

PROCESSING AND CHARACTERIZATION OF AA2618/SiCp METAL MATRIX COMPOSITES BY STIR CASTING METHOD

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Abstract

The future performance requirements of aero-engines must have improved thrust to weight ratios, reduced SFC and reduced signatures. Current materials technology within aero engines will restrict the thermodynamic cycle improvements and thus new materials and manufacturing techniques must be developed if the predicted improvements in engine performance will be due to material technology. The potential of metal matrix composite (MMC) materials for significant improvement in performance over conventional alloys have been recognized widely. However, their manufacturing costs are still relatively high. A critical step in the processing of cast particle reinforced MMCs is the incorporation of the ceramic particles into the molten matrix alloy. Therefore, wettability of the reinforcement particle by the matrix alloy must be optimized even though some of the methods are expensive and complex and some are cheap and simple technique. In order to produce 2618/SiCp MMC with maximum yield, two types of mixing i.e. liquid state and semi-solid state mixings have been introduced in the stir casting process with the support of process parameters from literatures. The process parameters utilized in each trial and results obtained in these processes are also highlighted. The density, hardness and tensile properties obtained in both the mixing processes are discussed. The study is carried out to assess the behaviour of AA2618/SiCp MMC for the fabrication of compressor blade.

Key words: Metal matrix composites, Tensile tests, High-cycle fatigue, AA 2618, SiCp

Introduction

The designing of metal matrix composite materials is to combine the desirable attributes of metals and ceramics. The addition of high strength and high modulus refractory particles to a ductile metal matrix produces a metal matrix material whose mechanical properties are intermediate between the matrix alloy and the ceramic reinforcement. Metals have a useful combination of properties such as high strength, ductility and high temperature resistance

but sometimes have low stiffness, whereas ceramics are stiff and strong, though brittle [1]. Aluminium matrix composites (AMC) are attractive since significant improvements in stiffness, strength, fatigue and wear resistance in addition to the high temperature capability [2]. There are several fabrication techniques available to manufacture MMC materials but there is no unique route in this respect. Due to the choice of material and reinforcement and types of reinforcement, the fabrication tech-

niques can vary considerably. Generally there are two types of fabrication methods available

- Solid phase fabrication method includes diffusion bonding, hot rolling, extrusion, drawing, explosive welding, PM route, pneumatic impaction etc.
- Liquid phase fabrication method includes liquid metal infiltration, squeeze casting, compo casting, pressure casting, spray co-deposition etc [3].

Among the variety of manufacturing processes available for short fiber metal matrix composites, stir casting is generally accepted as a promising route because of its simplicity, flexibility and applicability to large quantity production. A successful casting process must be able to produce a composite in which the particles are uniformly dispersed throughout the matrix. The importance of the agitation is determined by many factors such as the shape of the stirrer, its speed and its placement relative to the melt surface and the wall of the crucible [4].

Good wetting is an essential condition for the generation of a satisfactory bond between particulate reinforcements and liquid metal during casting to allow transfer and distribution of load from the matrix to the reinforcements without failure. These bonds may be formed by mutual dissolution or reaction of the particulates and metal. The reaction phenomena are very detrimental to the composites as they may bring down the mechanical properties [5].

Al-SiC system is a reactive system, as it produces Al_4SiC_4 or Al_4C_3 . The formation of Al_4C_3 is detrimental for the composite properties. The formation of Al_4C_3 can be minimized by using suitable coating on particles, such as high silicon content Al alloy and pre-oxide coated particles [6]. The only reaction at the interface of Al- Al_2O_3 composites is Al_2O_3 dissolving into aluminium. Small addition of Mg favours the formation of MgAl_2O_4 spinel with Al_2O_3 [7]. The purpose of Mg addition is: (a) to enhance the wetting behavior with SiC particles which is important for pressureless infiltration [8] (b) for the formation of spinel (MgAl_2O_4) at the interface of oxidized SiC, thus protecting the SiC particles from reaction with Al [9] (c) to enhance the interfacial bonding (d) strengthening of the Al matrix (by solid solution hardening) [10].

The agglomerates of the particulate reinforcement during MMC production has an important influence on MMC properties. This is undesirable as it leads to non-homogeneous response and lower macroscopic mechanical prop-

erties. The tendency of particle clustering depends on the solidification rate of the melt, lower solidification leads to an increase in particle agglomerates. The long elevated pre-heating of the SiC particles might have contributed to chemical bonding between the particles [11]. At higher speeds, the surface layer might have broken down; the authors have noted the particles agglomeration [12]. In the recent work of Kathiresan, it is noted that particle agglomeration occurred at a stirring speed of 500 rpm during the stir cast production of aluminium alloy A384 with 10% of 64 μm sized SiC reinforcement [13]. Because of higher fluidity, the casting shows in-homogeneity in distribution of Al_2O_3 particles due to settling and pushing of particles by growing α -dendrites. Extended holdings of Al alloy MMCs in the liquid state indicate that there is no observable chemical reaction between Al alloy and Al_2O_3 , where as there is a severe reaction between Al alloy and silicon carbide [14].

