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Process Parameter-Microstructure-Mechanical Property Relations of SiC_p-Reinforced Aluminum Composites Produced by Powder-Injection Casting

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Abstract

Aluminum composites are of interest for engineering applications such as electrical and especially automotive applications and their final physical and mechanical properties are usually determined by fabrication techniques. This research aimed to study effects of process parameters, which are i) argon gas flow rates at 5 and 10 l/min, and ii) casting temperatures at 620 and 680°C, on integrity of the SiC_p-reinforced 356 aluminum composites fabricated by powder-injection casting using a modified flux injection degassing machine. The SiC_p additions are 0, 10 and 15 wt.%. Microstructure - mechanical property relations were constructed based on the predetermined process parameters. Aluminum 356 alloy was melted at 700°C and injected with pre-heat-treated SiC_p at 590°C. The injection was carried out via the argon gas for 15 minutes at a rotational speed of 1000 rpm using the modified SiC_p injection degassing machine prior to pouring into cylindrical permanent molds for microstructure and mechanical property investigation. Experimental results showed that hydrogen degassing at 5 l/min of argon gas flow rate helped to produce good distribution of SiC_p within the aluminum matrix and to decrease porosity in aluminum composites. Casting temperature at 680°C in the liquid state was found to be a key factor in improving density and hardness properties.

Keywords: Aluminum Composites, SiC_p Reinforcement, Powder – Injection Casting, and Mechanical Properties

Introduction

Composite materials have been used for advanced structural and non-structural applications in automotive, aircraft, marine and electrical industries. The metal matrix composites (MMCs) consist of reinforcing materials and metal matrices such as aluminum, titanium, steel to obtain new materials with good mechanical properties such as high stiffness, strength and high temperature resistance. In recent years, SiC_p-Al MMCs have received significant attention and their fabrication techniques have been the major interest, which affect the mechanical properties of the composites. There are many commercial processes for the fabrication of MMCs such as stir casting, squeeze infiltration, extrusion and hot pressing. However, stir casting technique is normally accepted because of its simplicity, flexibility and least expensive.[1-4] Since uniform distribution of SiC_p is desirable, the techniques such as manual mixing plus stir-mixing, and two-step stir-mixing have been investigated. Parameters for instance mixing temperature, pouring temperature, stirring time, stirring speed and content of reinforcing particles significantly affect the mechanical properties. Improper process control leads to defects in MMCs such as non-uniform microstructure, porosity, and inclusion yielding poor mechanical properties. Nonetheless powder injection technique has been rarely observed.[5-7] Injections of activated powders such as AlN-TiC/Al and

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milled SiC_p-Al powder have been investigated to produce good mechanical properties. However the effect of hydrogen degassing during injection has not been included. This research therefore aimed to study the effect of powder-injection casting process parameters on microstructure and mechanical properties of SiC_p-reinforced 356 aluminum composites by using the modified SiC_p injection hydrogen degassing unit as shown in Figure 1.

Figure 1. The modified SiC_p Injection Mobile Degassing Unit (SiC_p-IMDU)

Materials and Experimental Procedures

Commercial grade 356 aluminum alloy and SiC_p with an average size of 10.5 micron were used as matrix and reinforcement respectively. The SiC_p were surface heat-treated at 1000 ºC for 4 h prior to mixing to produce SiO_2 layer on SiC_p surface to prevent the undesirable brittle Al_4C_3 phase formation.[8] After aluminum alloy was completely melted at 700 ºC, 1 wt.% Al-5Ti - B, 0.02 wt.% Sr and 1 wt.% Mg were added. These additions were aimed for grain refinement, modification of eutectic phase and wettability improvement between SiC_p and aluminum melt respectively. The melt was then cooled down below the liquidus temperature at 590 ºC to keep the slurry in a semi-solid state. At this stage, SiC_p was injected through the graphite shaft and nozzle into the aluminum slurry. The injection was carried out via the Ar gas at a rotational speed of 1000 rpm by using a modified SiC_p-injection hydrogen degassing machine prior to pouring into cylindrical permanent molds having dimensions of 25 mm. in diameter and 200 mm. in height. The studied process parameters are i) argon gas flow rates at 5 and 10 l/min, and ii) casting temperatures at 620 and 680°C. The SiC_p additions were 0, 10 and 15 wt.%. Microstructure examination was carried out using a digitized optical microscope whereas the density was determined using Archimedes's method. Brinell hardness and tensile properties were examined to reveal the effects of powder-injection casting process parameters on mechanical properties of aluminum composites.

