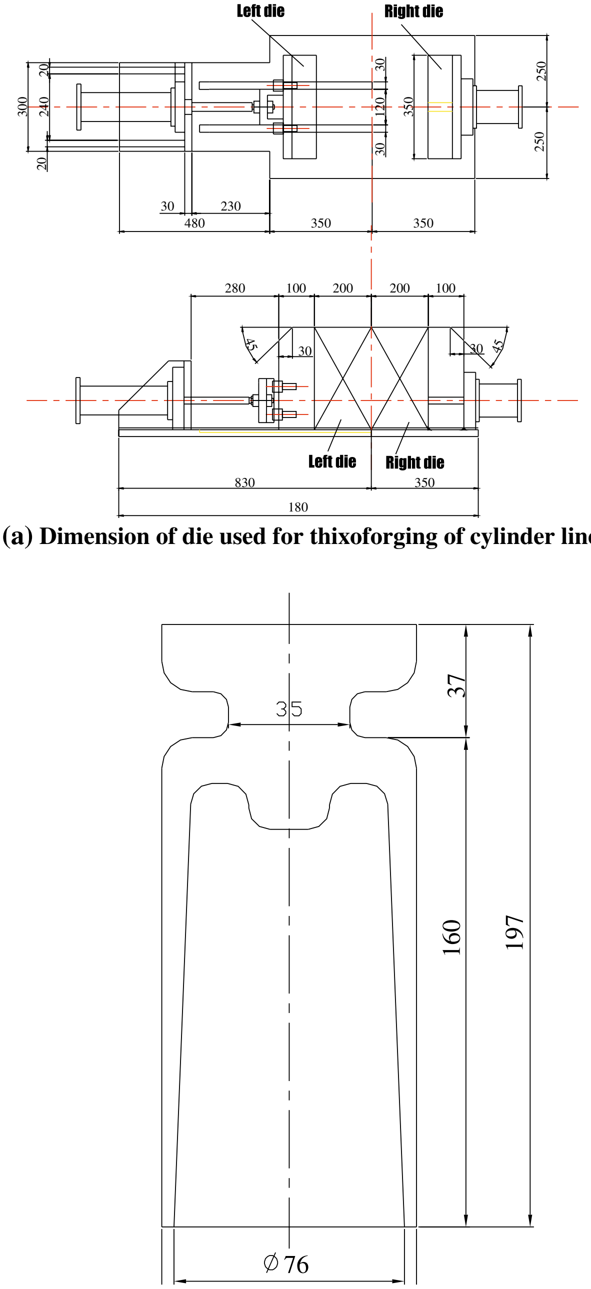

Fig. 7 Schematic diagram of die set and dimension of cylinder liner fabricated by thixoforging process

Figure 9 shows the thixoforged A380 cylinder liner for the variation of pressing-holding time under the condition of thixoforging pressure 80 MPa, die temperature 250 °C, and thixoforging velocity 250 mm/s. When pressing-holding time was 1 min (Fig. 9(a)), a crack along with the parting line of the dies was observed. Because right and left dies as shown in Fig. 7(a) were separated from each other before full solidification of the part, the force was concentrated on the divided surface. For a pressing-holding time of 2 min (Fig. 9(b)), the defects were not observed. It seems that the reason for these results was related to the shape of the product. It was found that in the case of fabrication of a thin part, such as cylinder liner with the thickness of 4 mm, ejection must be performed after the full solidification of product to minimize such defects.

Fig. 8 Composite cylinder liner fabricated for variation of die temperature (P = 80 MPa, t = 2 min, V_p = 250 mm/s, f_s = 0.55)

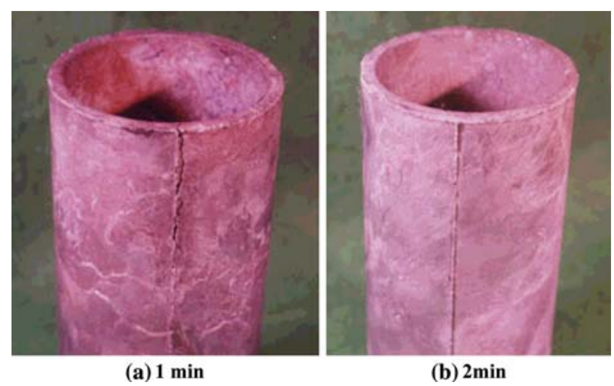

Fig. 9 Composite cylinder liner fabricated at press holding time 1 and 2 min (P = 80 MPa, T_d = 250 °C, V_p = 250 mm/s)

