

## Effect of molten liquid temperature on microstructure of rapidly solidified Al-Si-Mg alloy

Manish Kumar Gupta<sup>1</sup>, Harshit Gangwar<sup>2</sup>, Krishna Kumar Soni<sup>3</sup>

<sup>1,2,3</sup>Assistant Professor, Mechanical Engineering Department,  
Rajshree Institute of Management & Technology, Bareilly (India)

### ABSTRACT

Rapid Solidification is a novel technique which is used for getting ultrafine grainstructure. It has been applied for getting high strength, hardness and wear resistance. In the present study, effect of molten liquid temperature had been studied on microstructure of rapidly solidified Al-Si-Mg alloy. It had been found that grain structure of Al-Si-Mg alloy was reduced to  $54\ \mu$  to  $8\ \mu$  as molten liquid temperature increased from  $800^{\circ}\text{C}$  to  $1100^{\circ}\text{C}$ . Wear test performed showed that wear resistance was increased as molten liquid temperature increased.

**Keywords:** Al-Si-Mg Alloy, Nucleation, Rapid solidification, Wear test.

### 1. INTRODUCTION

Aluminium is the second-most plentiful element on earth and it became an economic competitor in the engineering applications at the end of the 19th century. There are three important industrial revolutions by demanding material characteristics consistent with unique qualities of Aluminium & its alloys greatly benefit growth in the production and use of the metal. Its versatility is most striking characteristics. It is remarkable to have the range of physical properties that can be developed-from refined high-purity Al to the most complex alloys.

Aluminium and its alloys are extensively used as the materials in transportation such as in aerospace and automobiles, engine components & structural applications [1]. Thus it becomes all the more vital to study the tribological characteristics of Aluminium & its alloys. Addition of Silicon to Aluminium gives high strength to weight ratio, low thermal expansion coefficient & high wear resistance. These alloys also show improved strength and wear properties as the silicon content is increased beyond eutectic composition. Such properties justify the use of these materials as structural components in automotive industries [2].

Alloys with Silicon as a major alloying element are most important commercial casting alloys because of their superior casting characteristics in comparison to other alloys. A wide range of physical & mechanical properties is afforded by aluminium-silicon alloys combine the advantages of high corrosion resistance, good weldability & low specific gravity. Although castings of Al-Si alloys are somewhat more difficult to machine than the aluminium-copper or aluminium-magnesium alloys. All types of machining operations are accomplished usually using Tungsten carbide tools and appropriate coolants and lubricants.

## II. RAPID SOLIDIFICATION

It is the process for obtaining high cooling rates. Rapid solidification process (RSP) and formation of metastable phases is said to be started around 1960 after Pol Duwez et al investigation in which a melt droplet was injected at high speed on a copper target to obtain high rate of heat transfer and to make very thin film of casting [3]. Pol Duwez experiment opened a new area of investigation which created several new methods of RSP techniques to obtain metastable phases and amorphous materials. There are several techniques used ever since to achieve high cooling rate ranging from  $\sim 107\text{K/s}$  to  $\sim 102\text{K/s}$  by melt spinning to metal mould casting respectively.

F. Schurack et al, 1999 studied high strength Al alloys with nanocrystalline phase as main component. They have reported that there is grain refining effect according to the expectations when milling in liquid nitrogen, hydrogen or in air. Hardness increases from 283HV to 383HV and strength enhances to 850MPa [4].

Zhonghua Zhang et al, 2003 investigated microstructures and grain refinement performance of rapidly solidified Al-5Ti-B alloy. They reported that microstructure of melt spun of the alloy are composed of two phases:  $\alpha$  Al supersaturated solid solution and spherical or near spherical uniformly dispersed  $\text{TiB}_2$  particles [5].

Zhonghua Zhang et al, 2002 studied microstructures and grain refinement performance of rapidly solidified Al-Ti-C alloy. They reported that microstructure of melt spun of the alloy are composed of two phases:  $\alpha$  Al supersaturated solid solution and spherical or near spherical uniformly dispersed TiC particles [6].

Yang huan Zhang et al, 2003 examined effect of boron addition on the microstructures of electrode alloy. They have found that addition of boron enhances the cycle life of the as quenched alloy dramatically. It is mainly because of its strong promoting action for the formation of an amorphous phase [7].

