SENRA Academic Publishers, Burnaby, British Columbia
Vol. 5, No. 2, pp. 1541-1546, June 2011
Online ISSN: 1920-3853; Print ISSN: 1715-9997

Canadian Journal of pure&applied sciences

SOLIDIFICATION BEHAVIOR AND FORGEABILITY OF STIR-CAST ALUMINUM ALLOY METAL MATRIX COMPOSITES

Rabindra Behera[1], S Kayal[1], D Chatterjee[2] and *G Sutradhar[3]
[1]Department of Mechanical Engineering, Jadavpur University, Kolkata, West Bengal
[2]Department of Mechanical Engineering, Bengal Engineering College, Kolkata, West Bengal
[3*]Department of Mechanical Engineering, Jadavpur University, Kolkata, West Bengal, India

ABSTRACT

The present paper aims to investigate the solidification behavior and the forgeability of Aluminum alloy (LM6)-SiCp composites at different section of three-stepped composite castings. LM6 metal matrix composites (MMCs) containing SiC particles (5 and 10 wt %) of 400mesh (average size) were prepared by using stir casting route. The temperature of the cast composites during solidification was measured by putting K-type thermocouples at the centre of the each step, from which the solidification curves were constructed. The forgeability of the as cast MMCs were also measured at different step of the casting. The results show that the forgeability of cast metal matrix composites at the middle section i.e. step-II of the casting is minimum compared to both end section of a three-step casting. The solidification curves of Aluminum alloy (LM6)-SiCp composites compared with the unreinforced alloy (LM6) and the results reveal that significant increase in solidification time with the addition of SiC particles. The curves also show that the rate cooling and the solidification time are different at different section of the castings. This practical research analysis and test results on solidification behavior and the forgeability of Al/SiCp-MMC will provide useful guidelines to the present day manufacturing engineers.

Keywords: Metal matrix composites (MMCs), casting, solidification, cooling rate, forgeability.

INTRODUCTION

The developments in materials technology have resulted in several new materials like metal–matrix composites (MMCs). Composites have developed with great success by the use of fiber reinforcement in metallic materials (ASM Metal Hand Book, 1998). Metal–matrix composites (MMCs) have been one of the key research subjects in materials science during the past two decades (Lindroos *et al*., 1995). MMCs have emerged as potential material alternatives to conventional alloys and widely used in aircraft and automobile industries because of its excellent physical, mechanical and development properties. But, the difficulties in production and the manufacturing cost is the key factor, which comes as an obstacle for their wider application in modern industry, although potential benefits in weight saving, improved mechanical properties and increased component life. Now a day, even in those terms, MMCs are still significantly more expensive than their competitors. Only simpler production methods, higher production volumes, and cheaper reinforcements can achieve the cost reductions (Charles, 1990; Klimowicz, 1994). The search for cheaper, easily available reinforcement has led to the wider use of SiC and Al_2O_3 particles (Klimowicz, 1994). Therefore, the particle reinforced MMCs are now dominating the MMC market. There are several methods are used for the manufacturing of MMCs, of which, stir casting method is quite popular due to its unique advantages. In this casting method, the reinforcing particles has introduced into the melt and stirred thoroughly to ensure their proper mixing with the matrix alloy. The properties of particle-reinforced metal matrix composites produced by stir cast method has influenced by various parameters such as type, size & weight fraction of reinforcement particles and its distribution in cast matrix metal. It also depends on their solidification behavior during casting. The rate of solidification has a significant effect on the microstructure of cast composites, which in turn affects their mechanical properties. Nath *et al*. (1987) studied on the distribution of mica particle in Al-Cu-Mg melt solidified in a variety of moulds under different heat flow configurations and concluded that thin castings of 12.5mm could easily be produced with a homogeneous distribution of mica particles. Dutta and Surappa (1998) studied macro- and micro-structure of Al–Cu–SiCp composites under multidirectional solidification conditions and concluded that an increase in particle volume fraction and cooling rate reduced the extent of macro-segregation of reinforcements in the composites. Rajan *et al*. (2007) studied on solidification and casting / mould interfacial heat transfer characteristics of aluminum matrix composite. They have shown that, addition of ceramic reinforcement particles with the aluminum alloy reduces the total solidification time in all the moulds (i.e. sand, graphite and metal mould) studied at lower volume fractions and increases at higher volume fractions. They

*Corresponding author email: cast_1963@rediffmail.com

have also concluded that the total solidification time is very less in case of graphite comparison to steel and sand mould, because of high thermal conductivity of graphite.