Results and Discussion

Chemical Composition and Microstructure Analysis

Chemical composition of the matrix phase is listed in Table 1. Slightly higher Mg content is due to Mg addition. The microstructure of monolithic aluminum alloy (without SiC_p) consisted of near-globular primary α phase surrounded by eutectic silicon as shown in Figures 2 (a) and (d). Considering the composites being cast at 620°C, their microstructures were not uniform, giving particle clustering in localized regions as illustrated in Figures 2 (b), (c), (e) and (f). It is noted that the injection carried out at higher gas flow rate (10 l/min) caused more melt turbulence and resulted in higher degree of SiC_p clustering. Large porosities were routinely observed as seen in Figures 2 (e) and (f). The porosities were present along with the clusters of SiC_p. As the casting temperature was raised up to 680°C, the microstructure of monolithic aluminum matrix consisted of typically dendritic primary α phase surrounded by

eutectic silicon, as illustrated in Figures 3 (a) and (d). The composite using Ar gas flow rate at 5 l/min provided more uniform SiC_p distribution, as seen in Figure 3 (b). However, large clusters of porosities and SiC_p were normally observed in the microstructures of the composite using 10 l/min Ar gas flow rate, as illustrated in Figures 3 (e) and (f) for 10 wt.% and 15 wt.% SiC_p additions respectively.

Table 1. Chemical composition of aluminum alloy (balanced Al)

Materials	Content (%)									
	Si	Cu	Fe	Zn	Ni	Mg	Cr	Mn	Pb	Sn
Al 356 + 1 wt.% Al-5Ti-B + 0.02 wt.% Sr + 1 wt.% Mg	7.35	1.685	0.517	>3.012	0.259	>0.552	0.04	0.161	0.057	0.017