Figure 10 shows thixoforged A380 alloy cylinder liner fabricated with a variation in the solid fraction under the condition of thixoforged pressure of 80 MPa, pressing-holding time of 2 min, die temperature of 250 °C, and thixoforged velocity of 250 mm/s. Temperatures which correspond to the solid fractions shown in the Fig. 10(a), (b), and (c) are 566 °C, 575 °C, and 583 °C, respectively. In the case of f_s = 0.6 (Fig. 10(a)), incomplete filling occurred at filling end point due to the billet with high solid fraction. Therefore thixoforging was conducted before sufficient reheating of billet and the remnant solid region was observed at the end filling point. In the case of f_s = 0.5 (Fig. 10(c)), the material volume which was used for thixoforging was far less than that of calculated result obtained by CATIA. This was mainly due to too much loss of materials that occurred due to the liquid drainage during reheating process. Hence, it was found that the material was insufficient to achieve filling in spite of maximum stroke of the punch. Therefore, it is very important to determine the proper solid fraction to prevent the unsuccessful filling and to minimize the loss of materials. At $f_s = 0.55$ (Fig. 10(b)), a sound cylinder liner was fabricated due to the correct balance of fluidity and temperature.

Figure 11 shows the cylinder liners fabricated with a variation of thixoforging pressure. When the thixoforging pressure was 80 MPa (Fig. 11(c)), the desired liner was fabricated. Under 40 and 50 MPa pressures (Fig. 11(a) and (b)), partial or incomplete filling occurred due to the insufficient pressure and fast solidification of final filling area, respectively.

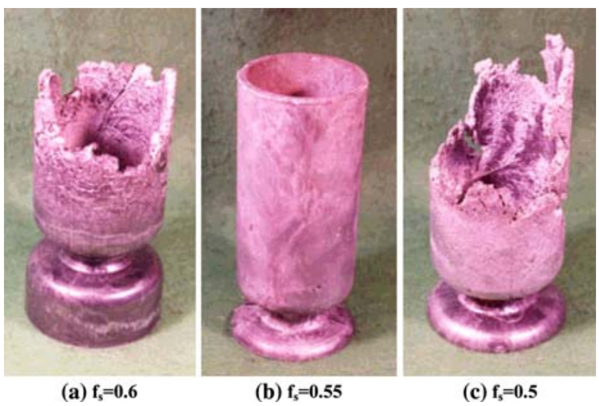

Fig. 10 Composite cylinder liner with unfilling phenomena fabricated for variation of solid-fraction. (P = 80 MPa, t = 2 min, T_d = 250 °C, V_p = 250 mm/s)

Influence of thixoforging velocity is shown in the Fig. 12. The cylinder liner was fabricated (Fig. 12(c)) without defects, when the forging velocity was V_p = 250 mm/s. But under the velocity of 90 and 120 mm/s, biased filling and local solidification occurred (Fig. 12(a) and (b)) at a few regions during thixoforming process. This was due to the insufficient thixoforging velocity.

Figure 13 shows the positions in the cylinder liner where microscopic observation was carried out. The microstructures of each specific position of A380 raw material after thixoforging are shown in Fig. 14. The microstructure of the thixoforged A380 shows that overflow position exhibited pores whereas the positions (a) to (f) did not. Overflow to cope with porosity generation was added, but it did not influence the outcome owing to the pores in raw material for thixoforming process (Ref 15). It is necessary for the dispersibility to be considered as standard to evaluate the cylinder liner.

Therefore, the dispersibility of A380 PMMC cylinder liner fabricated under the optimal condition of the thixoforging pressure 80 MPa, holding time of 2 min, and die temperature of 250 °C, velocity of 250 mm/s, and solid fraction of 0.55 was investigated for pore defects. Figure 15 and 16 show the micrographs of SiCp/A380 composites cylinder liner with a volume fraction of 10% and 20%, and with a particle size of 14 μm. In both cases, it was found that SiCp was homogeneously dispersed in the part. Figure 17 and 18 show the micrographs of SiCp/A380 composite cylinder liner with a volume fraction of 10% and 20% respectively, and with a particle size of 5.5 μm. In broad terms a homogeneous distribution of SiCp was generally found. However, the dispersibility of SiCp in Fig. 17 was worse than that of Fig. 15. This was due to segregation with cluster of the

