Statistical analysis for strength and spatial distribution of reinforcement in SiC particulate reinforced aluminum alloy composites fabricated by die-casting

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Statistical analysis for strength and spatial distribution of reinforcement in die-cast SiC_p/Al alloy composites was performed in order to predict the reliability of composites. Microstructural analysis was also done to determine the critical features of the composites. Die-casting was carried out using the preheated die at the casting temperature range of 620–750°C. It was found that the SiC pacticulates were homogeneously dispersed in die-cast Al matrix alloy, resulting from the refinement of dendritic cell size due to rapid cooling rate. The tensile strength of die-cast SiC_p/Al alloy composites was higher than that of die-cast Al matrix alloy. Also, the tensile strength was slightly increased with increasing SiC particulate volume fraction at the casting temperature range of 650–700°C. It was concluded that the die-cast temperatures of 750 and 700°C are optimum condition for the distribution of SiC particulates in consequence of good fluidity of melt for 10 and 20 vol.% SiC_p/Al alloy composites, respectively. However, the strength scattering of composites was increased with increasing SiC particulate volume fraction. For the statistical evaluation of strength, the maximum Weibull modulus of die-cast SiC_p/Al alloy composites, which was obtained at the cast temperature of 700°C, was 29.6 in Al matrix alloy, 22.2 in 10 vol.% SiC_p and 14.2 in 20 vol.% SiC_p, respectively.

1. Introduction

Al alloy matrix composites are attractive for application of aerospace and automobile industries requiring light weight, higher specific modulus, specific strength and wear resistance [1–4]. In spite of its attractive properties, Al matrix composites have been afforded only limited use in very specific applications, such as aerospace industries and military weapon because of the high manufacturing cost, complex fabrication process and difficult mass production. Recently, Al matrix composites have been practically used for the automobile products, such as engine piston and cylinder liner, as a result of significant efforts for cost down as well as improvement of mechanical properties [5]. Fabrication methods of Al matrix composites can be widely divided into the solid state process and liquid state process. A majority of commercial applications are now produced by liquid state process including semi-solid process. The gravity mold casting, sand casting and squeeze casting of liquid state processes have been usually used as fabrication methods of Al matrix composites, but these were not suitable for productivity. Recently, die-casting process has been adapted to the fabrication of SiC particulate dispersed Al matrix composites [6–8]. Demonstrated advantages of die-casting process as a method for the fabrication of Al alloy matrix composites include the accuracy of dimension, the beauty of product surface, higher productivity and mass automatic production [9]. It is considered that this process is available for the fabrication of Al alloy matrix composites.

Although many papers in the literature focus on the mechanical behavior of Al alloy matrix composites, few of them mention the reliability of the composites. Generally, SiC_p/Al alloy composites demonstrate various brittle fracture modes by amount of SiC particulate addition into the matrix, and then the strength distribution of the composites is typically exhibit scatter in fracture strength with the volume fraction of SiC particulate and the fabrication process and condition. Therefore, the composites materials have not been frequently used as structural materials due to their low reliability. As a consequence, the reliability and statistical strength analysis are more and more necessary for quality assurance. Most statistical strength analysis has been discussed using Weibull distribution function equation [10–12]. This equation is based on the theory

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in which the fracture is controlled by the weakest defect of all the defects in the materials, the so-called "Weakest link theory".

In this work, we perform the statistical analysis for strength and spatial distribution of reinforcement in die-cast SiC_p/Al alloy composites in order to predict the die-cast Al MMCs reliability. Microstructural analysis was also done to determine the critical features of the composites.

2. Experimental procedure

2.1. Materials

The materials used in this work were Al alloy composites reinforced with 0, 10 (particulate size: 9 μm), and 20 (particulate size:14 μm) vol.% SiC particulate, which were obtained from DURALCAN Co., in the form of a cast ingot. The chemical compositions of Al matrix alloy are shown in Table I.

2.2. Fabrication of composites

Al alloy composites ingot was re-cast by die-casting method. A 150 ton die-casting machine was used throughout this work. Schematic diagram of the apparatus used in the die-casting processes is shown in Fig. 1. For the fabrication of Al alloy matrix composites by die-casting method, many casting conditions, such as casting temperature, mold temperature, casting pressure and injection speed were needed to control. Particularly, a dual injection mode was used to avoid an air entrapment during injection of melt. It is well known that a dual injection condition consisting of a pre-charging low speed and a following high speed is effective [13]. Details of die-casting conditions are represented in Table II. Also, to investigate the effect of cooling rate on the microstructure and SiC particulates distribution, Al alloy composites ingot was re-cast by the gravity mold casting and furnace cooling.

TABLE I Chemical composition of the aluminum base alloy

Chemical composition (wt.%)							
Si	Fe	Cu	Mn	Mg	Ni	Ti	Al
9.7	0.8	3.1	0.39	0.39	1.2	0.1	Bal.

