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ROLE OF SiCp ON THE SOLIDIFICATION RATE AND FORGEABILITY OF STIR CAST LM6/SiCp MMCs

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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. The temperature of the cast composites during solidification has measured by putting K-type thermocouples at the center of the each step/section, from which the solidification curves were constructed. The forgeability of the as cast MMCs were also measured at different section of the casting. The results show that the forgeability of cast metal matrix composites at the middle section of the casting is minimum compared to both end section of a three-step casting. Experiments were carried out over range of particle weight percentage of 7.5 -12.5 wt% in steps of 2.5wt%. 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/SiC-MMC will provide useful guidelines to the present day manufacturing engineers.

Key words: Metal matrix composites (MMCs), Solidification, Cooling curve, Forgeability.

1. INTRODUCTION

Metal–matrix composites (MMCs) have been one of the key research subjects in materials science during the past two decades **[1].**MMCs have emerged as potential alternatives to conventional alloys and are widely used in aerospace and automobile industries because of their excellent physical, mechanical and development properties. However, the difficulties in production and the high manufacturing cost restricts 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 simple production methods, higher production volumes, and cheaper reinforcements **[2,3]** can achieve the cost reductions. The search for cheaper, easily available reinforcement has led to the wider use of SiC and Al_2O_3 particles **[3]**. Therefore, the application of 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 **[4-7]**. 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. From the moment of crystallization and solidification commencement, the crystalline phase begins to grow. Its growth proceeds in a direction opposite to the particles' movement. Thus, apart from the geometric factor, i.e. the type, volume fraction and size of reinforcing particles, it is the crystallization rate and the casting's solidification time that determine the structure obtained and particles' distribution in the matrix.

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 **[8-11].**

The study aims at determining and comparing the cooling curves obtained at different section of the castings (three-stepped casting) in sand mould for the matrix (LM6) and for its composites containing varying weight percentage of SiCp. The forgeability of as cast MMCs at different section of the castings have also studied.

2. Experimental procedure

LM6, 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 7.5 to 12.5 wt% in steps of 2.5% 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 **table-1 & table-2**. The composites are fabricated by the liquid metal stir casting technique. The aluminum alloy is melted in 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 pre-heated silicon carbide particles (about 850-900^{0}C) added with the liquid metal and then mechanically stirred by using an impeller. The processing of the composite has carried out at a temperature of 750^{0}C with a stirring speed of 400-500 rpm. 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 0.3 mm size has used at the centre of the different section of the mould to measure the temperature variation in the casting during solidification has shown in **Fig.1**. One thermocouple has inserted into the sand 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 **Fig.2**. The figure of composite casting with thermocouples has shown below in **Fig.3.** Experiments carried out for a wide range of particle weight percentage varying from 7.5% to 12.5% in steps of 2.5%. 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

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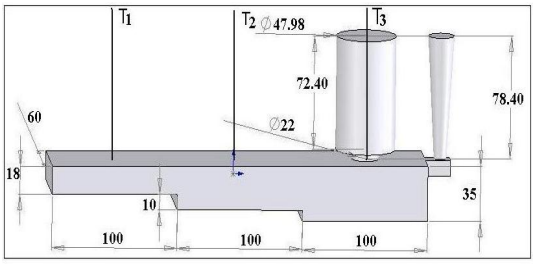

Fig1.The geometry of mould cavity with K-thermocouples (T_1,T_2&T_3). (All dimensions are in mm)