If process parameters are not adequately controlled, non-homogeneous particle distribution can arise due to insufficient particulate dispersion, sedimentation, solid front particle pushing or flow generated segregation [15]. Zhou [16] have proposed two step mixing method to improve the wettability of the SiC particles and ensure a good particle distribution. The furnace temperature is raised above the liquidous temperature to melt the alloy scraps completely and then cooled down just below the liquidous temperature to keep slurry in semi-solid state. At this stage the preheated SiC particles were added manually. Further the composite slurry is reheated to fully liquid state for stirrer mixing. Naher [17,18] has stated that castings from the liquid stage mixing are found in poor incorporation of SiC particles whereas the castings from the semi-solid stage mixing are found to produce a uniform distribution of SiC particles.

Several studies have highlighted the production methods of MMC for Al alloy with ceramic particles. Most of them are available on Al 2014/SiC_p, Al 2014/ Al_2O_3 and Al 6061/SiC_p materials with extrusion as a secondary process for manufacturing. Although, less research has been carried out on forged MMC, there are useful studies [19,20] available on 2618 alloy reinforced with 20% alumina particles by employing hot compression tests in the temperature and strain rate ranges of 450-500°C and 10^{-2} - 10^{-1} s^{-1} respectively. Few articles on powder metallurgy, squeeze casting and in-situ spray process route of manufacturing are available. Most of the articles have projected on the stir casting method. Each author has followed the different methods of preparation of specimen for testing.

This study differs from the earlier investigations in the following ways (i) the material, namely, 2618 (Al-2.3Cu) is used as the matrix, SiC particles are used as a reinforcing material medium, (ii) Process parameters for liquid state mixing and semi-solid state mixing of particles in the stir casting method and (iii) forging as the secondary route. In addition, the effects of SiC particles content and size and the mechanical properties of SiC particle reinforced 2618 aluminum alloy composites are studied.

Experimental Work

Material System

In this study, 2618 aluminum alloy with the theoretical density of 2760 Kg/m^3 is used as the matrix material and SiC (Silicon Carbide) particles of two sizes of 7(F) and 33(C) μm (Average) with density of 3200 Kg/m^3 are used as the reinforcement. Carborundum Universal Ltd have supplied the SiC particles. The particle sizes of SiC particles are determined using Scanning Electron Microscope (SEM). The chemical composition of 2618 Al alloy is presented in Table-1. Different types of test specimens are made, which are classified based on the particle sizes and percentage weight (5 and 10%).

Specimen Preparation

An electrical resistance-heating furnace with 9kW power rating and maximum temperature of 1000°C is used to heat the aluminium alloy above the liquidous temperature. The temperature is measured by chromel/alumel thermocouples using digital controller with the temperature accuracy of $\pm 1^\circ\text{C}$. The melting process is carried out in a graphite crucible with upper diameter 130 mm and lower diameter 110 mm. Another experimental set up is made for stirring. Fig.1 shows the photograph of the set up. The silicon type heater with 2 kW power rating and maximum temperature capacity of 1000°C is used. The turbine type stirrer is used for mixing (Fig.2) with variable speed universal motor of portable hand drilling machine. It has the speed range of 500 - 2400 rpm. The turbine rotor has 4 blades with 90° angles to each other. The stirrer has the provision to remove from the stand during the heating of the melt and also pouring the molten MMC into the die. The furnace can be tilted while pouring the melt to the die.

In the lid, two holes are provided for particle feeding and thermocouples for temperature measurement. Glass wool is filled between outer wall and crucible for insulation purpose. The preparation of MMC is made by stir casting method using liquid and semi solid state mixings of ceramic particles. Table-2 illustrates the process parameters used for the production of MMC with four trials (2- liquid and 2- semi solid state mixings). Fig.3 indicates the sequence of MMC preparation using liquid state mixing. Fig.4 indicates the sequence of MMC preparation using semi solid state mixing.