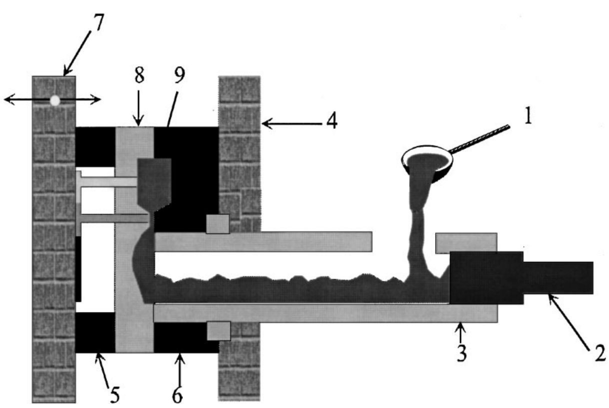

Figure 1 Schematic diagram of cold chamber type die-casting machine; 1: Pouring ladle, 2: Plunger, 3: Sleeve, 4: Stationary platen, 5: Ejector box, 6: Stationary die, 7: Sliding platen, 8: Ejector die and 9: Cavity.

TABLE II Details of die-casting conditions

Die-casting machine	150 ton cold chamber type
Casting pressure	1,039 Kgf/cm^2
Injection speed	1st : 0.4 m/s, 2nd : 2.1 m/s
Casting temperature	620–750°C
Mold temperature	130°C

2.3. Tensile test

Tensile test were carried out using an Instron model 8501 Universal Testing Instrument with a constant cross-head speed of 1.0 mm min^{-1}. The number of specimens for evaluation of Weibull distribution was 20 for each test. The gage length and gage diameter of round tensile specimens were 50 mm and 6 mm, respectively.

2.4. Microstructural evolution and DTA analysis

Microstructural characterization of the die-cast composites was examined by optical microscopy. Image analyzer was used to examine the dendrite cell size and the distribution of SiC particulate. For a given specimen, the distribution of SiC particulate in terms of the SiC particulate density (measured by the number of SiC particulate per square area) versus square area, n, was plotted. The thermal behavior of the Al matrix alloy was determined using a differential thermal analyzer (DTA) in the temperature range of 50–700°C. The DTA scans were run with heating rate of 15°C/min in a purified argon atmosphere with alumina liners.

3. Results and discussion

3.1. Microstructure

As-received cast SiC_p/Al alloy composites ingot have shown that SiC particulates are largely segregated in the intercellular regions and many cast defects are observed as shown in Fig. 2. Therefore, new fabrication methods, such as die-casting and squeeze-casting were

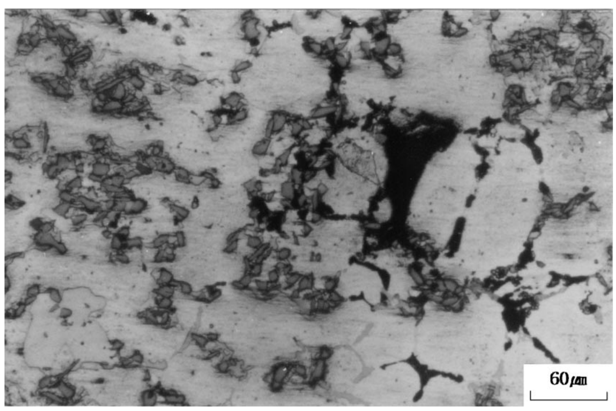

Figure 2 Microstructure of cast 10 vol.% SiC_p/Al alloy composites ingot.

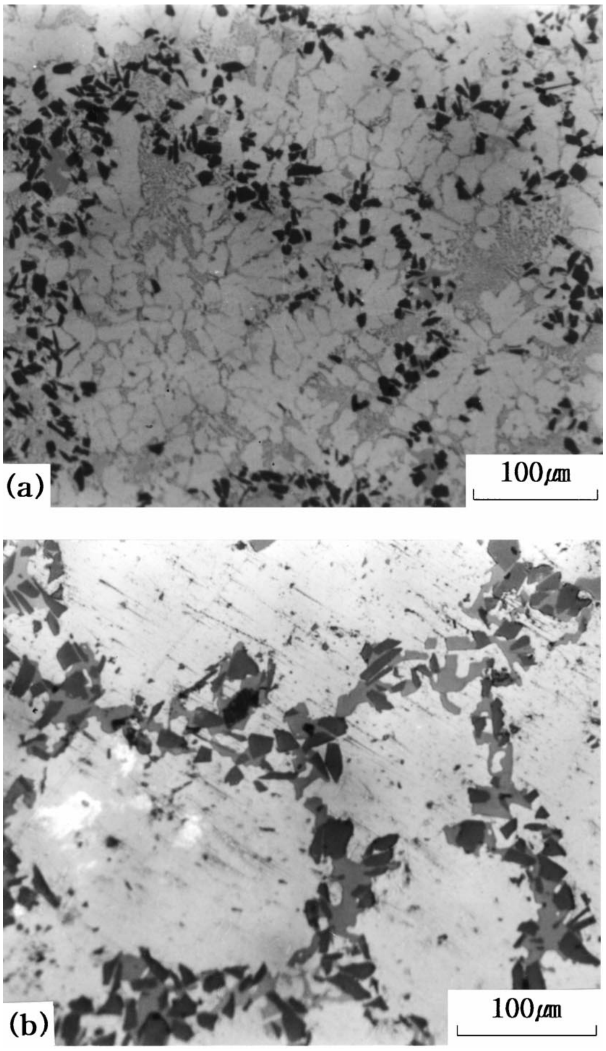

Figure 3 Optical microstructures of the (a) furnace cooled and (b) gravity mold cast 10 vol.% SiC_p/Al alloy composites at the cast temperature of 650°C.