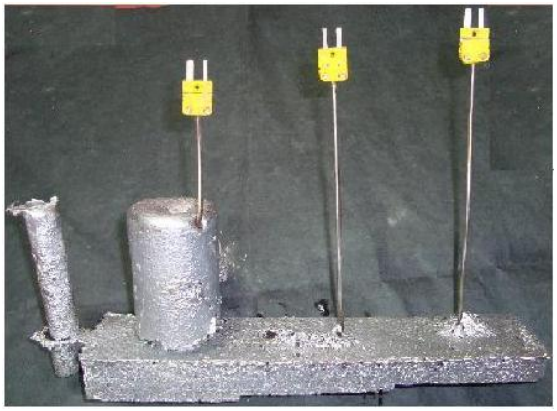

Fig3. Composite casting with thermocouples

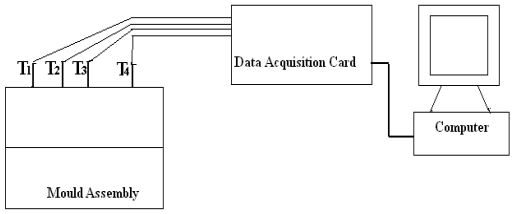

Fig2.Schematic sketch of the computer aided temperature data acquisition set up. Thermocouples (T_1, T_2 & T_3 } connected with different section of casting and T_4 inserted into the sand

3. Addition of alloying elements and particle treatment

The addition of reactive elements with the liquid metal during the production of composites by liquid metallurgy techniques promotes excellent bonding between reinforcement particles and molten matrix **[12].** For examples, the addition of magnesium, calcium, titanium, or zirconium with the liquid metal may promotes its wettability by reducing the surface tension of the melt, decreasing the solid- liquid interfacial energy of the melt, or by chemical reaction. It has been observed that in case aluminum based composites, magnesium has a greater effect incorporating reinforcement particles in the melt and improving their distribution than other elements such as cerium, lanthanum, zirconium, titanium, bismuth, lead, zinc and copper **[13-15].**

Magnesium is a powerful surfactant element, the addition of magnesium with the liquid aluminum and its alloy melt improves its wettability because of its lower surface tension (0.599 Nm^{-1}) compared with that of aluminum (0.760 Nm^{-1}) or aluminum-11.8 wt% Si (0.817 Nm^{-1}) **[16].** The addition of 3 wt% magnesium to melt reduces its surface tension from 0.760 to 0.620 Nm^{-1} at 720°C. In the work of Sukumaran et al.**[16]** they concluded that the addition of magnesium is necessary during the synthesis of A356-SiCp composites by a stir casting route, and found the optimum addition of magnesium for obtaining the best distribution and maximum mechanical to be 1 wt%. the addition of magnesium lower than the optimum value results in the formation of agglomerates of reinforcement particles and their non-uniform dispersion in the melt.

Magnesium is also acts as a powerful scavenger of oxygen, it reacts with the oxygen present on the surface of particles, thinning the gas layer, and thus improving wetting and reducing the agglomeration tendency. A composite prepared by the liquid metallurgy route with SiCp in A356 alloy matrix, shown that the addition of magnesium helped in thinning the gas layer, which was present over the SiC particles **[17].** So, it has concluded that the presence of magnesium in aluminum alloy matrix during manufacturing of composites, not only enhance the fluidity of the liquid matrix, but also scavenges the oxygen from the surface of the particles, leading to an increase in the surface energy of the particles. But, the excess addition of magnesium in an aluminum melt will alter the microstructure of the matrix alloy and deteriorates the mechanical properties.

The heat treatment of particles before dispersion in the liquid metal aids their transfer by causing description of adsorbed gases from the particle surface. Agarwala and dixit **[18]** observed that the importance of preheating in the incorporation of graphite particles in an aluminum alloy. There was no retention when the graphite particles were not preheated, whereas the particles were retained when

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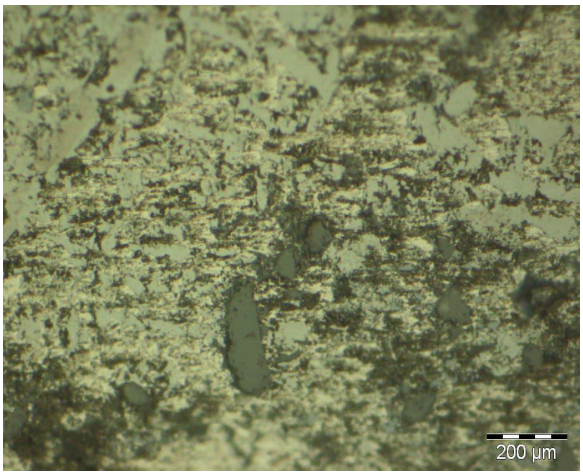
preheated. Heating of SiC particles to 900°C assist in removing surface impurities, desorption of gases, and altering the surface composition due to the formation of an oxide layer on the surface**[19].** The ability of this particle oxide layer to improve the wettability of SiC particles by an alloy melt has been suggested by several investigators **[20,21]**. In the present experiment the SiC particles were heated for 2 hours at 850-900°C in a electrical resistance muffle furnace and then introduced into the liquid metal within a short period of time of about 1-2 minutes during stirring of the melt. After stirring the liquid metal for 10-15 min., the metal tapped immediately and poured into the mold cavity.