Zhonghua Zhang et al, 2003 investigated microstructures and grain refinement performance of rapidly solidified Al-5Sb alloy. They have reported that rapid solidification has no effect on phase constitution and the microstructure of the melt spun alloy is composed of primary Al-Sb particles embedded in the matrix comprising  $\alpha$ Al cells with intercellular nanoscale Al-Sb [8].

Yan Wang et al, 2004 studied effect of quenching rate on the microstructure of rapidly solidified Al-5Sb alloy. They have observed that the quenching rate has no effect on the phase constitution of the alloy. The microstructure of the melt spun alloy at 500 rpm is composed of primary AlSb particles embedded in a matrix comprising  $\alpha$ Al cells, intercellular nanoscale AlSb particles and  $\alpha$ Al/AlSb eutectic. At 1500rpm, microstructure is composed of primary AlSb particles embedded in a matrix comprising elongated  $\alpha$ Al cells and intercellular nanoscale AlSb particles [9].

However the production and application of such materials are limited to small sizes due to the cooling rates essential except for some non ferrous materials where Pd and Zr based bulk amorphous metals have been formed in size of several centimeters.

## III. NUCLEATION AND ITS MECHANISM

The conventional division of nucleation is in two main groups:

- 1) homogenous nucleation
- 2) heterogeneous nucleation

In homogenous nucleation, nuclei/nucleus would be produced by solidification parameters and no other source of nucleation such as the mould wall or external seeds would interfere in the nucleation. The homogeneous nucleation is used for specific purposes; one simple example of this is carbonate decomposition in which  $\text{BaCO}_3$  transforms to  $\text{BaO}$  where nucleation and transformation would be homogenous since only heat is involved [10]. However, in heterogeneous nucleation, external particles would assist the nucleation.

### 3.1 Homogeneous nucleation

Heterogeneous nucleation generally is regarded as a geometrical concept in which the process is mainly affected by the geometry of the substrate. In the classical model, in order to create a spherical capped nucleus on a substrate, a minimum surface energy and suitable wet ability must be provided. Homogenous nucleation requires a large driving force because of the relatively large contribution of surface energy to the total free energy of very small particles. Results of Holloman and Turnbull [11] have shown that for metals the required undercooling (driving force) for homogenous nucleation is about 0.18-0.3 of the absolute melting point (theoretically). In normal case the heterogeneous nuclei are available and that large undercooling for homogenous nucleation never achieved. If such undercooling could be acquired in alloys, then large bodies of melt could be solidified adiabatically in an exceedingly short time and very fine microstructure is gained. Homogenous nucleation theory suggests that formation of liquid nuclei should not become perceptible until the superheating becomes almost as great as the required supercooling (e.g.  $195^\circ\text{C}$  for Al) . In fact, as most crystals are completely wet by liquid phase of the same composition at their melting temperature; hence, there is no net increase in surface energy when a liquid forms on a solid surface in a homogenous nucleation and it mainly dependent on under cooling . However, the homogenous nucleation undercooling is not obtainable in metallic alloys of commercial interest. In real case, under cooling by a few degrees would activate nucleation on impurities, nucleating agents or mould walls in which surface energy changes and by doing so avoids the very large thermodynamic barrier to homogenous nucleation. In homogenous nucleation, it is assumed for simplicity that the Gibbs free energies of two phases are independent of pressure and hence: the change in free energy corresponding to a spherical solid of radius  $r$  is therefore made up of a volume term  $\frac{4}{3}\pi r^3\Delta G_v$  which is negative below  $T_{\text{Equil}}$  and a surface energy which is always positive, so

$$\Delta G_{(r)} = \frac{4}{3}\pi r^3 \Delta G_v + 4\pi r^2 \gamma_{\text{SL}}$$

where  $r$  is the radius of the nucleus and  $\gamma_{\text{SL}}$  is the interfacial energy.