needed to obtain the sound microstructure and good mechanical properties. S. Mochizuki tried to fabricate Al matrix composites by die-casting [8]. Die-casting improves mechanical properties by the improvement of particulate distribution due to rapid solidification and the reduction of cast defects. First, we focused to investigate the relations of dendritic cell size and SiC particulate distribution of the furnace cooled, gravity mold cast and die-cast SiC_p/Al alloy composites in terms of cooling rate. Fig. 3 shows optical microstructures of the furnace cooled and gravity mold cast 10 vol.% SiC_p/Al alloy composites at the cast temperature of 650°C. The microstructures of SiC_p/Al alloy composites consist of the dendritic structure of the primary α phase, eutectic Si and SiC particulates. It was observed that SiC particulates in furnace cooled composites are largely segregated in the intercellular regions as shown Fig. 3a.

Eutectic Si particulates are formed mostly in intercellular regions, and also continuous networks of SiC particulates and eutectic Si particulates are commonly observed. The dendrritic cell size of the furnace cooled composites was about 350 μm. The gravity mold cast composites have fine dendritic structure in comparision with furnace cooled composites, and the dendritic cell size was about 45 μm as shown in Fig. 3b. Also, it is observed that SiC particulates are partially segregated in the intercellular regions. However, the die-cast composites have a fine dendritic structure, which was about 6.4 μm, as shown in Fig. 3c. Also, it was observed that the SiC particulates were homogeneously dispersed in refined Al matrix alloy compared with the gravity mold cast and furnace-cooled composites. D. J. Lioyd reported that SiC particulates are rejected ahead of solidification front and trapped by converging dendrite in the intercellular regions with decreasing cooling rate [14]. Since the particulates are intensively pushed to the intercellular regions at slower cooling rate condition. The distribution of SiC particulates in the solidification microstructure is determined mainly by the cell size, in turn, depends on cooling rate. Therefore, it was approved that the SiC pacticulates were homogeneously distributed in Al matrix, resulting from the refinement of dendritic cell size due to rapid cooling rate.

3.2. Tensile properties

Fig. 4 shows the room-temperature tensile strength and elongation of the die-cast Al alloy composites as a

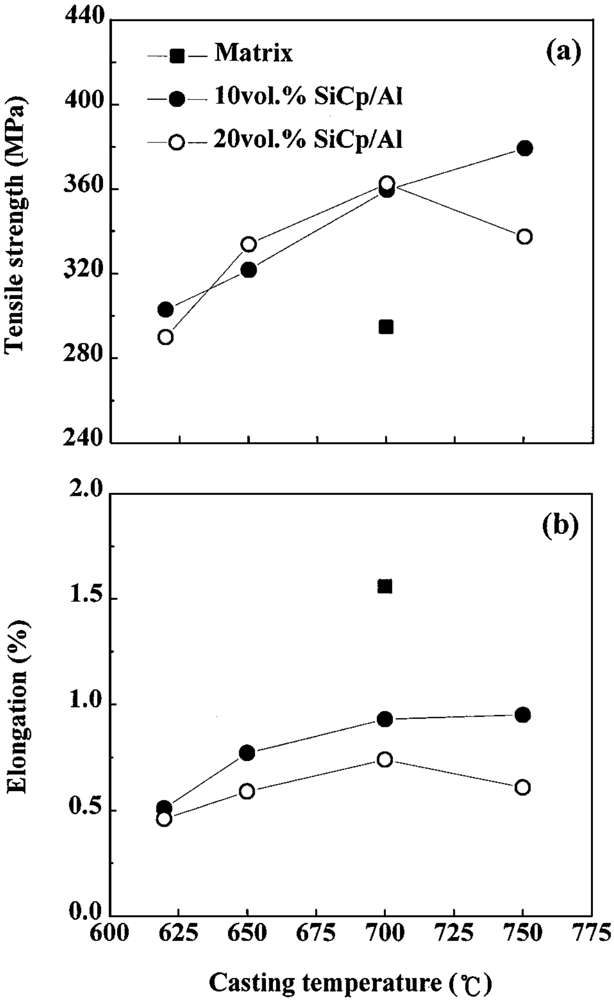

Figure 4 (a) Tensile strength and (b) elongation of the die-cast SiC_p/Al alloy composites as a function of die-casting temperature and volume fraction of SiC particulate.