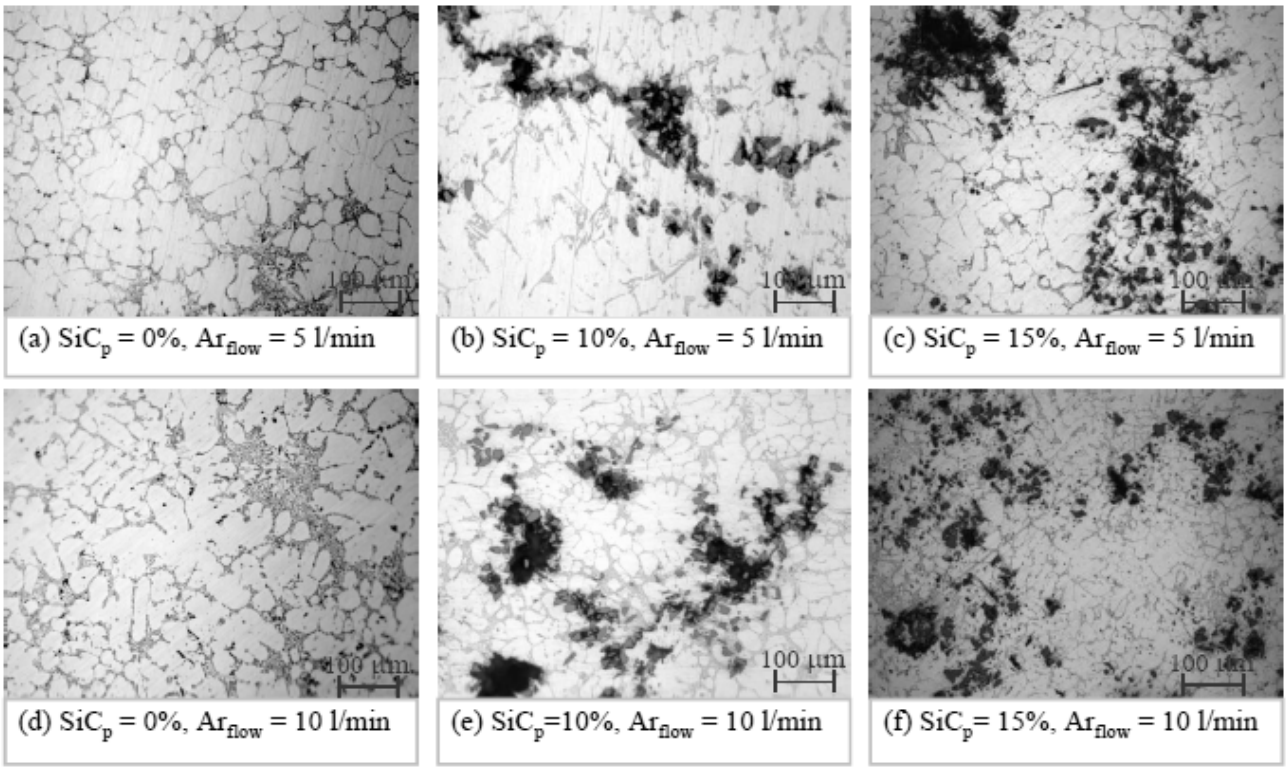


Figure 2. Microstructures at 620 ºC casting temperature