At  $r^*$  (the critical radius) in which before that clusters and beyond that nuclei are available and stable, Gibbs free energy should be zero. It should be mentioned Gibbs free energy is thermodynamic equation and it consider equilibrium condition. Hence, the differentiation of  $\Delta G$  (the barrier for nucleation) by  $r$  should be zero, because  $r^*$  is an extremum. So  $r^*$  can be given as

$$\gamma^* = -2\gamma_{\text{SL}}/\Delta G_v = -2\gamma_{\text{SL}} T_m/\Delta H_v \Delta T$$

Associated energy barrier can be given as

$$\begin{aligned} \Delta G^* &= 16\pi\gamma_{\text{SL}}^5/3\Delta G_v^2 \\ &= 16\pi\gamma_{\text{SL}}^5 T_m^2/\Delta H_v^2 \Delta T^2 \end{aligned}$$

In other words, once this critical radius is met, the total Gibbs free energy will reduce and nucleation will occur and growth would be possible. This radius would not achieve unless undercooling increases. Homogenous solidification occurs in pure metals in which the composition of the embryo is identical with the melt. The above mentioned equations are the basis of nucleation; however, in most cases homogenous nucleation would not occur.

### 3.2 Heterogeneous nucleation

Turnbull [12] proposed that the formation of a nucleus of a critical size can be catalysed by a suitable surface in contact with the liquid. The process is called heterogeneous nucleation. However, all the heterogeneous nucleation models and hypotheses discuss grain initiation rather than nucleation. In other words, models have solved the problem of nucleation on a substrate and discuss the beginning of grains. Heterogeneous nucleation on a substrate is conventionally considered in terms of a classical model with a solid embryo in the form of a spherical cap making a contact angle  $\theta$ . In fact for the liquid/solid interface stability, the following equation should be fulfilled:

$$\gamma_{LN} = \gamma_{SN} + \gamma_{SL} \cos \theta$$

where  $\gamma_{LN}$  is the liquid/ nucleant interfacial energy,  $\gamma_{SN}$  is the solid/ nucleant interfacial energy and  $\gamma_{SL}$  is the liquid/ solid interfacial energy.

## IV. EXPERIMENTAL

### 4.1 Material used and chemical composition:

For the study of rapid solidification, Al-Si-Mg alloy is taken. Al-Si-Mg alloy comes under 6061 series. There is 4.62% Si and 3.96% Mg in its chemical composition.

Element	Mass %	Atom %
Al	84.39	85.70
Si	4.62	4.50
Mg	3.96	4.46
O <sub>2</sub>	6.65	5.14
Mn	0.39	0.20
Total	100	100

### 4.2 Sample Preparation:

1) To observe the effect of temperature, Al alloy of suitable amount (say 10 gm) is taken into steel crucible. It is kept inside muffle furnace. Muffle furnace is a device used for getting high temperatures. This muffle furnace can achieve temperatures upto 1200°C. Al alloy is melted and heated to required temperature (800°C, 900°C, 1000°C, 1100°C) separately, then they are rapidly solidified in water

#### 4.3 Wear Measurement

During the wear tests the weight loss,  $\Delta w$ , for each specimen was recorded and wear rate,  $W(t)$ , in terms of volume loss, was calculated according to the following equation.

$$W(t) = \Delta w / \rho t$$

where ,

$\rho$  = density of the sample

t = sliding time.

#### V. RESULTS AND DISCUSSIONS

Here, effect of pouring temperature is studied when Al alloy is rapidly solidified in water. If there is increase in pouring temperature, it increases cooling rate ,therefore there is refinement of grainstructure . As pouring temperature increase from 800°C to 1100°C, grainstructure is refining from 54 $\mu$  to 8 $\mu$ .