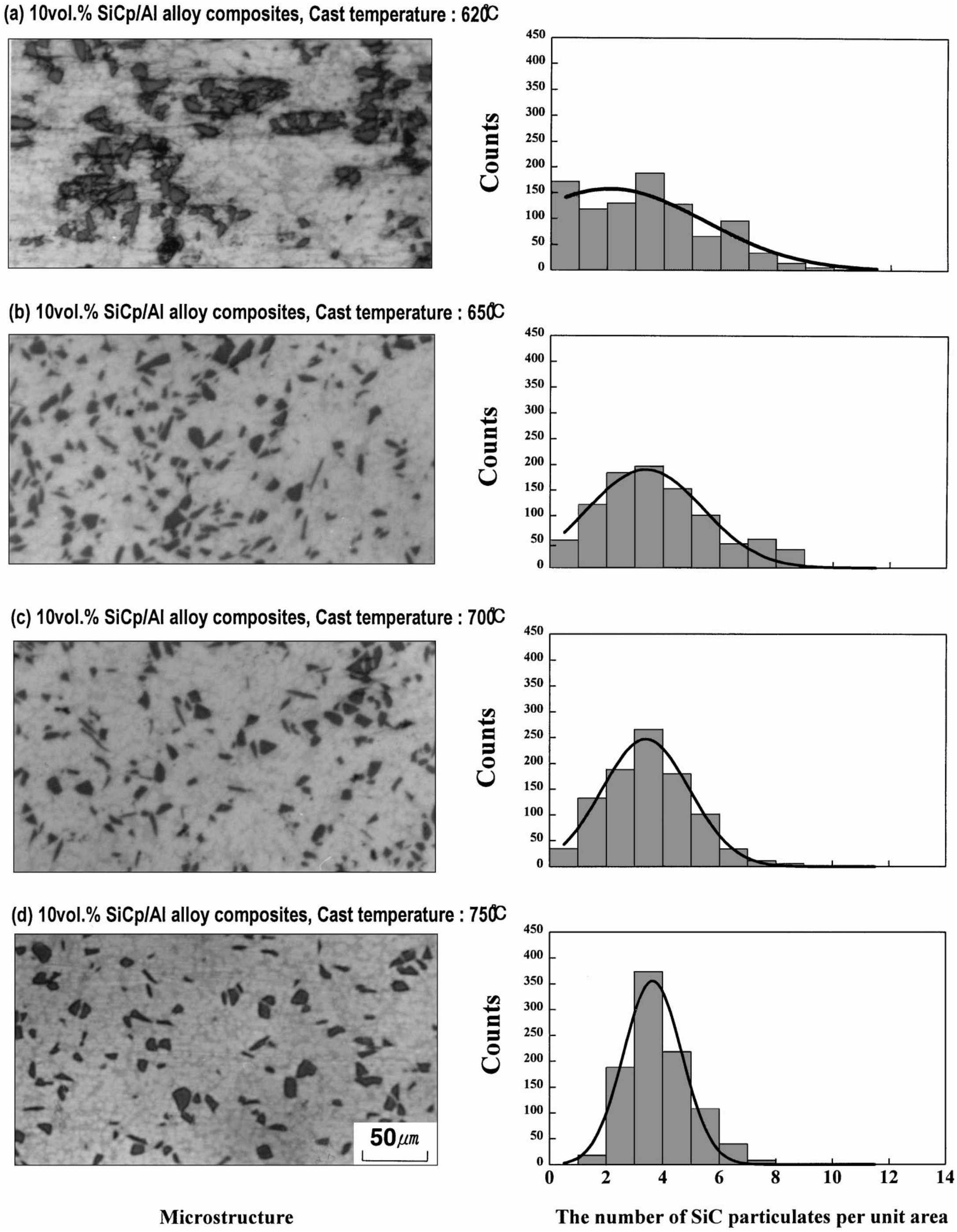

Figure 5 Microstructures and the distribution of SiC particulate measured by image analyzer for die-cast 10 vol.% SiC_p/Al alloy composites to reveal the effect of cast temperature on the distribution of reinforcement.

function of die-casting temperature and volume fraction of SiC particulate. The tensile strength of die-cast composites was higher than that of the die-cast Al matrix alloy. The tensile strength of 10 vol.% SiC_p/Al alloy composites was increased with increasing cast temperature. The increase is attributed to the better distribution of SiC particulates and reduction of defects in consequence of good fluidity of melt. Fig. 5 shows microstructures and the distribution of SiC particulate measured by image analyzer for die-cast 10 vol.% SiC_p/Al alloy composites to reveal the effect of cast temperature on the distribution of reinforcement. In particular, SiC particulate segregated regions were apparently observed at cast temperatures of 620 and 650°C as shown in Fig. 5a. It is believed that tensile strength at the cast temperatures of 620 and 650°C was smaller than that of another cast temperatures because of the poorly distributed SiC particulates in consequence of bad fluidity of melt. In addition, Fig. 6 shows DTA curve of Al matrix alloy in the temperature ranges of 50–700°C. The liquidus temperature is about 582°C. This result indicates that worse-distribution of SiC particulates at the cast temperatures of 620 and 650°C is concerned with bad fluidity of melt due to low casting temperature. Also, it was ascertained that the deviation of SiC particulate distribution become mostly broad at the cast temperature of 620 and 650°C as shown in Fig. 5. Fig. 5c and d show microstructures of 10 vol.% SiC_p/Al