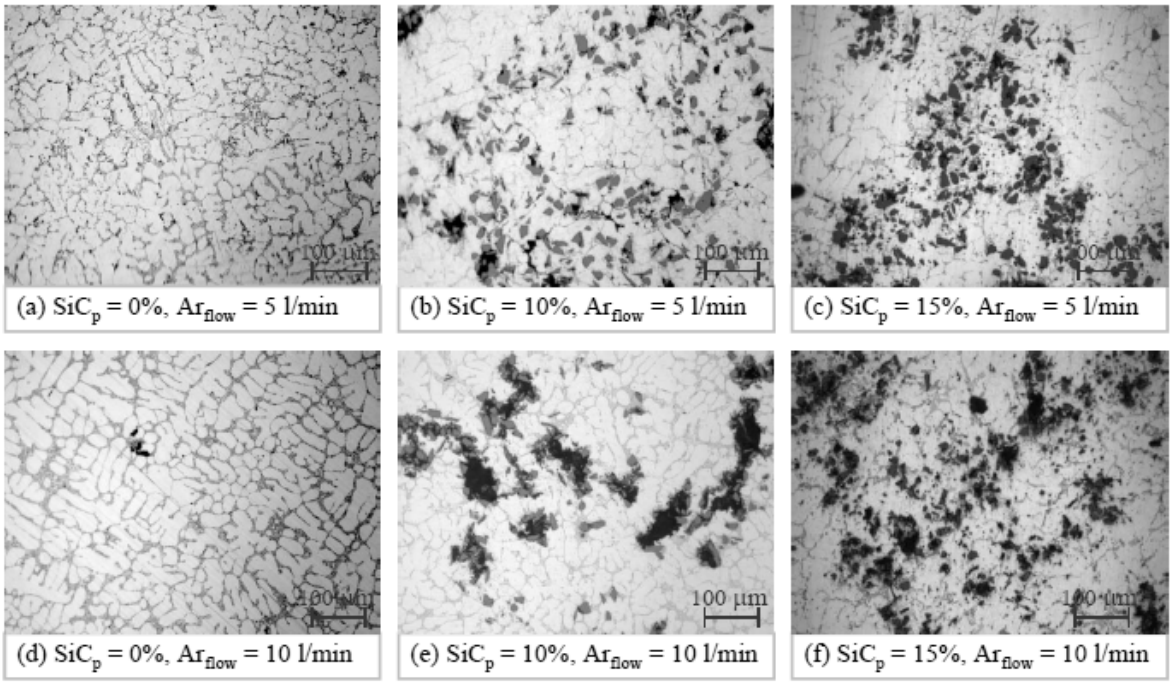
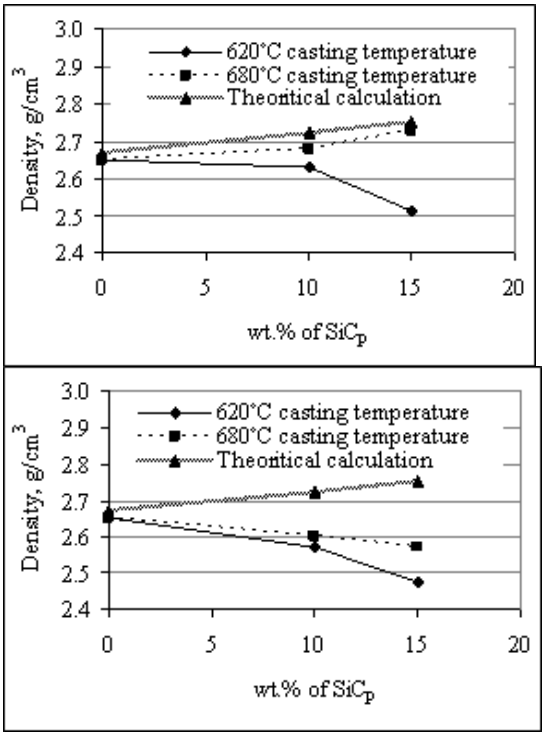