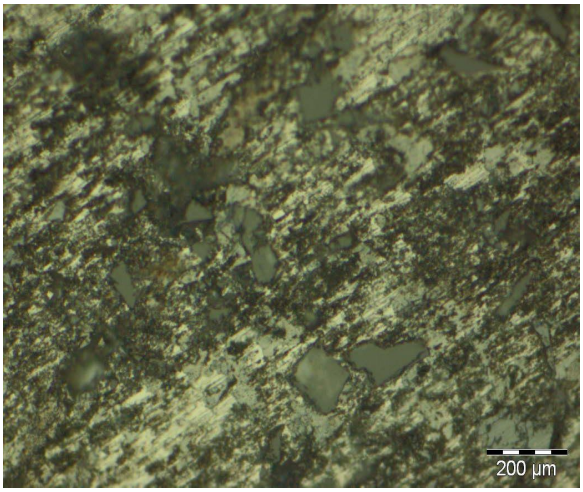
4. Results and Discussion

4.1. Microstructural Analysis

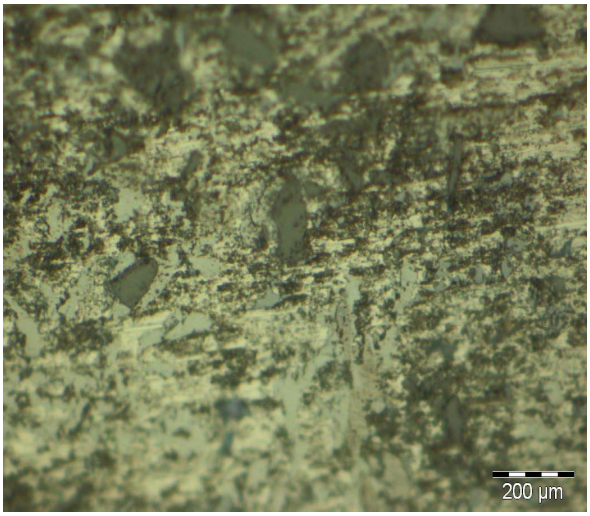
Samples of as cast MMCs for metallographic examination were prepared by grinding through 320, 400, 600, 800, 1200 and 1500 grit papers followed by polishing with 6 µm diamond paste. Then the samples were etched with the etchant i.e. Keller's reagent. The microstructure of etched and dried sample has observed by using optical microscope (Olympus, CK40M). The microstructure of the as cast LM6 MMCs are shown in Fig.**4-6** at different section of the casting. The micrograph of MMC castings at different section 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 slower rate of cooling in the sand mold.



a. Section-I



b. Section-II



c. Section-III

Fig4. Microstructure of LM6/7.5wt% SiCp as cast MMC at different section of the casting.