Particulate metal matrix composites have produced economically by conventional casting techniques. However, the stiffness, hardness and strength to weight ratio of cast MMCs are increased, but a substantial decrease in ductility has obtained. It has observed that some improvements in strength and ductility has found with the application of plastic forming processes i.e. forging to the cast composites. The forged MMCs having better mechanical properties compared to cast MMCs, such as it improves density, hardness and tensile strength etc. the forging process also avoids the use of secondary operation like machining. The forgeability is one of the important parameter, which gives information regarding the limitation of forging.

Ismail *et al*. (2000) studied on the effect of forging on the properties of particulate-SiC reinforced aluminium-alloy composites. They have shown that the forged samples had strength values superior to those of the as-cast counterparts. After forging, the yield strength and tensile strength increased and there has improvement in ductility of the composite material. Ceschini *et al*. (2009) studied on forging of the AA6061/23 vol. % Al_2O_3p and AA2618/20 vol. % Al_2O_3p composite: Effects on microstructure and tensile properties. They have shown that forging process induced a slight increase in hardness, tensile strength, elastic modulus and an evident increase in tensile elongation. SEM analyses of the fracture surfaces of the tensile specimens showed substantially similar morphologies for the as-cast and forged composites, both at room and high temperature. He *et al.* (1996) studied on the microstructure and mechanical properties of an Al/SiC composite cold die forged gear. They have observed that cold forging of SiC reinforced Aluminium based metal matrix composites reduce the grain size, defects, and the fracturing of the secondary phase and SiC particulates. Because of a cold plastic deformation, a large crystal distortion occurred resulting in the increase in the dislocation density that enhanced mechanical properties. The minimum isostatic pressure to prevent fracturing during cold die forging has found to be 650 MPa.

The objective of the present investigation is to study the effect of varying weight percentage of SiCp on the solidification curves of aluminum-silicon alloy (LM6) matrix composites during solidification at different step of the casting in sand mould and the forgeability of as cast MMCs at different step. The rate of solidification at section of the casting and the metallographic properties has studied at different weight percentage of silicon carbide particles. The results are compared with the solidification behavior of aluminum alloy i.e.LM6.

MATERIALS AND METHODS

Experimental procedure

The aluminum–silicon alloy i.e.LM6, which is a well-known alloy of aluminum, is used as the base/matrix metal in the experiments for the fabrication of the composites that has been reinforced with 5 and 10 wt% of SiCp of average 400 mesh size. The chemical composition of the matrix material (LM6) and the thermo physical properties of aluminum alloy, SiCp & sand have given in the tables 1 and 2. The composites have fabricated by the liquid metal stir casting technique. The aluminum alloy i.e. LM6 is melted in clay graphite crucible using an electric resistance furnace and 3wt% Mg has been added with the liquid metal, in order to achieve a strong bonding by decreasing the surface energy (wetting angle) between the matrix alloy and the reinforcement particles. The addition of pure magnesium has also enhanced the fluidity of the molten metal. The melt has mechanically stirred by using an impeller after addition of the pre-heated silicon carbide particle (about 850-900^{0}C). The processing of the composite has carried out at a temperature of 750^{0}C with a stirring speed of 400-500rpm. The melt has poured at a temperature of 745^{0}C into a stepped silica sand mould. Three (i.e.T_1, T_2 & T_3) K-type thermocouples of 0.3mm size has used at the centre of the different section of the mould to measure the temperature variation with respect to time in seconds in the casting during solidification has shown in figure1. One more K-type thermocouple has inserted into the sand mould to measure the temperature variation of the molding sand after pouring of molten metal and during solidification of the castings. The solidification curves of the castings and the variation of temperatures at different sections in the mould are recorded with the help of a computer aided data acquisition system, the schematic sketch of the computer aided temperature data acquisition set up has shown in figure 2. The figure of composite casting with thermocouples has shown below in figure 3. Finally, the solidification curves of LM6-SiCp composites have compared with the unreinforced LM6 matrix alloy at different section of the casting. The micro structural characteristics of the alloys and composites at different section of the castings have also evaluated.

Table 1. Chemical Composition (LM6).

Elements	Si	Cu	Mg	Fe	Mn	Ni	Zn	Pb	Sb	Ti	Al
Percentage (%)	10-13.0	0.1	0.1	0.6	0.5	0.1	0.1	0.1	0.05	0.2	Remaining

Table 2. Thermo physical properties of the matrix, reinforcement particle and sand.