Figure 3. Microstructures at 680 ºC casting temperature

Properties of SiC_p-Al composites

Density

The density determined by Archimedes's method is illustrated Figures 4 (a) and (b). The density result is compared with theoretical density of the composites based on the rule of mixture. The measured density was found to be lower than the theoretical alloy density due to the absence of porosity in the theoretical density calculation. It is seen that when 5 l/min Ar gas flow rate was applied, the casting temperature provided different trends. Casting at 620 ºC gave decreasing specimen density with increasing SiC_p addition, while casting at 680 ºC offered an opposite trend. However, when 10 l/min Ar gas flow rate was used, casting temperatures at 620 ºC (semi solid state) and 680 ºC (liquid state) both provided decreasing trends of density with increasing SiC_p contents. This observed result is associated with the presence of gas-shrinkage porosity, as well as its distribution and morphology, which will be later discussed.



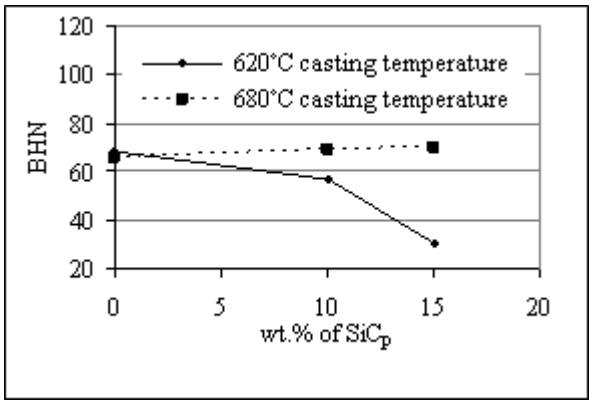
(a)Ar gas flow rate = 5l/min

(b)Ar gas flow rate = 10 l/min

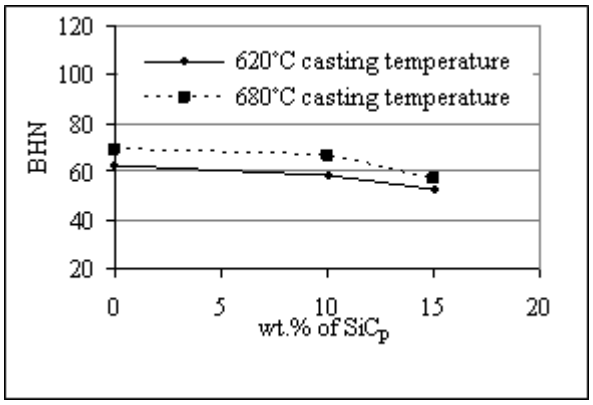
Figure 4. Density of SiC_p-Al composite

Brinell Hardness

Brinell hardness result followed the same trends observed from the measured density result, as illustrated in Figures 5 (a) and (b). This is influenced by the process parameters (gas flow rate and casting temperature) to control the occurrence and distribution of porosity. Nevertheless, other factors such as non-uniform distribution of SiC_p, and cooling rate also gave differences in hardness values of the composite.



(a)Ar gas flow rate = 5l/min

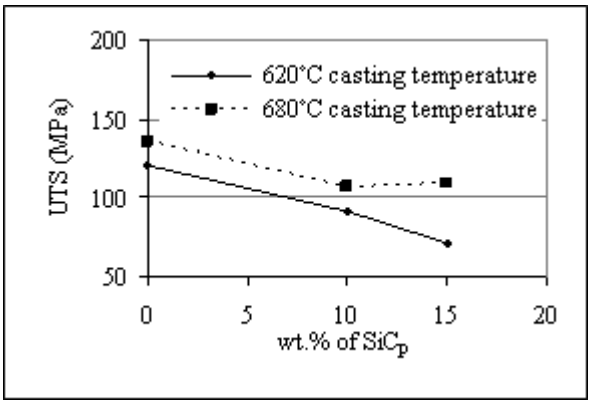


(b)Ar gas flow rate = 10 l/min

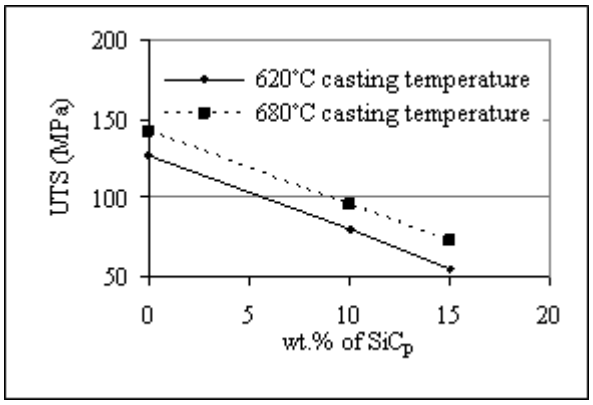
Figure 5. Brinell hardness of SiC_p-Al Composites

Tensile Strength

Experimental result showed that ultimate tensile strength more or less reduced with the addition of SiC_p as illustrated in Figure 6 in all cases and did not completely follow the same trends as observed from density and hardness results. It might be that the presence of porosity and their morphology responded differently when subjected to tensile loading.



(a) Ar gas flow rate = 5l/min



(b) Ar gas flow rate = 10 l/min

Figure 6. Ultimate tensile strength (UTS) of SiC_p-Al composites

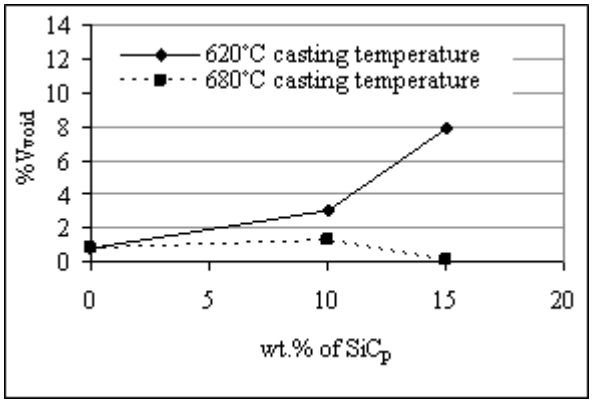
Effect of Process Parameters on the Presence of Porosity