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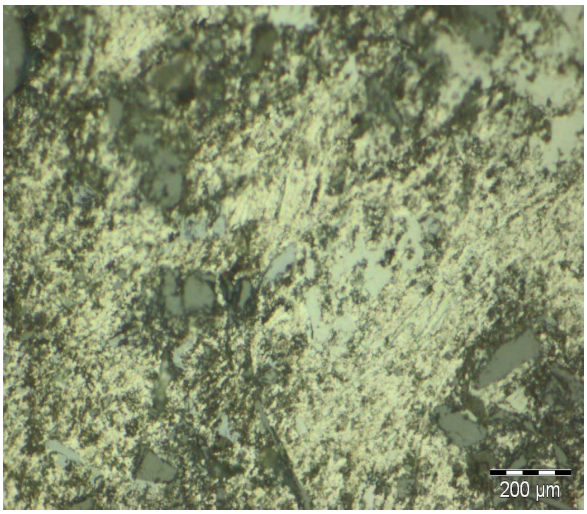
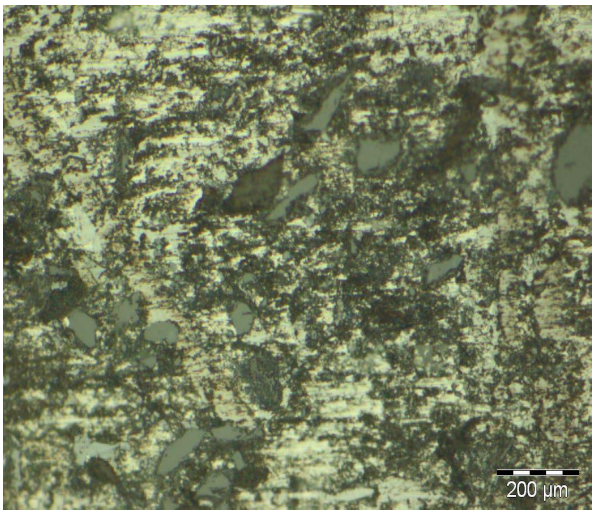
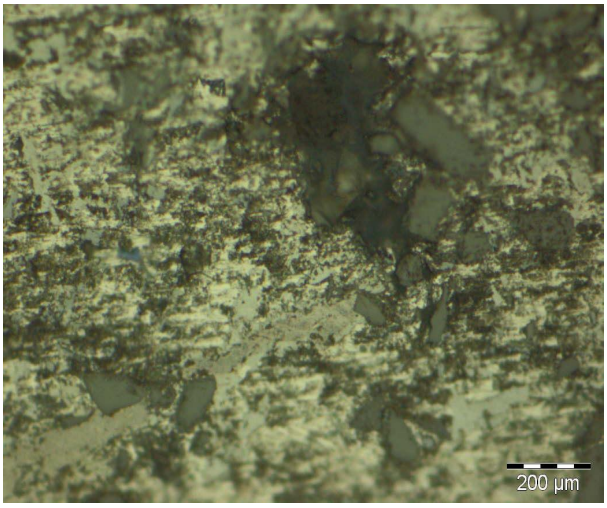