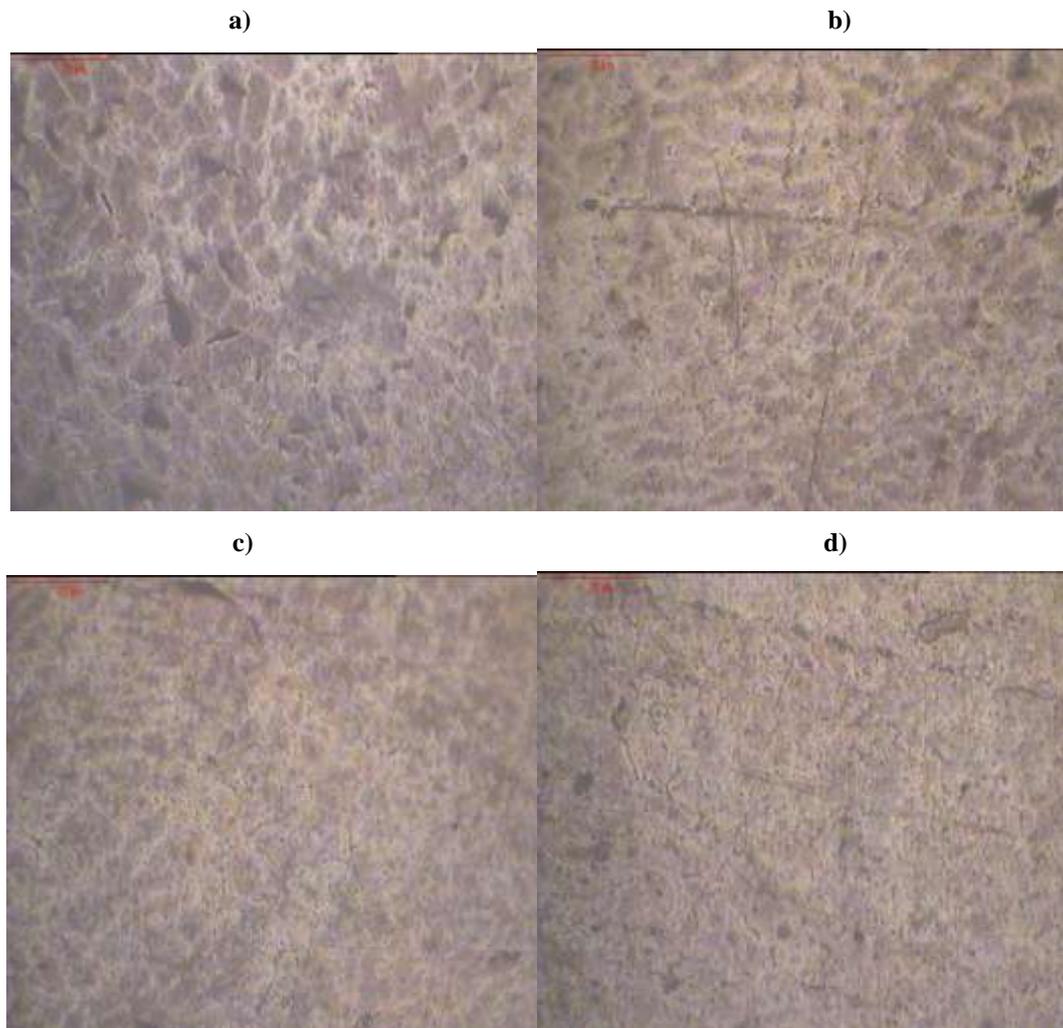


Fig. 5.1 Micrographs of rapidly solidified Al alloy from different pouring temperature (a) 800°C (b) 900°C (c) 1000°C (d) 1100°C at 100x.

It can also be seen in figure 4.6, there is morphology changes from planar to equiaxed grains when Al alloy is rapidly solidified in water from pouring temperature 1100°C. It is so because there is higher cooling rate, more under cooling, more nucleation rate.

X ray diffraction shows phases present in Al alloy when it is rapidly solidified from temperature 1000°C. These phases mainly are Al and Mg<sub>2</sub>Si. XRD Analysis can be shown as following.