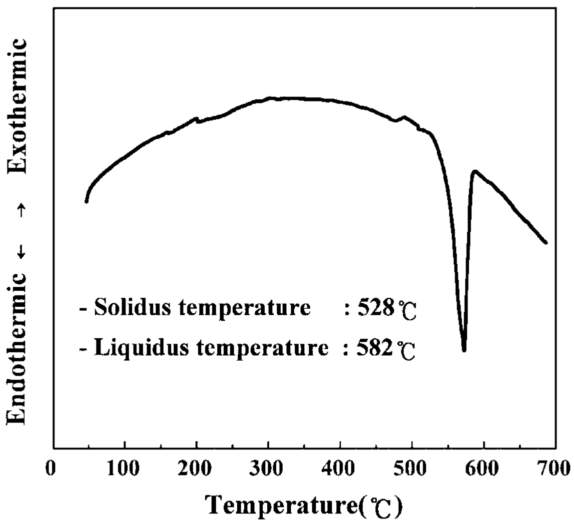

Figure 6 DTA curve of Al matrix alloy in the temperature range of 50–700°C.

alloy composites fabricated at the cast temperatures of 700 and 750°C, respectively. SiC particulates are distributed randomly and uniformly with showing some difference. Therefore, image analysis was needed to investigate the accurate distribution of SiC particulates. As shown in Fig. 5, it was found that the deviation of SiC particulate distribution become mostly narrow at the cast temperature of 750°C. Also, this result is well matched to tensile test result as shown in Fig. 4a. According to J. David, the spiral lengths, i.e., the distance the melt will flow before it solidifies, obtained in 10 vol.% SiC_p/A356 Al alloy composites are comparable to those of the matrix alloy, and increase with increasing cast temperature [14]. Therefore, it is believed that cast temperature of 750°C is optimum condition for the distribution of SiC particulates in consequence of good fluidity of melt. On the other hand, the tensile strength of 20 vol.% SiC_p/Al alloy composites was increased with increasing cast temperature. But, it was

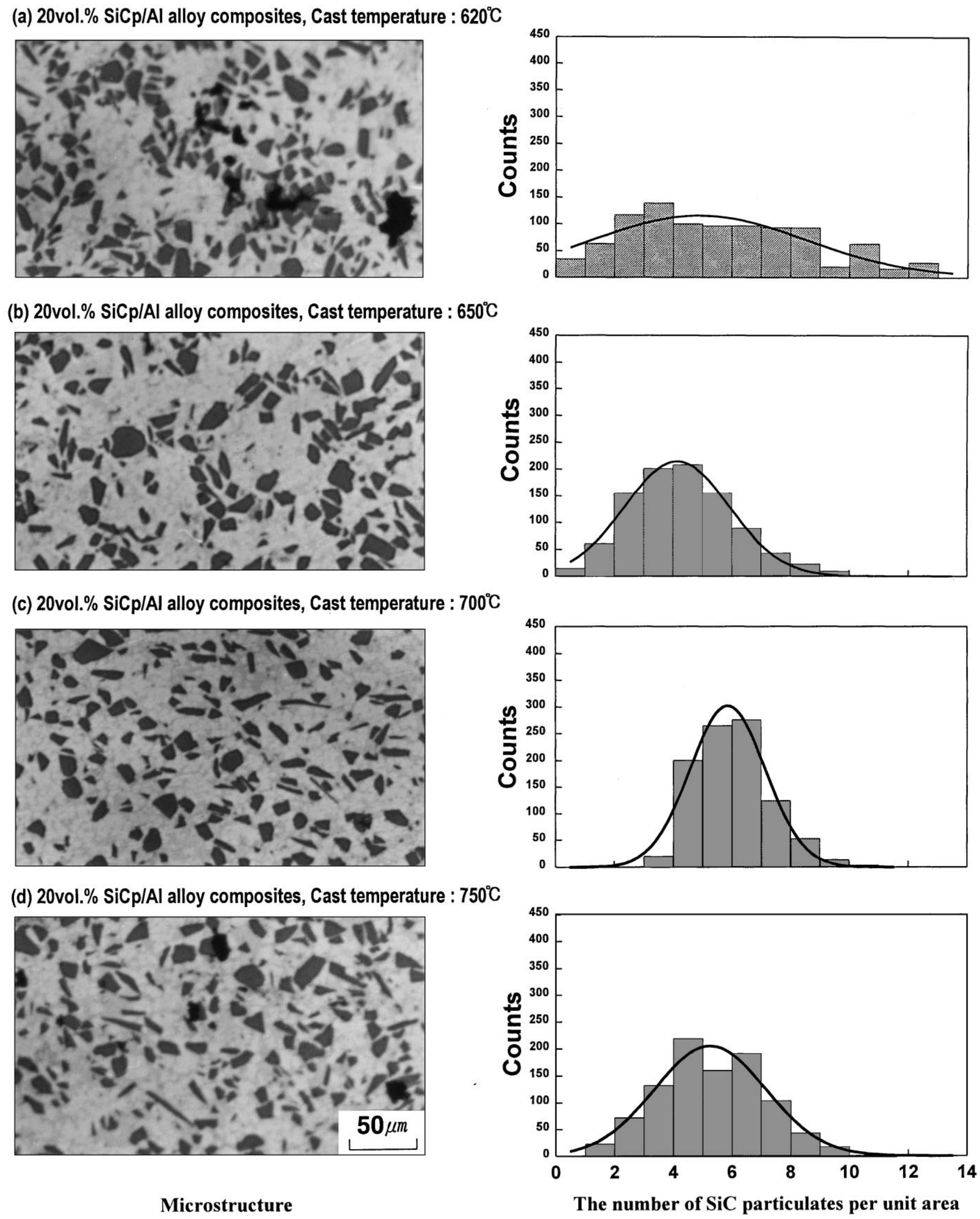

Figure 7 Microstructures and the distribution of SiC particulate measured by image analyzer for die-cast 20 vol.% SiC_p/Al alloy composites to reveal the effect of cast temperature on the distribution of reinforcement.

decreased at the cast temperature of 750°C, which was found to be lower than that of 10 vol.% SiC_p/Al alloy composites at the same cast temperature.