According to experimental results, general microstructure observation indicated that porosity is lesser when the modified hydrogen degassing was applied in monolithic aluminum melt. For composite melt, degassing is more difficult than monolithic alloy because gas bubbles are stabilized by reinforcing particles. This is observed when 10 l/min of argon gas flow rate was employed, as shown in Figures 2(a),

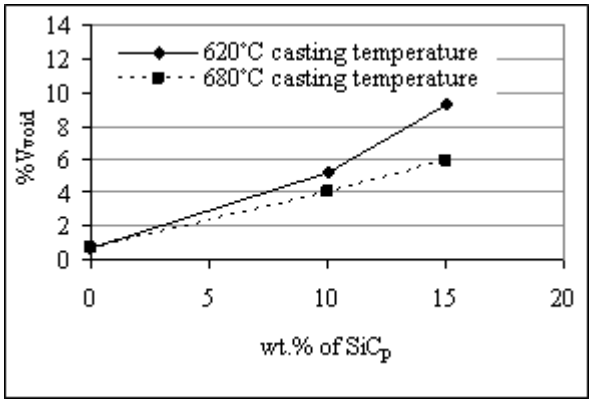
2(d), 3(a) and 3(d). Additions of SiC_p however increased porosity level especially with increasing Ar gas flow rate. If % porosity is now considered as % internal voids by applying the theoretical density of aluminum matrix and SiC_p following the equation.[9]

$$\% \text{ Internal void} = \frac{\rho_{th} - \rho_{Arch}}{\rho_{th}} \times 100 \qquad (1)$$

Where ρ_{th} is theoretical density calculated by using the rule of mixture and ρ_{Arch} is density determined by Archimedes's method. Figure 7 illustrates % internal void of the composites.



(a) Ar gas flow rate = 5 l/min



(b) Ar gas flow rate = 10 l/min

Figure 7. Porosity of composite in terms of % internal voids

It can be seen that the % internal void is closely associated with density and hardness properties which relied on Ar gas flow rate and casting. If we first consider the effect of casting temperature, the composites cast at 680ºC has a decreasing trend of % porosity in comparison to that of 620ºC casting temperature. It might be that the higher casting temperature in the liquid state lowered the melt viscosity and allowed higher efficiency of hydrogen degassing. The air-gas bubbles can then escape from the molten metal up to the melt surface more easily. Secondly, if we consider the effect of gas flow rate, the higher Ar gas flow rate (10 l/min), in all cases irrespective to the casting temperature, caused melt turbulent during particle injection. This Ar gas flow rate might be too high and blocking of SiC_p occasionally occurred along the Ar gas carrying path (though the graphite shaft and nozzle). This eventually caused SiC_p jetting into the aluminum melt, appearing as large clusters of porosity and SiC_p in combination. On the contrary, as the 5 l/min gas flow rate was applied, smoother particle injection was observed; thereby, resulting in less porosity and more uniform distribution of SiC_p. Since porosity certainly influenced the composite properties, the cause of pore/void formation in this research should be explored to explain the effect of processing parameters on the presence of porosity and its consequence on the mechanical properties of the composite.

There are mainly two kinds of porosity; shrinkage and (hydrogen) gas normally observed in the monolithic aluminum alloy. However, the presence of reinforcing material (foreign particles) was considered to significantly interfere with the nucleation and growth of both shrinkage and gas porosities. It was summarized[10] that the increase in porosity level of the SiC_p-Al composite casings with increasing SiC_p content is due to the following mechanisms; i) increasing surface gas layers surrounding particles, ii) increasing viscosity of composite mixture resulting in higher gas hold up as well as improper melt filling of the gaps between adjacent particles, and iii) increasing

sites for heterogeneous pore nucleation by foreign particles. Previous studies [3,11-13] have explained the nucleation and growth of pores taking place during the solidification of SiC_p-Al composite when the solidification started and a network of α-aluminum dendrites was developed. The SiC_p that has already existed in the melt were rejected in front of the α-aluminum dendrite network. At this stage, there was an accumulation of hydrogen gas in the inter-dendritic liquid due to decreasing hydrogen solubility in the aluminum melt accompanying solidification. As the temperature approached the eutectic temperature, the growth of pores was limited by their abilities to expand in the remaining melt. Hence, the escape of gas bubbles from the molten mixture of composite is more difficult than from the monolithic alloy melt since the gas bubbles were anchored by the reinforcing particles, which were usually suffered from wetting problem.[12,13] Poorly bonded SiC_p particles with the aluminum matrix also provided appropriate sites for shrinkage and gas nucleation occurring on a micro level as micro shrinkage or microporosity. This porosity is dispersed in the interstices of dendritic solidification regions.[14]