Properties	LM6	SiC particulates	Sand
Density (gm/cm^3)	2.66	3.2	1.6
Average particle size (mesh)	--------	400	-----
Thermal conductivity (W/m-K)	155	100	0.52
Specific heat (J/Kg-K)	960	1300	1170

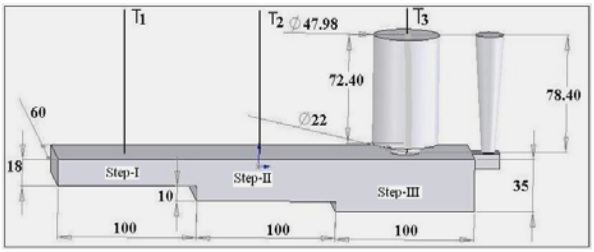


Fig. 1. The geometry of mould cavity with K type-thermocouples (T_1,T_2&T_3). (All dimensions are in mm).

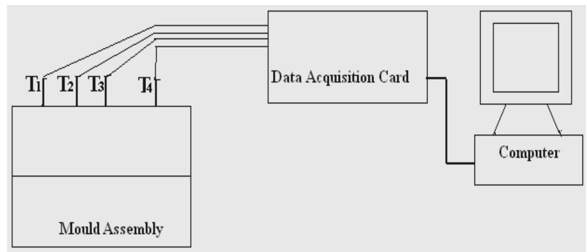


Fig. 2. Schematic sketch of the computer aided temperature data acquisition set up. (T_1, T_2 & T_3 Thermocouples attached different section of casting and T_4 inserted into the sand).

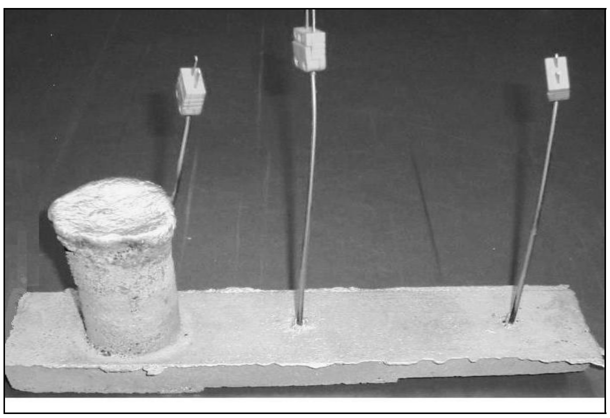
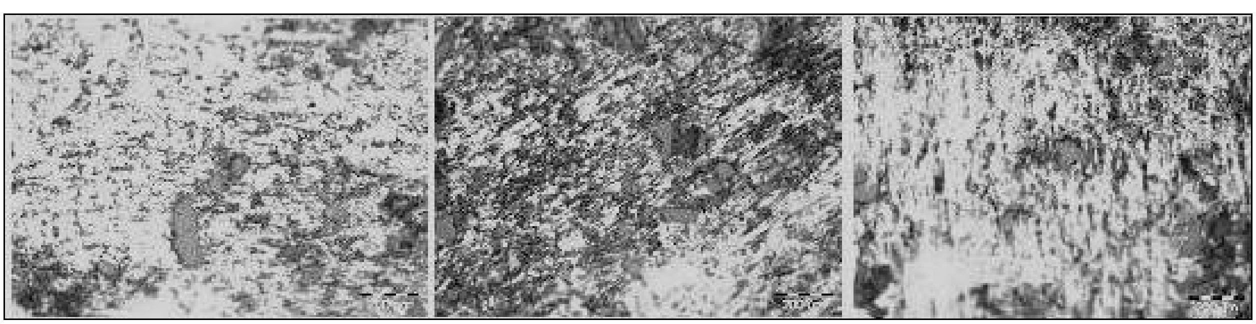


Fig. 3. Composite casting with thermocouples.