a. Section-I

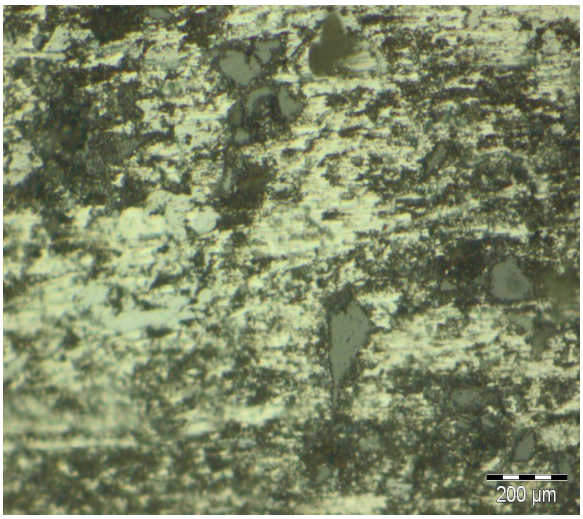


b. Section-II

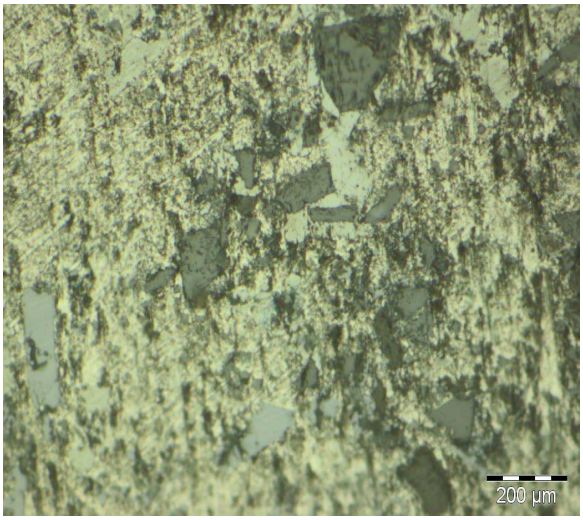


c. Section-III

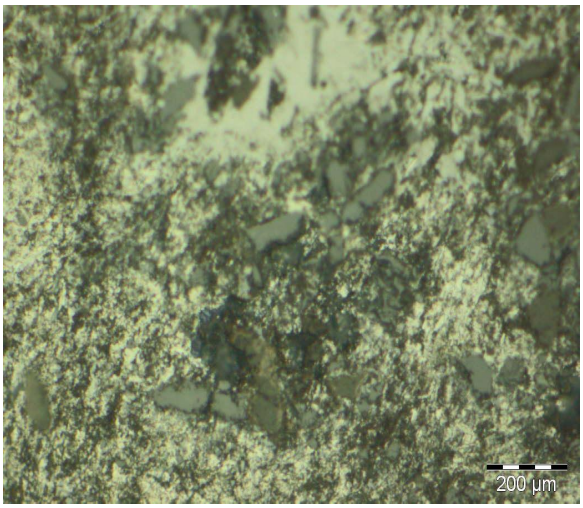
Fig5. Microstructure of LM6/10wt% SiCp as cast MMC at different section of the casting.



a. Section-I



b. Section-II



c. Section-III

Fig6. Microstructure of LM6/12.5wt% SiCp as cast MMC at different section of the casting.

4.2. Solidification curves and their analysis

Addition of an alloying element or second phase particles into a matrix alloy usually affects the various time and temperature parameters of its solidification curve. The variation in the nature of the cooling curve always has a significant impact on the microstructure and mechanical behavior of the material. **Fig.7-10** shows the cooling curve of the Al alloy (LM6) and LM6 reinforced with 7.5wt%, 10wt% and 12.5 wt% of SiCp metal matrix composites. The cooling curves for different section 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 rate from the cooling curves it has observed 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 lowered the liquidus temperature when compared with the unreinforced alloy. **Fig.11** shows the variation of liquidus temperature with increase in weight percentage of SiC particle. 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 **[22]** have also shown that addition of particles lowers the liquidus temperature by about 10 ^{o}C. The similar trend has also observed by T.P.D.Rajan et al. **[23]**.It is observed that the start of eutectic solidification of the matrix alloy (LM6) at a temperature of 574°C with the solidification ending 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 addition of SiCp, increasing the eutectic solidification time as compared with the cooling curve of 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 **[24,25]**. The cooling curve shows that the eutectic solidification time enhanced on increasing the weight fraction of reinforcement particles compared to unreinforced matrix alloy. **Fig.12** shows the variation in eutectic solidification time with respect to different weight percentage of SiCp and at different section of the castings. It has observed that on increasing the weight percentage of SiCp in the cast Al alloy (LM6) metal matrix composites the eutectic solidification time increases at different modulus of the castings. 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**[23].**

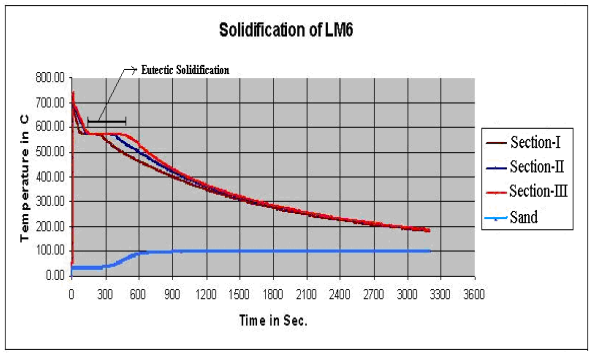


Fig7.Cooling curves of Al (LM6) composites at different section of the casting.