As shown in Fig. 7a, SiC particulate largely segregated regions in company with porosity were observed surely in cast temperature of 620°C. It is found that tensile strength at the cast temperature of 620°C was mostly smaller than those of another cast temperature condition, and also that of 10 vol.% SiC_p/Al alloy composites at the same cast temperature. It is believed that the lower tensile strength at the cast temperature of 620°C is due to poorly distributed SiC particulates and formation of cast defects in consequence of bad fluidity of melt. It was ascertained that the deviation of SiC particle distribution become mostly broad at the cast temperature of 620°C as shown in Fig. 7. Also, in cast temperature of 620°C, the decrease of tensile strength with increasing SiC particulate volume fraction results from the decreasing of fluidity because of increased viscosity of the melt. As shown in Fig. 7c, we observed that particulate distribution became more uniform in comparison with another cast temperature condition in cast temperature of 700°C. Also, it was found that the deviation of SiC particle distribution become mostly narrow at the cast temperature of 700°C. This result is well matched to tensile test result as shown in Fig. 4a. However, the tensile strength of 20 vol.% SiC_p/Al alloy composites fabricated with cast temperature of 750°C was decreased, and also smaller than that of 10 vol.% SiC_p/Al alloy composites at the same cast temperature. The primary reason for the segregation of SiC particulates and the formation of cast defects is attributed to air-entrapment during injection in consequence of increasing SiC particulates volume fraction.

Therefore, it is believed that cast temperature of 700°C is optimum condition for the distribution of SiC particulates in consequence of good fluidity of melt. On the other hand, it is found that the optimum cast temperature of 10 vol.% SiC_p/Al alloy composites does not correspond to the optimum cast temperature of 20 vol.% SiC_p/Al alloy composites. According to J. David, the spiral lengths, obtained in 20 vol.% SiC_p/A356 Al alloy composites are shapely increased up to 710°C, and then not changed further [14]. However, 10 vol.% SiC_p/Al alloy composites are continuously increased with increasing temperature. Therefore, it is believed that a difference of optimum cast temperature with SiC particulate volume fractions results from the discrepancy in fluidity of melt with increasing temperature.

3.3. Statistical analysis for strength

The tensile strength of die-cast composites was higher than that of the die-cast Al matrix alloy, and also the tensile strength was increased with increasing SiC particulate volume fraction as discussed in Section 3.2. However, the room temperature tensile elongation of SiC_p/Al alloy composites was ∼1% as shown in Fig. 4b and the fracture mode of SiC_p/Al alloy composites was appeared brittle fracture mode, which typically exhibit scatter in fracture strength. Therefore, the statistical evaluation for strength of die-cast SiC_p/Al alloy composites is required to predict the reliability of composites.

Statistical strength analysis discussed using Weibull distribution function equation [15–17]. For discussion of the strength distribution of brittle materials, the following two terms are generally assumed. They are: (1) the materials are statistically uniform and (2) the strength of the materials depends on the weakest defect of all of them. We let link is flaw, suppose that the sample has n-numbers link, the probability of fracture is described as flaws. When the number of link in the sample is one, $F_1(\sigma)$ means a probability of fracture and $1 - F_1(\sigma)$ is probability of non-fracture under the applied stress, σ. When the number of link is n, the probability of fracture, $F_n(\sigma)$, under the applied stress, σ, is $F_n(\sigma) = 1 -$ (the probability of non-fracture) from the weakest link theory. Thus the probability is expressed as the following equation from multiplication rule.