RESULTS AND DISCUSSION

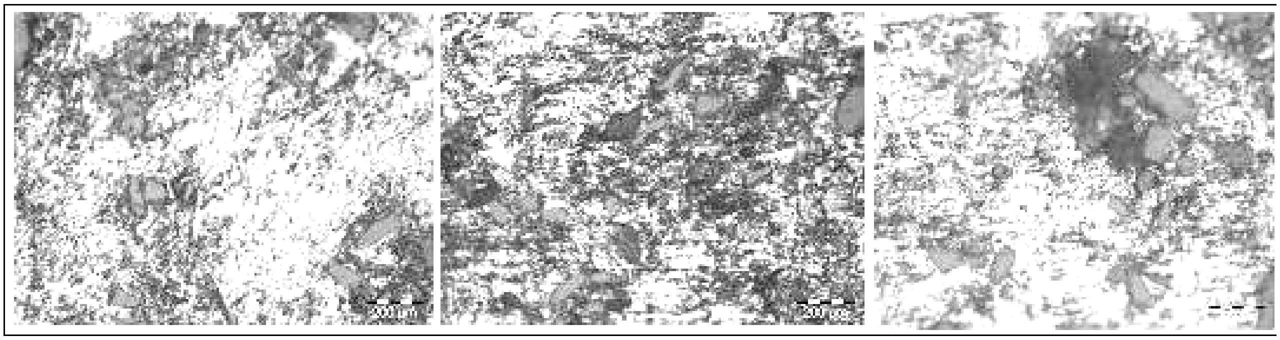
Microstructural Analysis

Samples of as cast MMCs for metallographic examination were prepared by grinding through 320, 400, 600, 800, 1200 and 1500 grit papers followed by polishing with 6μm diamond paste. Then the samples were etched with the etchant i.e. Keller's reagent. The etched samples were dried by using electric drier and then the microstructure observed by using optical microscope (Olympus, CK40M) at different magnification. The microstructure of the as cast LM6 MMCs are shown in figures 4 and 5 at different modulus of the casting. The micrograph of MMC castings at different step shows that the distributions of SiC particles are not uniform throughout the casting and segregation of particles are more in the eutectic region. This tendency may be attributed to the fact that the rate of cooling is not uniform throughout the casting due to change in thickness of the casting and lower rate of cooling in the sand mold.



a. Modulus 6.97 (step-I) b. Modulus 8.69(step-II) c. Modulus 8.95(step-III)

Fig. 4. Microstructure of LM6/5wt% SiCp as cast MMC at different modulus of the casting.



a. Modulus 6.97 b. Modulus 8.69 c. Modulus 8.95

Fig. 5. Microstructure of LM6/10wt% SiCp as cast MMC at different modulus of the casting.

Analysis of Cooling curves and Solidification Behavior of cast MMCs

When any alloying element or second phase particles added with the matrix alloy then the various time and temperature parameters of its solidification curve has affected. The variation in the nature of the cooling curve always has a significant impact on the microstructure and mechanical behavior of the material. Figures 6-8 shows the cooling curve of the Al alloy (LM6) and LM6 reinforced with 5 and 10wt% of SiCp metal matrix composites. The cooling curves for different step of castings at different weight fraction of SiCp indicates that the rate of cooling decreasing on increasing the weight percentage of SiCp in the cast MMCs. The cooling curves also show that the eutectic solidification time (i.e. the time interval between the start and the end of the eutectic phase solidification) increases on increasing the weight percentage of SiC particles in the aluminum alloy matrix. It has also observed that the introduction of SiC particles in the matrix metal lowers the liquidus temperature when compared with the unreinforced alloy. This can be attributed to the unfavorable primary aluminum nucleation condition prevailing at the reinforcement surface and the depression in the freezing point due to the presence of reinforcement, which is considered as an impurity. Studies by Gowri and Samuel (1992) have also shown that addition of particles lowers the liquidus temperature by about 10^{o}C. The similar trend has also observed by Rajan *et al*. (2007). It is observed that the eutectic solidification of the matrix alloy (LM6) starts at a temperature of 574^{o}C and ends at 572^{o}C. After addition of reinforcement particles i.e. SiCp in matrix alloy, the start and end temperature of eutectic solidification changes.

The reinforcement of SiCp with matrix metal increases the eutectic solidification time as compared with the cooling curve of unreinforced aluminum alloy (LM6). The eutectic solidification time also changed with the modulus of the casting, the cooling curve indicates that on decreasing the section modulus of the MMC castings the eutectic solidification time decreases at different weight fraction of SiC particles i.e. in case of lowest modulus the eutectic solidification time is less compared to highest modulus. This validates that the Chvorinov's rule still applies to the solidification process, irrespective of what additives are added to the molten metal (Stefanescu, 2000; Cambell, 1991). The cooling curve shows that the eutectic solidification time enhanced on increasing the weight fraction of reinforcement particles compared to unreinforced matrix alloy. That means the total solidification time (i.e. the time interval between the start of primary aluminum phase nucleation and the end of the eutectic phase solidification) increases on increasing wt% of SiCp. This trend may be attributed to the fact that the amount of heat extraction reduced on increasing the weight percentage of SiC particles in the liquid matrix metal as the presence of SiC particles in the matrix metal reduced the thermal conductivity and thermal diffusivity (Rajan *et al*., 2007).