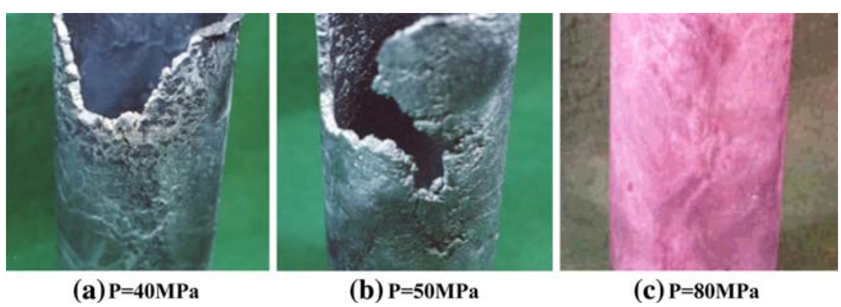

Fig. 11 Partially unfilling phenomena of composite cylinder liner fabricated for variation of forging pressure (t = 2 min, T_d = 250 °C, V_p = 250 mm/s, f_s = 0.55)

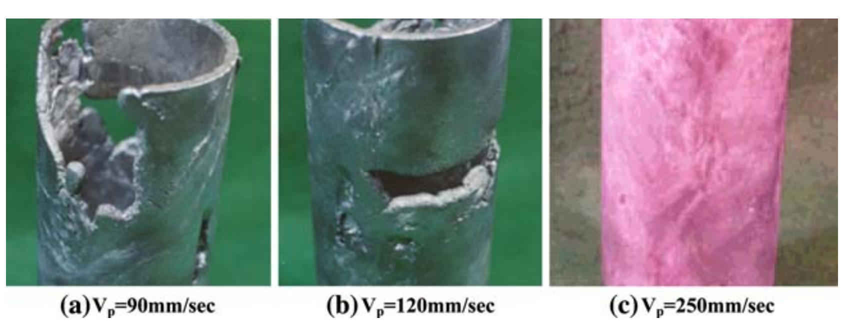

Fig. 12 The defect phenomenon in composite cylinder liner fabricated for variation of punch velocity during thixoforging (P = 80 MPa, t = 2 min, T_d = 250 °C, f_s = 0.55)

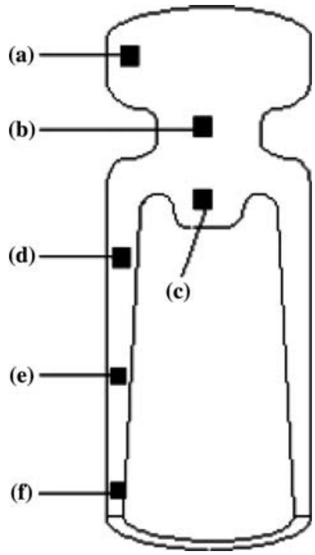

Fig. 13 Schematic diagram of observation point for microstructure

reinforcement, which was observed at the several regions in Fig. 17.

Particle distribution for grain size of 5.5 and 14 μm was measured. As can be seen from Fig. 15 to 18, particles with 20% volume fraction of reinforcement content distributed more uniformly than that with 10% volume fraction. As volume fraction of reinforcement material increases, flow of reinforcement particles, which enhances fluidity of matrix during thixoforging, enforces to disperse reinforcement material uniformly into matrix. In addition, as can be seen in Fig. 19, flow of semisolid phase material made dispersion of reinforcement particulates uniform when semisolid phase material filled die cavity. The phenomenon of reinforcement particle dispersion was depicted in Fig. 20. The phenomenon can be explained that the semisolid phase material flows in the die cavity, and thus the solid phase particles extends the gap between reinforcement particulates as the solid phase particle deforms plastically, which causes uniform dispersion of reinforcement particulates.

Figure 21 shows the variation in the volume fraction of SiCp with a variation in the position in thixoforged cylinder