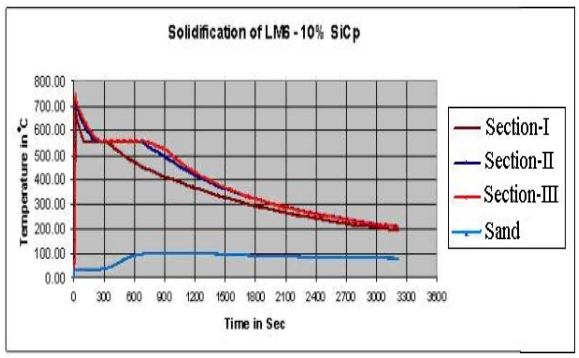


Fig.9 Cooling curves of Al (LM6)- 10wt%SiC composites at different section of casting.

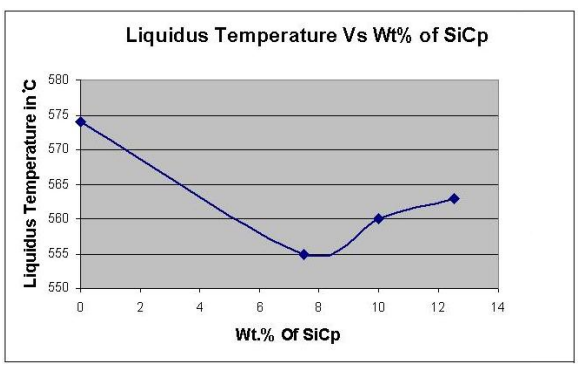


Fig11. Effect of wt% SiC on Liquidus Temperature of composite casting.

4.3. Forgeability of cast MMCs

The forgeability test of as cast aluminum alloy metal matrix composites carried out by upset method at room temperature. The L/D(L-height of the cylindrical sample and D- diameter of the sample) ratio the samples is 1.5. The limit of forgeability has expressed as the critical reduction in height, by the following equation:

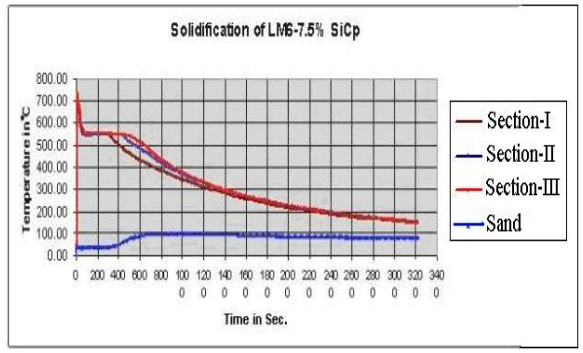


Fig8. Cooling curves of Al (LM6)-7.5wt%SiC composites at different section of casting.

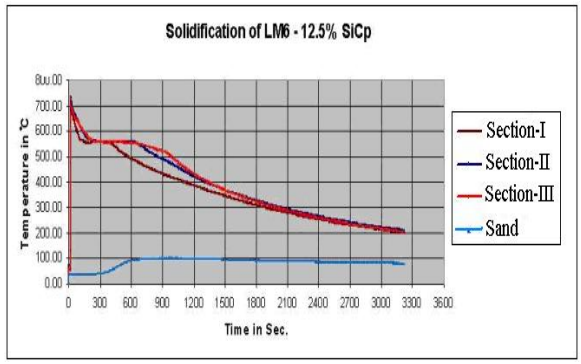


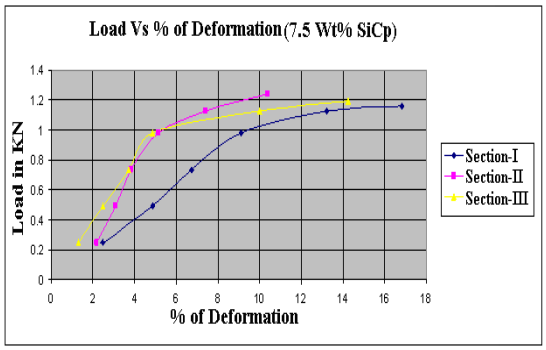
Fig.10 Cooling curves of Al (LM6)- 12.5wt%SiC composites at different section of casting.