The cast MMC samples of size $100 \times 100 \times 25 \text{ cu.mm}$ are prepared and are milled to the perfect shape to remove the remnant particles or cold shuts. The samples are forged to break the cast structure to get uniform grains for the improvement of properties to the level of extruded bar. The minimum requirement for the forgings is with the reduction ratio of 4. Fig.5 indicates the method of converting cast billet into forge billet. The forged MMCs are then subjected to heat treatment cycle mentioned below.

- Maintained at 525°C for 2 hrs followed by water quenching.
- Precipitate hardening at 175°C for 10 hrs.

The forgings are then checked for any new cracks due to water quenching and found no cracks. It is observed that MMCs are behaving differently in different directions while forging compared to the un-reinforced material.

Microstructure Characterization

Metallographic samples are cut from the forge billet; mounted on bakelite with wet ground of 400 and 600 grit SiCp impregnated emery surface using copious amounts of water as lubricant. The polishing operation is carried out on Mecapol P230 programmable polishing machine with the speed range from 20 to 600 rpm. Fine polishing to near mirror like finish is achieved using lavigated alumina powder suspended in distilled water. The samples in an optical microscope (Nikon EPIPHOT-TME inverted Microscope) with metal power image analyzer are examined for reinforcement morphology and its distribution in the MMC along with other intrinsic microstructure.

Table-1 : Chemical Composition (in %) of 2618 Al Alloy Matrix

Si	Mn	Cu	Fe	Mg	Ni	Ti	Ti-Zr	Zn	Al
0.2	0.2	2.3	1.1	1.5	1.1	0.2	0.25	0.15	Balance

Table-2 : Parameters for Experiment					
Sl. No.	Process Parameters	Stir Cast Method			
		Liquid State Mixing / Ref.		Semi-solid State Mixing / Ref.	
		Trial-1	Trial-2	Trial-3	Trial-4
1.	Heating Temperature (° C)	800 [27]	750 [25]	750 [25]	750 [25]
2.	Particles Preheating Temperature (° C)	800 [21]	900 [6]	900 [6]	900 [6]
3.	Duration of Particles Preheating Temperature (hr)	1 [21]	1 [6, 18]	1 [6, 18]	1 [6, 18]
4.	Particle Addition Temperature (° C)	720 [16, 25]	720 [16, 25]	610-650 [16]	610-650 [16]
5.	Die Temperature (° C)	400	550 [25]	200 [24]	200 [24]
6.	Stirrer rpm	500 [17]	700 [22,25]	500 [18]	500 [18]
7.	Pouring Temperature	700 [25]	700-720 [16]	720 [21]	720 [21]
8.	Addition of Magnesium	-	-	-	1 % [21]

Testing

The experimental density of the composites is obtained by the Archimedeian method of weighing small pieces cut from the composite billet, first in air and then in water. The porosities of the produced composites can be evaluated from the difference between the expected and the observed density of each sample. Six specimens for each percent weight of SiCp are used for density measurement.

Hardness of the MMC samples is measured in the EMCO hardness tester after polishing to 1 µm finish. The brinell hardness values of the samples are measured using a ball diameter of 1 mm with 10 kg load to obtain an indentation which will be representative of the macro-structure of the material. In order to eliminate the possible segregation effects, the mean of the six tests is considered out for each specimen.

The tensile and hot tensile tests are performed on a TIRA 2820S universal material testing machine with a modular test system. The testing machine is suitable for examining the strength and deformation behavior of solid materials during tensile, compression and bending tests up to 20 KN. It has the capability of operating in the speed range of 0.01-1000 mm/min. The tests are conducted in the controlled laboratory air environment at ambient temperature (27° C). Tensile tests are conducted in accordance with procedures outlined in ASTM E8 at a strain rate of 2 mm/min. The strain is measured with the help of LVDT.

Hot tensile tests are conducted in the same machine in accordance with procedures outlined in ASTM E8 at a strain rate of 2 mm/min. The maximum temperature capability to perform hot tensile test is 1100° C. The de-rated temperature is chosen as 120° C and 200° C for the maximum temperature of the end product application.

Results and Discussions

Production of Composites

In this study, AA 2618 reinforced with two average particle sizes (7 and 33 µm) and weight percentages (5 and 10%) of SiC particles have been produced using stir casting method and subsequent forging operation. Various trials have been carried out before making MMC samples. Four trials are carried out (2 on liquid state mixing and 2 on semi solid mixing)

Trial - 1 : In this experiment, heating the aluminium alloy in the furnace and particle mixing is done at the outside of the furnace. Insufficient time is noticed for mixing of particles due to the fast temperature reduction before pouring. Some of the ceramic particles are floating on the surface of the melt while stirring and some of them are settled at the bottom of the crucibles. Tensile properties of the MMC are same as that of the basic Al. alloy. It is inferred from the experiment that ceramic particles are not fully dispersed into the matrix alloy and insufficient stirring action. Hence, it is decided to develop new experimental set up for stirring action.