$$F_n(\sigma) = 1 - [1 - F_1(\sigma)]^n \tag{1}$$

$$1 - F_n(\sigma) = 1 - [1 - F_1(\sigma)]^n \tag{2}$$

If n values is vary large, the probability is described as follows

$$1 - F_n(\sigma) = 1 - [1 - F_1(\sigma)]^n = \exp[-nF_1(\sigma)] \tag{3}$$

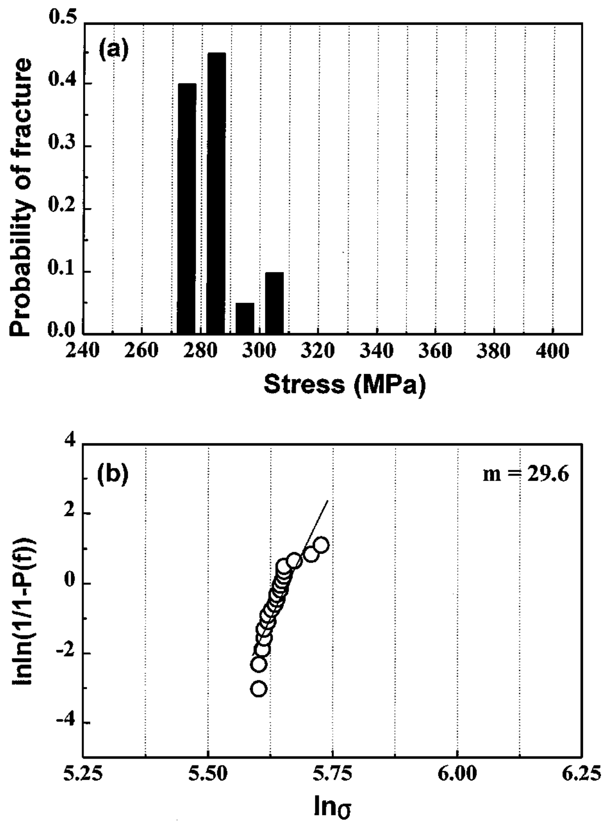

Figure 8 (a) The histogram of probability of fracture and (b) Weibull plots of strength for Al matrix alloy fabricated by die-casting at the temperature of 700°C.

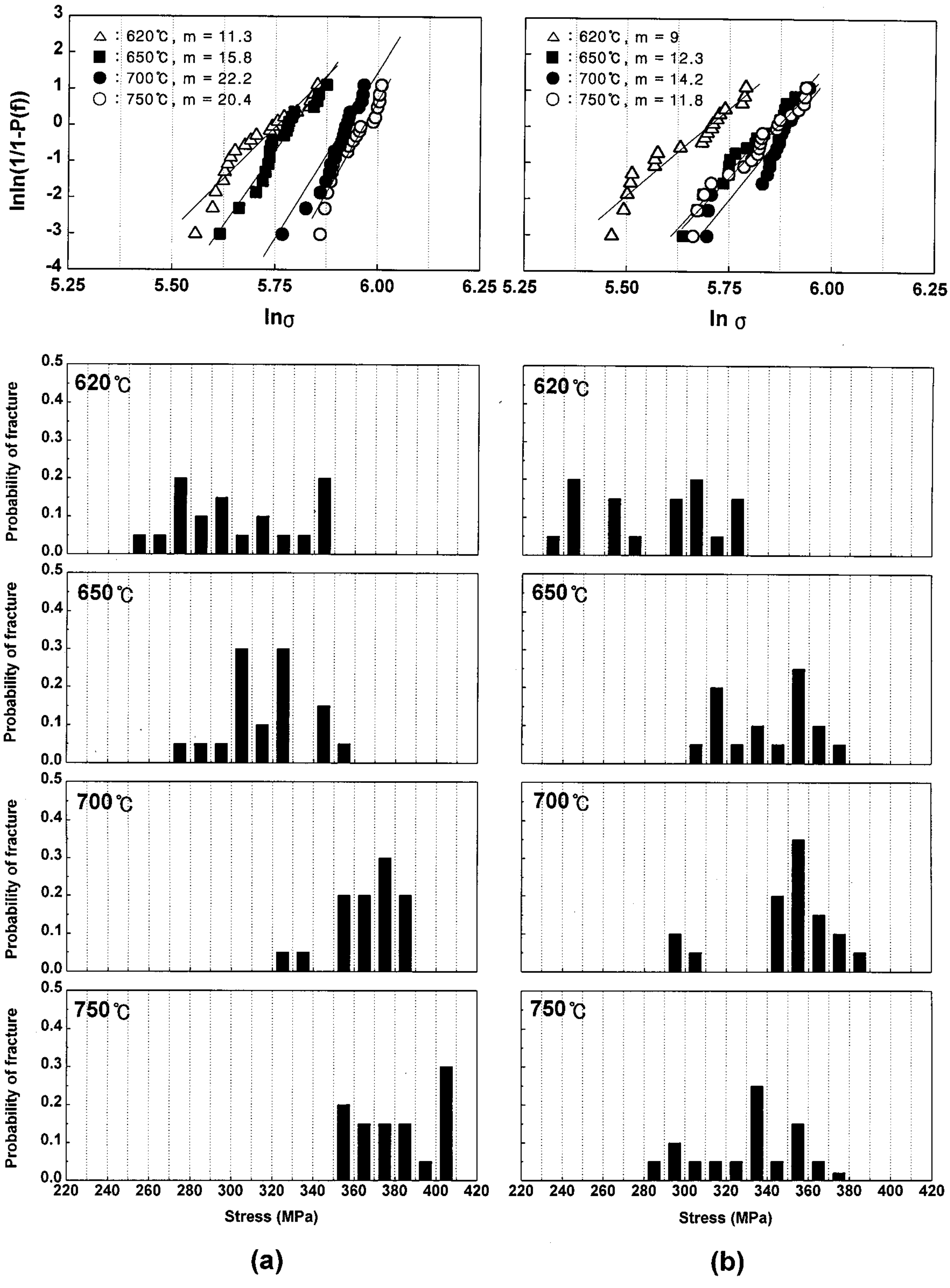

Figure 9 Weibull plots and histogram of probability of fracture of strength for die-cast SiC_p/Al alloy composites as a function of die-casting temperature and volume fraction of SiC particulate: (a) 10 vol.% SiC_p/Al and (b) 20 vol.% SiC_p/Al.