% of Critical reduction= $$\frac{H_f - H_i}{H_i} \times 100$$

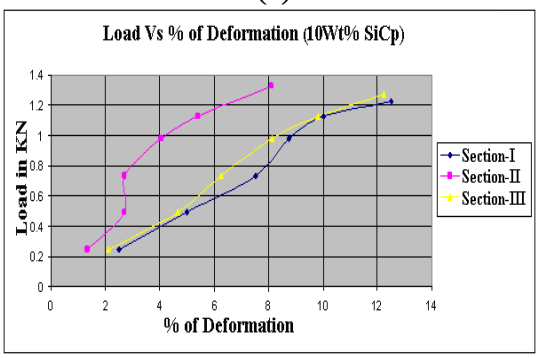
Where, Hi = the initial height of the sample in mm. and H_f is the final height of the sample in mm.

Critical reductions under unlubricated conditions only were 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 7.5 wt%, 10 wt% &12.5WT% SiCp. At different load, the percentage of deformation investigated. These results have presented in **Fig.12.** The figure shown the percentage of deformation due to acting load is different at different section of the casting i.e. the percentage of deformation is lowest in section –II (middle section) comparison to Section-III & I. The percentage of deformation is highest in section-I and the percentage of deformation in section-III are remains in between section-I&II. This indicates that the higher percentages of SiC particles have accumulated at the middle section of the casting i.e. at section-II, in comparison to the section-III & I. The above result

indicates that the distributions of silicon carbide particles are not uniform through out the casting. This has occurred because of non-uniform rate of solidification of liquid metal at different section 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 enhance its hardness & brittleness.



(a)



(b)

(c)

Fig.12. Load Vs % of Deformation curve of as cast MMCs at different section of MMCs casting reinforced with (a) 7.5wt% SiCp ,(b) 10wt% SiC and (c) 12.5 wt%.

5. Conclusions

The solidification curves have recorded experimentally for Al alloy (LM6) and its composites having varied percentage of SiC particles from 7.5 wt% to 12.5 wt% in steps of 2.5 wt% and compared with the unreinforced matrix alloy.i.e.LM6.

- The introduction of SiCp in the matrix metal decreases the cooling rate, as the presence of SiCp in matrix metal lower heat transfer rates during solidification owing to the reduction of thermal conductivity and effective thermal diffusivity of the composite system. The increase in weight percentage of SiCp in matrix metal decreases the rate of solidification rate. That indicates the solidification rate is faster in case of unreinforced matrix alloy or containing low fraction of SiCp in the matrix.
- 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 has 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.
- Additions of Mg to the composite melt has multifunctional role. Apart from its well-known function as a wetting promoter of ceramic particle with the aluminum alloy matrix, it leads to better contact at the metal/mould interface, thereby by enhancing the heat transfer rate.
- The forgeability test has carried out at room temperature by upset method. The forgeability i.e. the percentage of deformation decreases on increasing the percentage of SiCp in the matrix metal and the middle part of the casting (i.e.section–II) shows low forgeability comparison to the

both end sections in the step casting component owing to accumulation of higher percentage of SiCp. That indicates the distribution of SiCp is not uniform through out the casting.