Trial - 2 : In this experiment, MMC preparation is made as per the sequence indicated in Fig.3. Ceramic particles are added in the liquid state. Some of the particles are floating on the surface of the melt during mixing and some of them are settled in the bottom of the crucible. This shows that wettability is poor. The ceramic particles are not fully dispersed in the matrix alloy. Few specimens are shown good result with respect to tensile properties in line with MMC system and few specimens are shown with basic alloy properties. It is inferred that particles are not fully dispersed into the matrix alloy due to the poor wettability. Specimens are made to carryout density and hardness measurement and tensile test.

Trial - 3 : When the SiC particles are added into the molten alloys, they are floating on the surface even though it has high specific density. It is due to high surface tension and poor wetting between the particles and the melt. Gas layers might be the main factor for the poor wettability. Gas layers can cause the buoyant migration of particles, making difficult to incorporate into the melts even by vigorous agitation. In a semi solid state, gas layer break can happen due to the collision between primary α Al nuclei and particles. Particles are added in the semi solid state and manual stirring by steel rod. Second mixing is done with stirrer in the liquid state. The percentage of SiC particles incorporated within the solidified composite is indicative of the success with which wetting is achieved. Therefore measuring the quantity of SiC is necessary. A weight-based measurement is carried out by filtering all the slag left out in the process with different sizes of sieves by step-by-step method. 40% of the SiC particles are not incorporated in the MMC billet. From the above experiment, it is observed that 60% of the SiC particles are utilized for wetting.

Trial - 4 : In this experiment, MMC is produced using the semi solid state mixing with magnesium addition [21] for the improvement of wettability. The sequence of the process for MMC preparation is illustrated in Fig.4. 20% of the SiC particles are not incorporated in the MMC billet. From the above experiment, it is observed that 80% of the SiC particles are utilized for proper wetting. Specimens are made from the billet to carry out density, hardness measurement and tensile tests.

Microstructure

Figures 6(a) and 6(b) are the optical micrograph of Al alloy reinforced with 5 and 10% weight SiC particles of size 'F' respectively produced through liquid state mixing

process. Fig.6(c) is the optical micrograph of Al alloy reinforced with 5% weight SiC particles of size 'C' with un-etched condition produced through semi-solid state mixing process. Fig.6(d) is the optical micrograph of Al alloy reinforced with 10% weight SiC particles of size 'F' with etched condition produced through semi-solid state mixing process.

Test Results

The experimental densities of the composites according to the percentage weight of particles, particle sizes and process of mixing are shown in Fig.7. It shows that theoretical density of the composites increases linearly with respect to percentage weight of the particles (as per rule of mixture) but the experimental densities are lower than that of the theoretical densities. The density of composites increases with percentage weight of particle and size of the particles. Density of SiC particle is higher than the Al alloy and hence the increase in percentage weight of SiC will increase the density of the composite based on the rule of mixtures [25]. Density of MMC produced through semi-solid state mixing process provides higher densities than the liquid state mixing process. This observation reveals that the percentage of particles dispersed in the matrix alloy is more than the liquid state mixing process. The porosity of the composites increases with the increase in percentage weight of the particle.

Hardness tests are performed on a Brinell hardness machine and the test results are represented in particle sizes, percentages of weight and process of mixing (Fig.8). From the figure, it is observed that hardness increases with amount of SiC particles and decreases with the increase of particle size [25]. The above phenomenon is same for both the process of particle mixing (liquid and semi-solid states). But, the marginal increase is noticed in the MMC prepared through semi-solid state mixing than liquid state mixing. Since, SiC particle is hard and the addition of the same with Al alloy can increase the hardness with increase in % weight of particles.

The results of the tensile tests at room temperature are shown in Figs.9,10 and 11 with the % weight for two particle sizes and process of mixing. Fig.9 indicates the variation of UTS with the percentage weight and size of SiCp and process of mixing. Fig.10 indicates the variation of 0.2% PS with the percentage weight and size of SiCp and process of mixing. From the figure, UTS and 0.2% PS increase with increase in percentage weight of particles and decrease with particle size. A small increase in

strength or nearly equal in strength of MMC is noticed for semi-solid state mixing with respect to the liquid state mixing. Fig.11 represents the variation of % elongation with the % weight and size of SiCp and process of mixing.