Where the $F_1(\sigma)$ represents a stress function of the samples regardless of link number and the number of link is proportional to the volume of the sample. Equation 3 is expressed as:

$$F_n(\sigma) = 1 - \exp[-V\phi(\sigma)] \quad (4)$$

Using $F_n(\sigma) = P(f)$ relation, Equation 4 is written as:

$$P(f) = 1 - \exp[-V\phi(\sigma)] \quad (5)$$

For Equation 4 and 5, $\phi(\sigma)$ means unknown function. Weibull express $\phi(\sigma)$ as the following experimental equation.

$$\phi(\sigma) = [(\sigma - \sigma_u)/\sigma_o]^m \quad (6)$$

Where σ is the applied stress, σ_u is the threshold stress $(P(f) = 0)$, σ_o is the normalizing stress $(P(f) = 0)$, and m is Weibull modulus. Thus the probability of fracture under the applied is expressed as:

$$P(f) = 1 - \exp\left[\frac{-V(\sigma - \sigma_u)}{\sigma_o}\right]^m \quad (7)$$

In term of logarithms, Equation 7 can be written as:

$$\ln \ln[1/(1 - P(f))] = \ln V + m \ \ln\sigma - m \ \ln\sigma_o \quad (8)$$

In Equation 8, as plot of $\ln\sigma$ against $[1/(1 - P(f))]$ gives line-relationship and a slop of the line is Weibull modulus, m. Where, if n number among N number samples are fractured under the applied stress, σ. The brittle materials were generally expressed with decreasing Weibull modulus, m.

Fig. 8 shows the histogram of probability of fracture and Weibull plots of strength for Al matrix alloy fabricated by die-casting at the temperature of 700°C. It was demonstrated that scatter of the strength for Al matrix alloy is narrowly and the Weibull modulus is 29.6. Fig. 9 shows histogram of probability of fracture and Weibull plots of strength for die-cast SiC_p/Al alloy composites as a function of die-casting temperature and SiC particulate volume fraction. It was demonstrated that scatter of the strength in SiC_p/Al alloy composites is broadly distributed and tend to gradually broad with an increase of SiC particulate volume fraction, whereas scatter of strength in Al matrix alloy is narrowly distributed. This may be due to the formation of a large amount of crack initiation sites, defect, resulting from an increase of SiC particulate volume fraction. Weibull modulus of die-cast SiC_p/Al alloy composites was 22.2 in 10 vol.% SiC_p and 14.2 in 20 vol.% SiC_p at the die-cast temperature of 700°C. It is found that Weibull modulus of the composites is linearly decreased by adding SiC particulate into the matrix. In addition, it was found that slope of line, become shapely steep at the cast temperature of 700°C for 10 vol.% SiC_p/Al alloy composites in comparison with another cast temperature condition. However, maximum tensile strength was obtained at the cast temperature of 750°C. It is believed that cast temperature of 750°C is optimum condition for the distribution of SiC particulates in consequence of good fluidity of melt, but it is supposed that an air-entrapment takes place during injection with increasing cast temperature. As a result, it is found that strength distribution of composites fabricated in 700°C was found to be more narrow than that of composites fabricated in 750°C. It is necessary for the SiC_p/Al alloy composites that the mechanical property is considered an angle of probability fracture in applied stress. Weibull plots for 20 vol.% SiC_p/Al alloy composites are shown in Fig. 9b. It was represented that slope of line become shapely steep at the cast temperature of 700°C in comparison with another cast temperature condition. This result agrees with tensile strength in Fig. 4a. Also, it was found that scatter of the strength of 20 vol.% SiCp/Al alloy composites is more broadly distributed than that of 10 vol.% SiC_p/Al alloy composites. It is approved that Weibull modulus of the composites is linearly decreased by adding brittle, hard SiC particle into the matrix. According to B.K. Suh, the Weibull modulus, obtained in SiC_p (0, 10 and 20 vol.%)/2024Al composites fabricated by powder extrusion method is 36.1, 22.3 and 17.8, respectively [18]. It was approved that the weibull modulus of die-cast SiC_p/Al alloy composites was found to be comparable with that of powder extruded composites.

4. Conclusions

(1) SiC pacticulates were homogeneously dispersed in die-cast Al matrix alloy, resulting from the refinement of dendrite cell size due to rapid cooling rate.

(2) The tensile strength of die-cast SiC_p/Al alloy composites was higher than that of the die-cast Al matrix alloy. Also, the tensile strength was slightly increased with increasing SiC particulate volume fraction at the cast temperature range of 650–700°C. However, the strength scattering of composites was increased with increasing SiC particulate volume fraction.

(3) It was found that die-cast temperature of 750 and 700°C are optimum condition for the distribution of SiC particulates in consequence of good fluidity of melt for 10 and 20 vol.% SiC_p/Al alloy composites, respectively.

(4) For the statistical evaluation of strength, the maximum Weibull modulus of die-cast SiC_p/Al alloy composites, which was obtained at the cast temperature of 700°C, was 29.6 in Al matrix alloy, 22.2 in 10 vol.% SiC_p and 14.2 in 20 vol.% SiC_p, respectively.

Acknowledgements

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