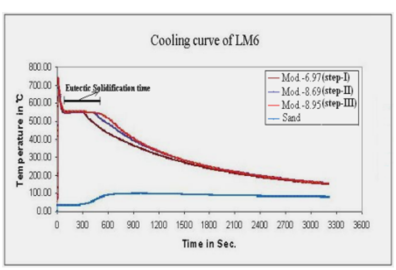


Fig.6.Cooling curves of Al (LM6) composites at different modulus of the casting.

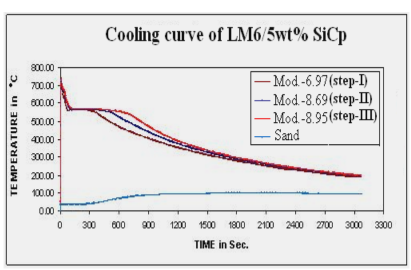


Fig.7.Cooling curves of Al (LM6) - 10wt%SiC composites at different modulus of casting.

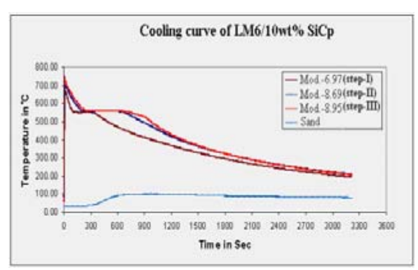


Fig.8. Cooling curves of Al (LM6) - 10wt%SiC composites at different modulus of casting.

Analysis of Forgeability

The forgeability of as cast composites at different step of castings have evaluated by means of upset method. Cylindrical specimens were prepared from each step of the castings by turning operation. The L/D ratio of the prepared specimens (L= height of the cylindrical specimen and D= diameter of the specimen) was 1.5, for forgeability test.

The limit of forgeability is expressed as the critical reduction in height by the following equation:

$$\%\text{ of Critical reduction in height} = \frac{100\,(\text{Initial height} - \text{Final height})}{\text{Initial height}}$$

Where, the initial height and the final height of the sample in mm. Critical reductions under unlubricated conditions only have compared to assess the forgeability of the experimental materials. The load was applied at room temperature on samples of different section of as cast MMCs reinforced with 5 and 10 wt% of SiCp. At different load, the percentage of deformation investigated. These results have presented in figure 9. The figure shown the percentage of deformation due to acting load is different at different step of the casting i.e. the percentage of deformation is lowest in step–II (middle section) comparison to step-III & I. The percentage of deformation is highest in step-I in comparison to step -III. This indicates that the higher percentages of SiC particles have accumulated at the middle section of the casting i.e. at step-II, in comparison to the step -III & I. The above result indicates that the distributions of silicon carbide particles are not uniform throughout the casting, which is same as micro structural result. This has occurred because of non-uniform rate of solidification of liquid metal at different step of the casting. It has also observed that on increasing the weight percentage of silicon carbide particles in cast composites the percentage of deformation decreases that means the forgeability of cast composites decreases on increasing the reinforcement ratios, as the presence of very hard SiCp in the cast MMCs decreases its ductility and enhances its hardness & brittleness.

CONCLUSIONS

The cooling curves have recorded experimentally for Al alloy (LM6) reinforced with 5 wt% & 10 wt% of SiC particles and compared with cooling curves of the unreinforced matrix alloy.i.e.LM6. The forgeability of cast MMCs have measured at the different step of the castings by upsetting method. The following conclusions are obtained:

a) The cooling rate decreases with the introduction of SiCp with increasing SiCp content due to lower heat transfer rates within the solidifying melt owing to the reduction of thermal conductivity and effective thermal diffusivity of the composite system. That indicates the cooling rate is faster in case of unreinforced matrix alloy or containing low fraction of SiCp in the matrix.
b) The addition of ceramic reinforcement to alloy enhances the eutectic solidification time, as the presence of insulating dispersoids i.e. SiCp plays a dominant role in reducing the cooling rates. The solidification time is also varied with the change in thickness of castings. The solidification time is less in case of thinner section in comparison with thicker section, due to rapid cooling of thinner section. This trend is similar to the monolithic metal and its alloys.
c) The forgeability i.e. percentage of deformation decreases on increasing the percentage of SiCp and the middle part of the casting (i.e. step–II) shows low forgeability comparison to the both end steps in the three-step casting component, due to accumulation of higher percentage of SiCp in this step. That indicates the distribution of SiCp is not uniform through out the casting.