Moreover the porosity shape and size were affected by the presence of the SiC_p reinforcement through the tendency of these particles in blocking melt feeding (liquid, mass, interdendritic and solid feeding) that occured from the initial stage through the final stage of solidification. Higher amount of SiC_p also provided higher melt viscosity due to increasing solid content of the molten mixture and even caused more harmful effect. It was also noted that[15] the presence of thermally insulating particles (SiC_p) in a significant amount might affect the solidification time, resulting in greater melt viscosity.

It can be seen that, metal properties (composition, melt super heat, viscosity, and surface tension), reinforcement characteristics (particle size, particle shape, and agglomeration), and solidification mechanism are key factors influencing fluidity of aluminum composite, while they have little effect in aluminum alloys. Therefore, the abovementioned factors have great impact on the present porosity and in turn affect mechanical properties of aluminum composite.

Through this research, the injection of the SiC_p was perhaps considered to increase surface gas layer surrounding SiC_p, though the technique was employed via the inert Ar gas and the SiC_p has also been surface-treated at high temperature. Decreasing hydrogen solubility in the aluminum melt during solidification caused gas porosity to be inhabitable in the interstices of primary α phase along with SiC_p. As the SiC_p limited melt feeding, clusters of SiC_p and gas-shrinkage porosity were seen as a regular event observed in the composite microstructure. However, the degassing technique and the casting temperature used in this research were observed to provide significant results. The degassing technique seemed to provide a positive effect when the casting temperature (after improvising degassing) was in the liquid state at 680 ^oC. Higher content of liquid phase not only promoted better metal feeding but also allowed degassing to practically remove hydrogen gas via finely dispersed Ar gas bubbles and then escaped up to the melt surface in time before solidification took place. This has been previously seen from density and hardness results, as shown in Figures 4 and 5. On the contrary, reducing the casting temperature down to the semi-solid state at 620 ^oC limited the melt feeding and also made degassing more difficult in the highly viscous melt. The escape of Ar gas bubbles produced via degassing was then blocked and the bubbles were left in the castings after solidification, giving poor density and hardness properties. In addition,

the Ar gas flow rate also provided a crucial effect in that smooth injection of SiC_p is more desirable via 5 l/min gas flow rate. Higher gas flow rate at 10 l/min unfortunately in all cases provided turbulent flow of SiC_p and caused huge clusters of porosity and SiC_p to non-uniformly distribute in the matrix.

The drawback of SiC_p addition seemed to be pronounced when the composite was subjected to tensile loading. It was indicated that[12,13] the decreasing strength of composites with increasing reinforcing particles was associated with the formation and growth of voids surrounding such particles. In many discontinuous reinforced systems, the specimen failure was related to the formation and growth of pores at the interface of reinforcement-matrix, leading to void agglomeration to initiate final failure. The reinforcing particles appeared to have important stress raising effect on the formation of slip bands at supposedly micropores or SiC_p as microstructure discontinuity. The formation of micropores at the weak reinforcement-matrix interface and especially the existing pores occurring from the fabrication process has played a key role in initiating stress raising effect during tensile loading. The size and distribution of pores influenced by process parameters (Ar gas flow rate and casting temperature) seemed to rule out the strengthening effect given by the reinforcing SiC_p. This in turn resulted in a decreasing trend of tensile strength with increasing SiC_p addition in all cases.