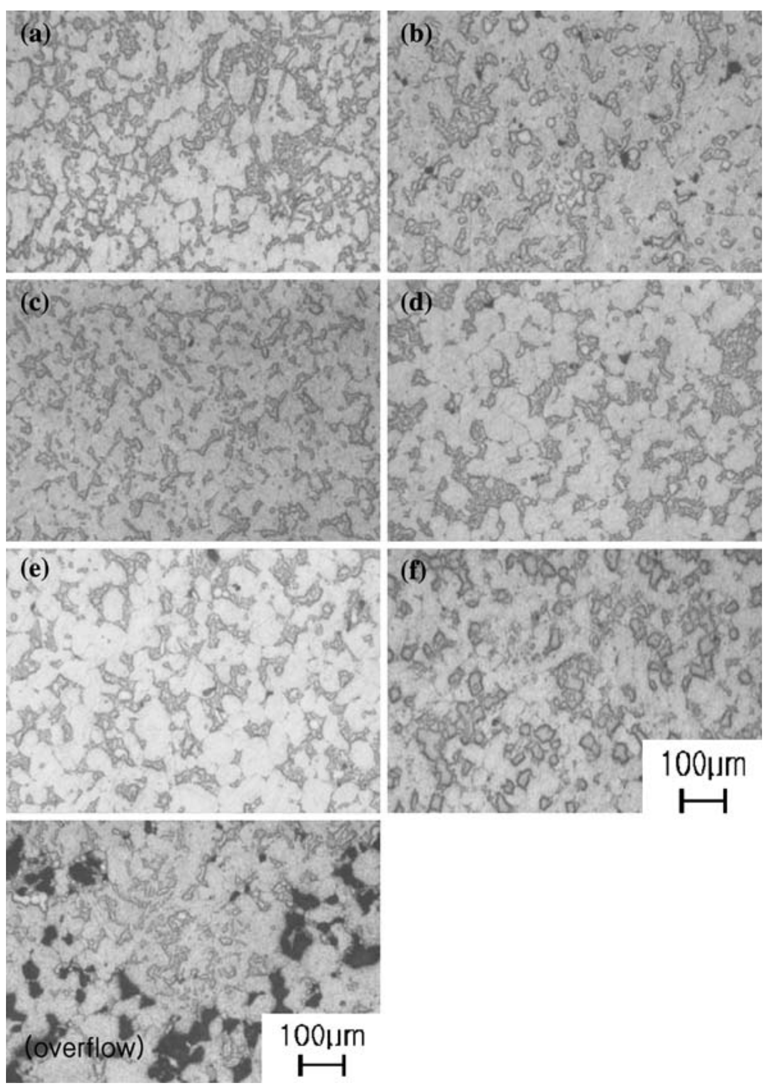

Fig. 14 The micrographs of A380 alloy raw material after thixoforging for each position indicated in Fig. 14

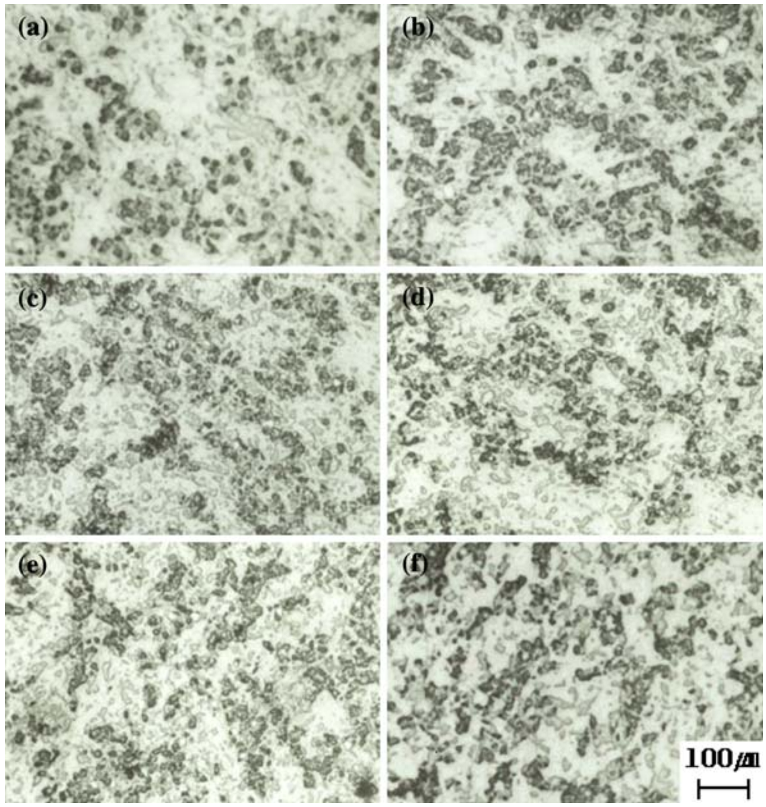

Fig. 15 The micrographs for dispersion state of reinforcement after thixoforming process of metal matrix composites (particle size 14 μm, 10 vol.%) for each position of Fig. 14