ACKNOWLEDGEMENT

Authors thankfully acknowledge the financial support provided by U.G.C, New Delhi under Major Research Project Grant [F.No.32-88/ 2006 (SR) dated 09.03.2007] without which this work could not be attempted.

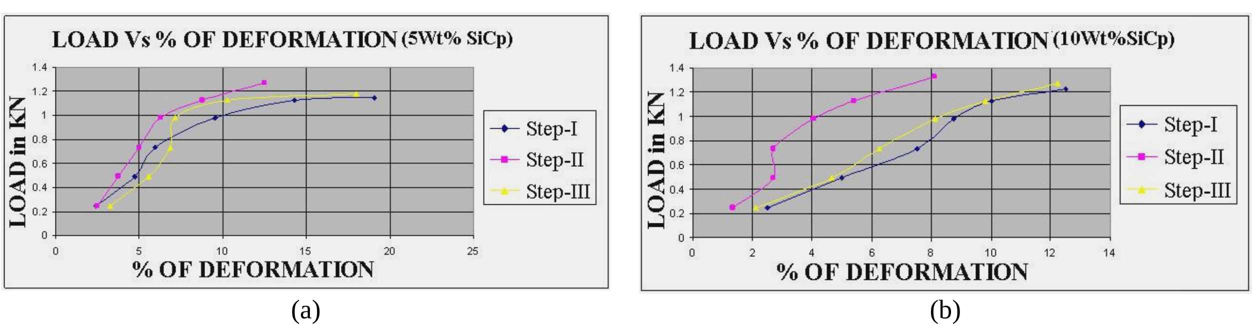


Fig. 9. Load Vs % of Deformation curve of as cast MMCs at different step of MMCs casting reinforced with (a) 5wt%SiCp and (b) 10wt%SiC.

REFERENCES

ASM Metals Hand Book. 1998. Casting. 15(9):323-327.

Charles, D. 1990. Metal matrix composites-ready for take-off? Methods Mater. 6:78-82.

Campbell, J. 1991. Castings, Butterworth Heinemann. 130-131.

Ceschini, L., Minak, G., Morria, A. and Tarterini, F. 2009. Forging of the AA6061/23 vol.%Al_2O_3p composite: Effects on microstructure and tensile properties. Materials Science and Engineering A. 513-514.

Ceschini , L., Minak, G. and Morri, A. 2009. Forging of the AA2618/20 vol.% Al_2O_3p composite: Effects on microstructure and tensile properties. Composites Science and Technology. 69:1783-1789.

Dutta, B., Surappa, MK. 1998. Microstructure evolution during multidirectional solidification of Al–Cu–SiC composites. Composites. 29A:565-573.

Gowri, S. and Samuel, FH. 1992. Effect of cooling rate on the solidification behaviour of Al-7Pct Si- SiCp metal matrix composites. Metall Trans A. 23:3369-76.

He, W., Zhang, YF., Lee, KS., Lu, L Xie, SS. and Jin, QJ. 1996. Microstructure and mechanicalproperties of an Al/SiCp, composite cold die forged gear. Materials & Design. 17(2): 97-102.

Ismail, OÈ zdemir, UÈ mit CoÈ cen. and Kazim OÈ nel. 2000. The effect of forging on the properties of particulate-SiC- reinforced aluminium-alloy composites, Composites Science and Technology. 60:411-419.

Klimowicz, TF. 1994. The large scale commercialization of aluminum-matrix composites. Journal of Materials. 46:49-53.

Lindroos, VK. and Talvite, MJ. 1995. Recent advances in metal matrix composites. Journal of Material Processing Technology. 53:273-284.

Nath, D., Asthana, R. and Rohatgi, PK. 1987. Particle distribution control in cast aluminium alloy–mica composites. Journal of Material Science. 22:170-176.

Rajan, TPD., Narayana, PK., Pillai, RM. and Pai, BC. 2007. Solidification and casting/mould interfacial heat transfer characteristics of aluminium matrix composites. Composite Science Technology. 67:70-78.

Stefanescu, DM. 2002. Science and Engineering of Casting Solidification, Kluwer Academic/Plenum Publishers,NewYork.311-319.

Received: Nov 25, 2011; Revised and Accepted: Feb 3, 2011