Conclusions

The SiC_p-reinforced 356 aluminum composites have been fabricated by powder-injection casting using different processing conditions. The effects of process parameters on microstructure and properties can be concluded as follows:

1. Unreinforced alloy gave minimum % internal void whereas the addition of SiC_p increased tendency of porosity formation.
2. Higher Ar gas flow rate at 10 l/ min provided undesirable disturbance in molten mixture, causing large SiC_p- gas porosity clustering, which resulted in degraded density and hardness.
3. Low casting temperature at 620 ºC provided inferior properties of the composites due to high degree of porosity as a result of highly viscous melt to limit metal feeding and effective degassing.
4. Composites produced by using 5 l/min Ar gas flow rate and 680ºC casting temperature offered increasing trends of density and hardness properties.

Acknowledgments

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References

1. Hull, D. and Clyne, T.W. (1996). *An Introduction to composite materials*. Cambridge: University Press

2. Van Paisarn Doungjak na Ayutthaya, (2004). Mechanical Properties of Silicon Carbide - Aluminum Tetroxy-carbide Nanofibers- Reinforced Aluminum Matrix Comp. Chiang Mai: University.

3. Hashim, J., Looney, L. Hashmi, M.S.J. (1999). Metal matrix composites production by stir casting method. *J. Mater. Pro. Technol.*:92-93.

4. Aigbodion, V. S. and Hassan, S. B. (2007). Effects of silicon carbide reinforcement on microstructure and properties of cast Al-Si-Fe / SiC particulate composite. *J. Mater. Sci. Eng.* :355-360.

5. Huashun, Y., Hongmei, C., Rendian, M.A. and Guanghui, M. (2006).Frabrication of AlN - TiC/Al composites by gas injection processing .*Rare Met*. **25** :6.

6. Amirkhanlou, S. and Niroumand, B. (2010). Synthesis and characterization of 356 - SiCp composites by stir casting and compocasting methods. *Trans. Nonferrous. Met. Soc. China*: s788-s793.

7. Maleki, A., Meratian, M., Niroumand, B. and Gupta, M. (2008). In-Situ aluminum matrix composite using a new activated powder injection method. *Metall. Mater. Trans*.**39** : 3034-3039.

8. Peach-Canul, M. I., Ortega-Celaya, F. and Peach-Canul, M. A. (2006). Influence of SiO_2 in SiC_p on microstructure and impact strength of Al/SiC_p composites fabricated by pressureless infiltration. *Mech. Compos. Mater.* **42 (3):** 401-418.

9. Emamy, M., Razaghian, A., Lashgari, H. R. and Abbasi, R. (2008). The effect of Al- 5Ti- 1B on the microstructure, hardness and tensile properties of Al_2O_3 and SiC - containing metal – matrix composites. *J. Mater. Sci. Eng.*: 210-217.

10. Akhlaghi, F., Lajevardi, A. and Maghanaki, H.M. (2004). Effects of casting temperature on the microstructure and wear resistance of compocast A356 / SiC_p composites : comparison between SS and SL route. *J. Mater. Pro. Technol.* :155-156, 1874-1880

11. Mohamed, A. T. (2001). Practicalization of cast metal matrix composites (MMCCs). *J. Mater. Design.* **22**: 431-441.

12. Hashim, K. J. (2001). The production of cast metal matrix composite by a modified stir casting method. *J. Tekhnologi*. **35(A):**9-20.

13. Aqida, S. N., Ghazali, M. I. and Hashim, J. (2004). Effects of porosity on mechanical properties of metal matrix composite:an overview. *J. Tekhnologi.* **40(A):** 17-32.

14. Samuel, A.M., Gotmare, A. and Samuel, F.H. (1995). Effects of solidification rate and metal feedability on porosity and SiC/ Al_2O_3 particle distribution in an Al-Si-Mg (359) alloy. *Comp. Sci. Technol.* **53** :301-315.

15. Ravi, K. R., Pillai, R. M., Amaranathan, K. R., Pai, B. C. and Chakraborty, M. (2008). Fluidity of aluminum alloys and composites : A review. *J. Alloys. Compd.* **456** :201-210.