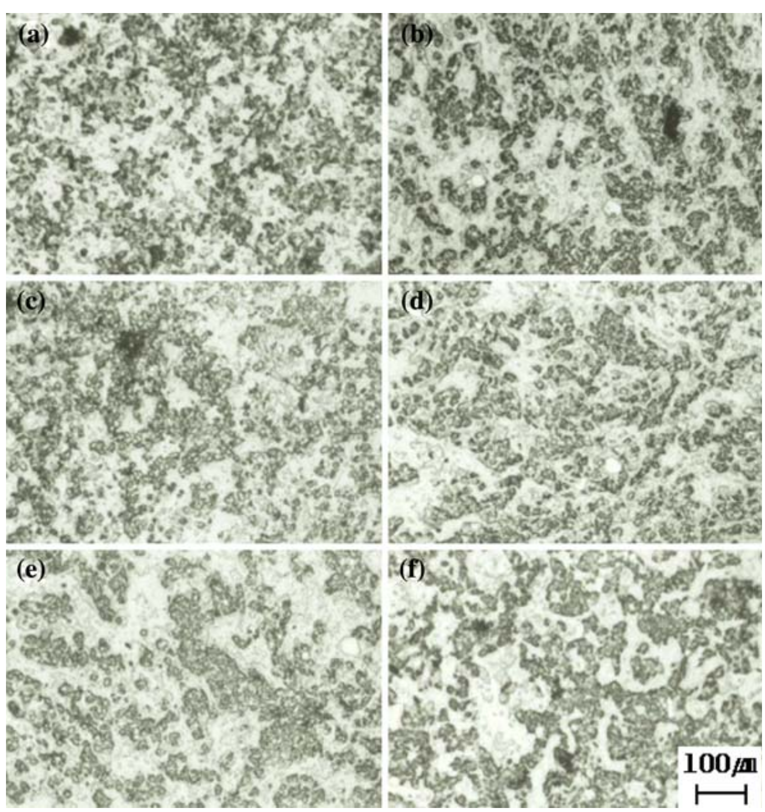

Fig. 16 The micrographs for dispersion state of reinforcement after thixoforming process of metal matrix composites (particle size 14 μm, 20 vol.%) for each position of Fig. 14

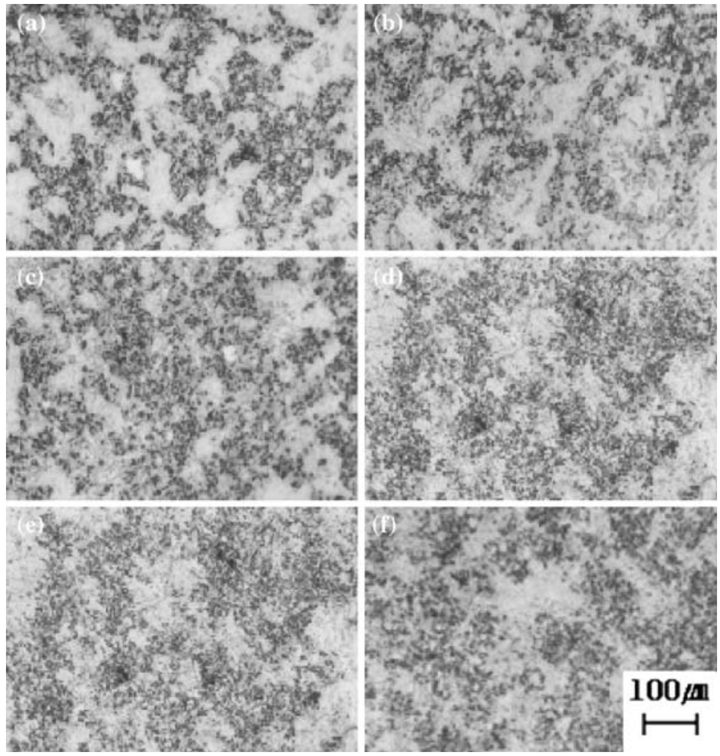

Fig. 17 The micrographs for dispersion state of reinforcement after thixoforming process of metal matrix composites (particle size 5.5 μm, 10 vol.%) for each position of Fig. 14