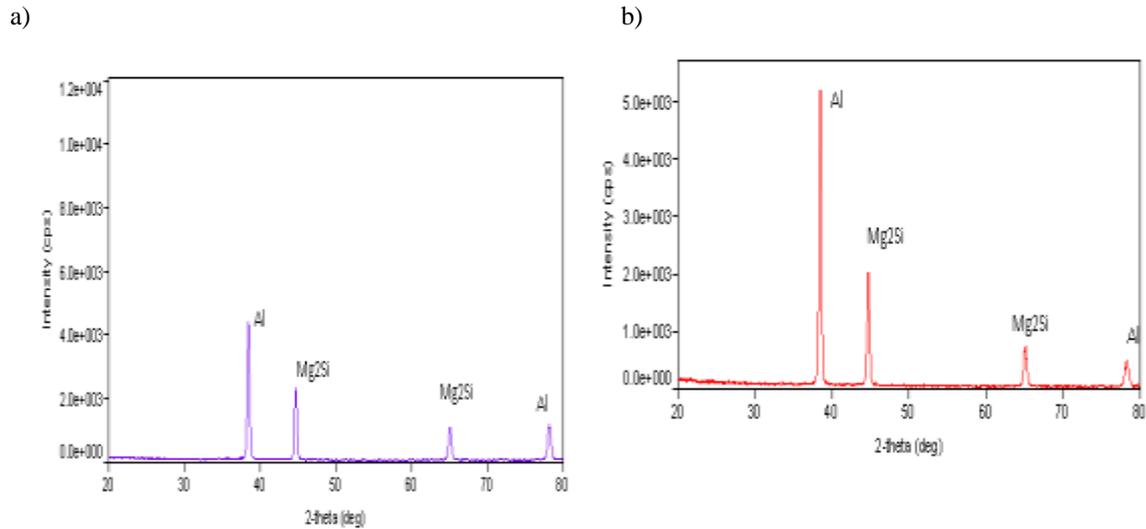


Fig. 5.2 X Ray Diffratograph of a) as cast b) rapidly solidified Al Alloy from molen liquid temperature 1000°C.

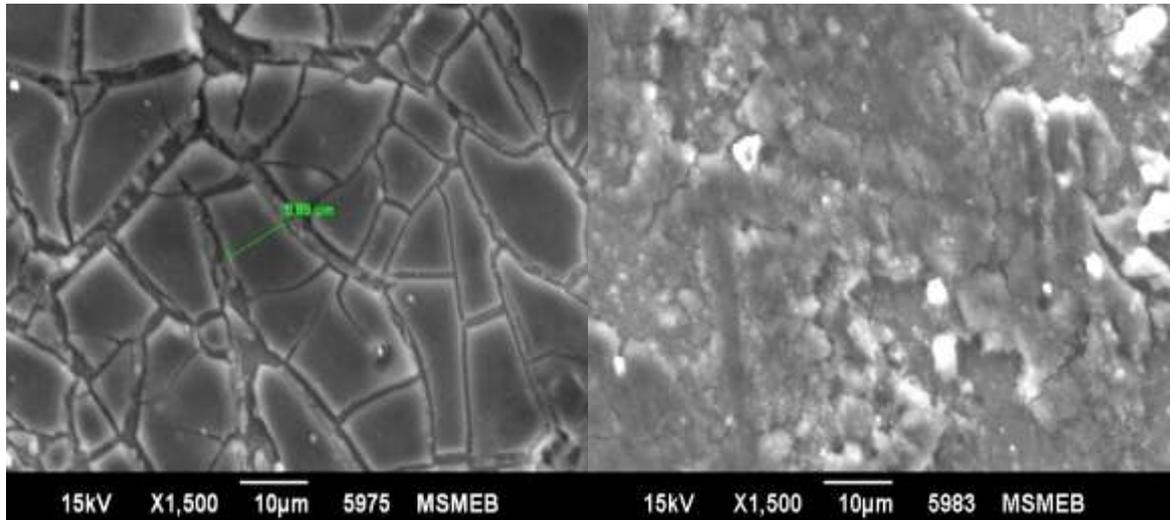


Fig. 5.3 SEM images of rapidly solidified Al alloy from different pouring temperature a) 800°C b) 1000°C

Wear test: Pin On Disk test:

Graphs wear vs time, frictional force vs time, coefficient of friction vs time can be plotted when Al alloy is rapidly solidified from pouring temperature 900°C. As shown in figure 4.11, wear increases rapidly at starting then linearly. At the beginning of contact of pin and sample surface, pin is in direct contact with oxide layer that covers aluminum and its related alloys. Oxide layer is continuous, brittle and has a high coefficient of friction in contact with metal . Due to fracture of the oxide layer, the maximum wear rate occurs at the beginning of the wear test.

As pouring temperature increases, wear rate decreases. It is so because hardness increases with pouring temperature which reduces wear rate as shown in following table.