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References

1. V.K.Lindroos, M.J.Talvite, Recent advances in metal matrix composites. J.Mater. Process. Technol. 53, 273–284, 1995.
2. D. Charles: Metal matrix composites-ready for take-off? *Methods Mater.* 6:78–82,1990.
3. T.F. Klimowicz: The large scale commercialization of aluminum-matrix composites.*JOM*46:49–53,1994.
4. J. Hashim, L. Looney. M.S.J. Hashim, Metal matrix composites: production by the stir casting method, Journal of Material Processing Technology, 92-93, 1-7, 1999.
5. J.W. Kaczmar, K. Pietrzak, W. Wlosinski, The production and application of metal matrix composites material, Journal of Material Processing Technology, 106 ,58-67,2000.
6. J. Sleziona, Forming of the properties Al. alloys-ceramic particles production by the foundry methods, ZN. 47; Silesian University of Technology, Gliwice 1994, (in Polish).
7. J. Sleziona, Influence ceramic particles on Al-SiC, Al-Al2O3 composites solidification, Archives of Material Science, 16 ,163-178, 1995,(in Polish).
8. Ismail OÈ zdemir, UÈ mit CoÈ cen and Kazim OÈ nel, ,The effect of forging on the properties of particulate-SiC-reinforced aluminium-alloy composites, Composites Science and Technology, 60: 411-419,2000.
9. L. Ceschinia, G. Minakb, A. Morria and F. Tarterini, Forging of the AA6061/23 vol.%Al2O3p composite: Effects on microstructure and tensile properties, Materials Science and Engineering A : 513–514,176–184, 2009.
10 . L. Ceschini , G. Minak and A. Morri, , Forging of the AA2618/20 vol.% Al2O3p composite: Effects on microstructure and tensile properties, Composites Science and Technology ,69:1783–1789,2009.
11. W. He, Y.F. Zhang, K.S. Lee, L. Lu, S.S. Xie, and Q.J.Jin, Microstructure and mechanical properties of an AI/SICp, composite cold die forged gear Materials & Design.17(2), 97- 102,1996.
12. S.Ray, M.Tech. Dissertation, IIT, Kanpur, INDIA,1969.
13.G.Ramani,R.M.Pillai, B.C.Pai, K.G.Satyanarayan, M.Tech.Dissertation, Vol.12, IIT, Kanpur, India, p.117, 1993.
14. M.Kobashi, T.Choh, J.Mater.SCi.28 ,684, 1993.
15. K. Sukumaran, S.G.G. Pillai, R.M. Pillai, V.S. Kelukutty, B.C.Pai, K.G. Satyanarayana, K.K. Ravikumar, J. Mater. Sci. 30 ,1469-1472.
16. L.F. Mondolfo, Aluminium Alloy, Consultany Bureau, New York,pp.26-27, 1963.
17. L.M. Mondolfo, Casting Properties of Metal and alloys, Consultant Bureau, New York, pp. 26-27, 1963.
18. V.Agarwala, D.Dixit, Trans. Jpn. Inst. Met.. 22, 521-526, 1981.
19. H.Ribes,R.R.Dasilva, M.Suery,T.Breteau, Mater. Sci. Technol. 6 ,621, 1990.
20. L.N.Thanh, M. Suery, Scripta Metall. 25,2781, 1991.
21. T.W.Clyne, Proceedings of ICCM-IV and ECCM-2, Vol.2, Elsevier, Amsterdam, pp.275-286, 1987.
22. S.Gowri, and FH.Samuel, Effect of cooling rate on the solidification behaviour of Al- 7Pct Si- SiCp metal matrix composites. Metall Trans A,23,3369–76, 1992.
23. T.P.D. Rajan, K.Narayana Prabhu, R.M. Pillai, B.C.Pai, Solidification and casting/mould interfacial heat transfer characteristics of aluminium matrix composites. Compos. Sci. Technol. 67, 70–78, 2007.
24. D.M.Stefanescu, Science And Engineering of Casting Solidification, Kluwer Academic/Plenum Publishers, New York, 311-319, 2002.
25. J.Campbell, Castings, Butterworth Heinemann, 130-131, 1991.
26. K.S. See and T.A. Dean, The effects of pre-forge processing on forgeability and mechanical properties of co- sprayed aluminium-based MMCs, J. Mater.Process.Technol,71,314 - 321,1997.
27. Ismail OÈ zdemir, UÈ mit CoÈ cen and Kazim OÈ nel, ,The effect of forging on the properties of particulate-SiC- reinforced aluminium-alloy composites, Composites Science and Technology, 60: 411-419,2000.