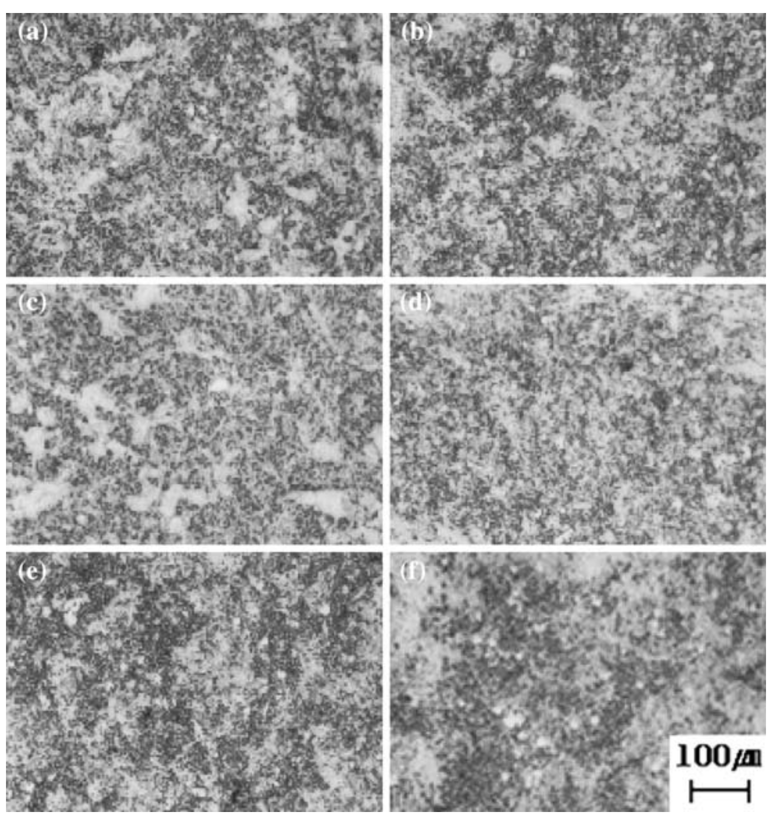

Fig. 18 The micrographs for dispersion state of reinforcement after thixoforming process of metal matrix composites (particle size 5.5 μm, 20 vol.%) for each position of Fig. 14

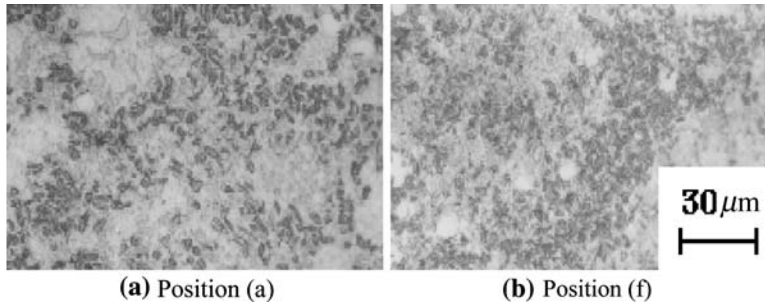

Fig. 19 Comparison of microstructure for reinforcement particle distribution

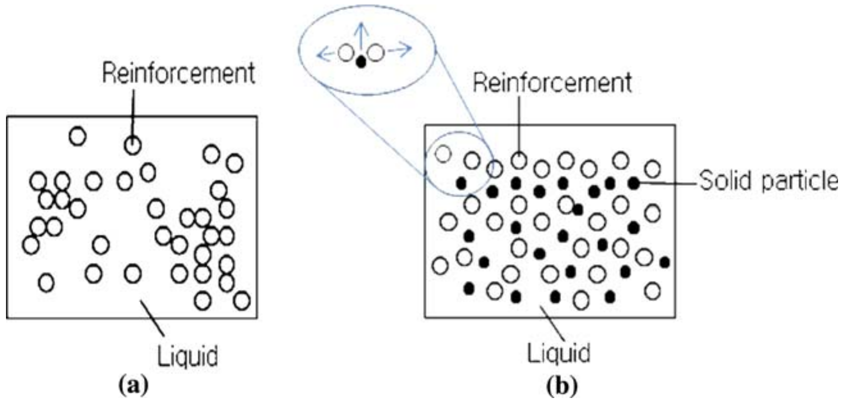

Fig. 20 Schematic diagram of reinforcement particles' dispersion by flow of solid phase particles in semisolid state

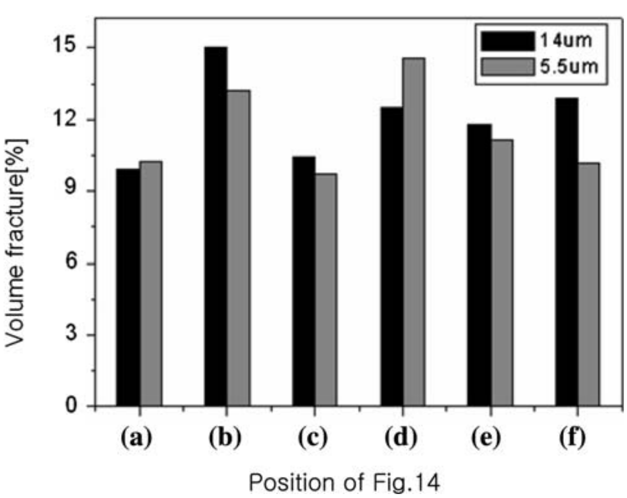

Fig. 21 Volume fraction of reinforcements in composites cylinder liner which is calculated by quantitative image analysis and initial volume fraction of reinforcements in composites billet is 10% after thixoforging