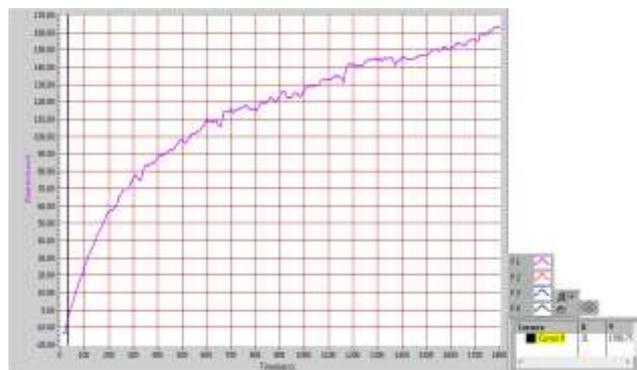


Fig. 5.4 Graph wear vs time

Wear rate can be calculated as following table.

Molten liquid temperature	Wt. before wear(gram)	Wt.after wear(gram)	Wt. loss( $\Delta w$ )	Wear rate $W=\Delta w/pt(\text{mm}^3/\text{sec})$
800°C	3.044	3.038	0.006	$12.3 \times 10^{-4}$
900°C	3.106	3.102	0.004	$8.23 \times 10^{-4}$
1000°C	2.738	2.735	0.003	$6.17 \times 10^{-4}$
1100°C	3.975	3.973	0.002	$4.11 \times 10^{-4}$

Where  $\rho = 2.7 \text{ gm/cm}^3$  and sliding time is taken as 30 minutes.

## VI. CONCLUSION

As molten liquid temperature increases from 800°C to 1100°C, grainstructure is refining from  $54\mu$  to  $8\mu$ . Due to formation of metastable phases  $\text{Mg}_2\text{Si}$  material is being harder and harder which increases wear resistance while the molten liquid temperature is increasing from 800°C to 1100°C.

## REFERENCES

- [1] Duwez P., Willens R.H., Klement W. 1960, Journal of Applied Physics, Vol. 31, pp.1136-37.
- [2] Anantharaman T.R., Suryanarayana C. 1987, Rapidly Solidified Metals, Trans Tech Publications, Switzerland.

- [3] Schumacher P., Greer A.L., Worth J., Evans P.V., Kearns M.A., Fisher P. and Green A.H.1998, Mater Sci Technol., Vol.14, pp.394-404.
- [4] Coudurier L., Eustathopoulos N., Desre P. and Passerone A.1978, Acta Metall, Vol.26, pp.465-475.
- [5] Schurack F., Eckert J. and Schultz L. 1999, High strength Al alloy with nanoquasicrystalline phase as main component, NanoStructured Materials, Vol. 12, pp. 107-110.
- [6] Zhang Zhonghua, Bian Xiufang , Wang Yan, Liu Xiangfa 2003, Microstructure and grain refining performance of melt-spun Al-5Ti-1B master alloy, Materials Science and Engineering A352 , pp.8-15.
- [7] Zhang Zhonghua, Bian Xiufang, Wang Zhenqing, Liu Xiangfa, Wang Yan 2002, Microstructures and grain refinement performance of rapidly solidified Al-Ti-C master alloys, Journal of Alloys and Compounds, Vol. 339 , pp.180-188.
- [8] Yang-huan Zhang et al 2004, Effect of boron addition on the microstructures and electrochemical properties of  $MmNi_{3.8}Co_{0.4}Mn_{0.6}Al_{0.2}$  electrode alloys prepared by casting and rapid quenching, Journal of Alloys and Compounds, Vol. 373, pp. 291-297.
- [9] Zhang Zhonghua , Biana Xiufang, Wang Yan 2003, Microstructural characterization of a rapidly solidified Al-5 Sb alloy, Journal of Alloys and Compounds, Vol. 351 , pp.184-189.
- [10] Southin R.T.1967, Metallurgical Transaction, AIME, Vol.239, pp. 220-225.
- [11] Ohno A., Motegi T., and Soda H. 1971, Transaction, ISIJ, Vol.11, pp.18-23.
- [12] Ropp R. C 2004, Luminescence and the Solid State, Elsevier Science, second edition, pp.164, 762.