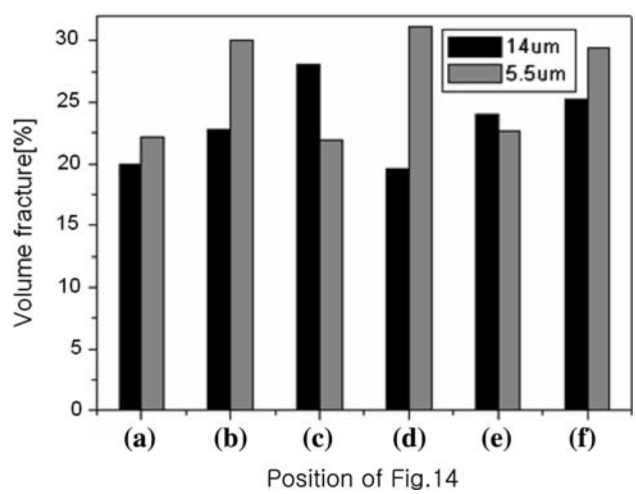

Fig. 22 Volume fraction of reinforcements in composites cylinder liner which is calculated by quantitative image analysis and initial volume fraction of reinforcements in composites billet is 20% after thixoforging

liner fabricated using a 10% SiCp/A380 composites billet. The maximum and minimum volume fractions of SiC particles were about 15% and 10% at the position (b) in Fig. 16 respectively. Figure 22 shows the variation on the volume fraction of SiC particles of the variation of the position in thixoforged cylinder liner fabricated using a 20% SiCp/A380 composites billet for each position, as shown in Fig. 14. In this case, the maximum and minimum volume fractions of SiCps were about 30% and 19%, respectively. From the graph(observation point (d)), it is seen that inhomogeneous reinforcement distributions of composites cylinder liner were observed, because the initial distribution in the composite billets was not uniform.

Figure 23 shows schematic diagram of specimen position to measure mechanical property of the products which fabricated by thixoforming under thixoforging velocity 250 mm/s and thixoforging pressure 80 MPa. Tensile specimens were taken

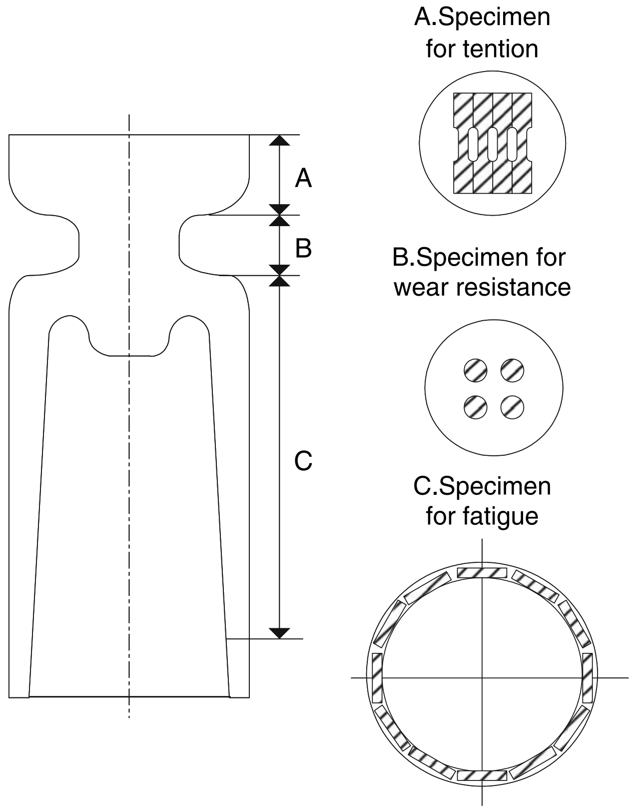

Fig. 23 Schematic diagram of specimen point for mechanical property

from position A, wear test specimens from position B, and fatigue specimens from position C along liner length direction, and then each tests were performed.

Figure 24 shows the mechanical properties of two kinds of cylinder liners and the cylinder liners of MMC developed in this study. In terms of the ultimate strength, the cylinder liner which contains the SiC particles with the size of 5.5 μm have better strength than the one with the size of 14 μm. The ultimate strengths of two kinds of the cylinder liners made by Duralcan company are higher than those made in this study as shown in Fig. 24(a). Although MMC cylinder liners had a relatively low strength as compared to the commercial liners, it was found that our liners exceeded the desired strength of 300 MPa.

Figure 24(b) and (c) show the wear and hardness of various parts, respectively. With the similarities shown in Fig. 24(a), in terms of wear and hardness, the cylinder liner which contains the SiC particles with the size of 5.5 μm had better strength than that with the size of 14 μm and wear and hardness of the cylinder liners made for this study were lower than those of two kinds of the cylinder liners made by Duralcan.

The strength of MMC increases with decrease of size in reinforcement material, as can be seen from Fig. 24(a). This is because area per unit volume, that reinforcement material occupied, decreased, as size of reinforcement material decreased, so dislocation movement was impeded. As can be seen from Fig. 24(b), it was seen that wear amount decreased by 1.1 mg, as solid fraction increased from 10% to 20%. With characteristics for cylinder liner component, wear resistance is more important than strength and hardness. Therefore, thixoforging process is feasible to produce cylinder liner as wear resistance material.

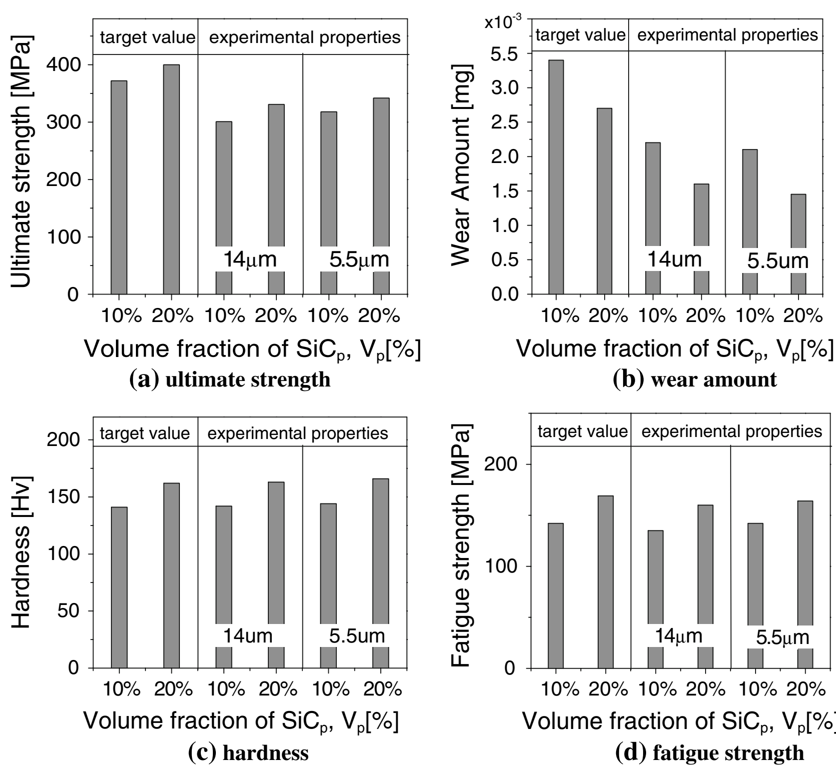

Fig. 24 Comparison of mechanical properties for composites cylinder liner and target values

4. Conclusion

From the investigation of various defects with variation of process parameters and an evaluation of fabricated automobile parts, the following results were obtained.

(1) In the case of thin and simple hollow parts, the effect of reheating temperature (solid fraction), thixoforging pressure, and velocity was more critical than that of press holding time and die temperature on the occurrence of defects in thixoforged products.
(2) Dispersed state of reinforcement of thixoforged part was better than that of the billet before thixoforming process.
(3) In the case of thixoforging of hollow parts with MMCs, incomplete filling in the end point of cylinder liner, surface defects, and inhomogeneous filling by earlier solidification and segregation were obtained.
(4) The proper forming conditions for fabrication of hollow composite cylinder liners without defects were thixoforging pressure of 80 MPa, thixoforging velocity of 200-300 mm/s, holding time of 2 min, solid fraction of 0.55, and the die temperature of 250 °C.
(5) Mechanical properties such as hardness and fatigue strength of cylinder liners fabricated in this study were similar to those of commercial composite cylinder liner. But in tensile strength, the mechanical properties are low. The wear resistance of 10 vol.% SiC_p and 20 vol.% SiC_p cylinder liners were inferior to that of commercial composite cylinder liners.

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