The % elongation of the MMC drastically reduced from the basic Al alloy. The % elongation marginally increases or almost same with increase of particle sizes and % weight of particles [23]. The % elongation decreases for the semi-solid state mixing process due to higher density of MMC. Most of the MMCs are less ductile at room temperature. The % elongation measured for the MMC lies with a very low range depending on SiC particle size and content. Higher the particle content, lower the elongation due to the increase in UTS and 0.2 % PS. This means that the ductility is controlled and brittleness is increased. Reinforcements have led to the strengthening of the non-uniform strain distribution. Strain in the local region is sufficiently high and the matrix fails in tension at lower strain than the unreinforced matrix. This leads to a decrease in tensile ductility than the unreinforced matrix.

In the stir casting method, liquid and semi-solid state mixings have been adopted to manufacture MMC billet followed by forging and the tensile properties have been established. Based on the findings of the investigation, tensile strength and ductility are within the intended application.

Conclusions

The optimum process conditions are found in the Preparation of SiC particle reinforced Al alloy composites using liquid and semi-solid state mixings in the stir casting method followed by forging. Optical micrograph, density, hardness, tensile strength and elongation at room temperature were investigated. The following conclusions have been drawn.

- Optical micrograph indicates the uniform distribution of SiC particles and more number of particles dispersed in the matrix alloy by introducing semi-solid state mixing in the stir casting process.
- Improved wettability is achieved in the semi-solid state mixing process.
- The density of the MMC increases with increasing weight percentage of particles and particle sizes. The density of the MMC billet produced by semi-solid state mixing more than the liquid state mixing.
- The hardness of the MMC increases with increasing weight percentage of particles and decreasing size of particles. The hardness variation in semi-solid state mixing process is not significant with respect to the liquid state mixing.
- UTS and 0.2 % PS increase with increase in weight percentage and decrease in particle sizes at room temperature. MMC specimens prepared by semi-solid state mixing provide better tensile strength.
- The % elongation is decreased nearly to 60% when compared with unreinforced alloy. The % elongation decreases for the semi-solid state mixing process compared to the liquid state mixing process.

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Fig.1 Experimental Set-up for Stirring

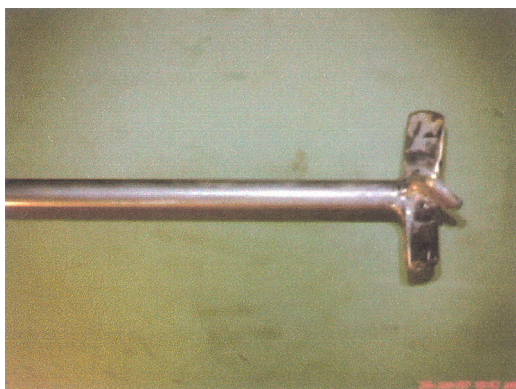


Fig.2 Turbine Type Stirrer

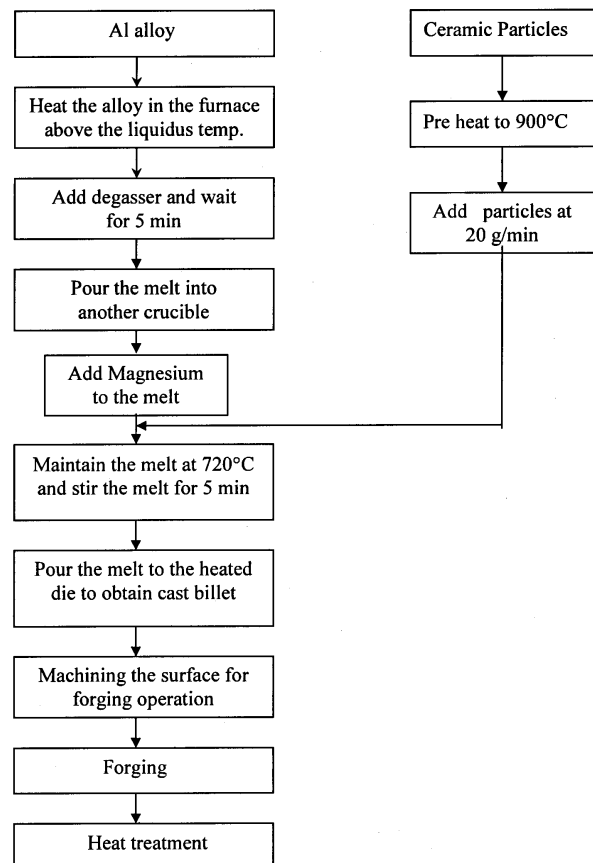


Fig.3 Sequence of MMC Preparation Using Liquid State Mixing

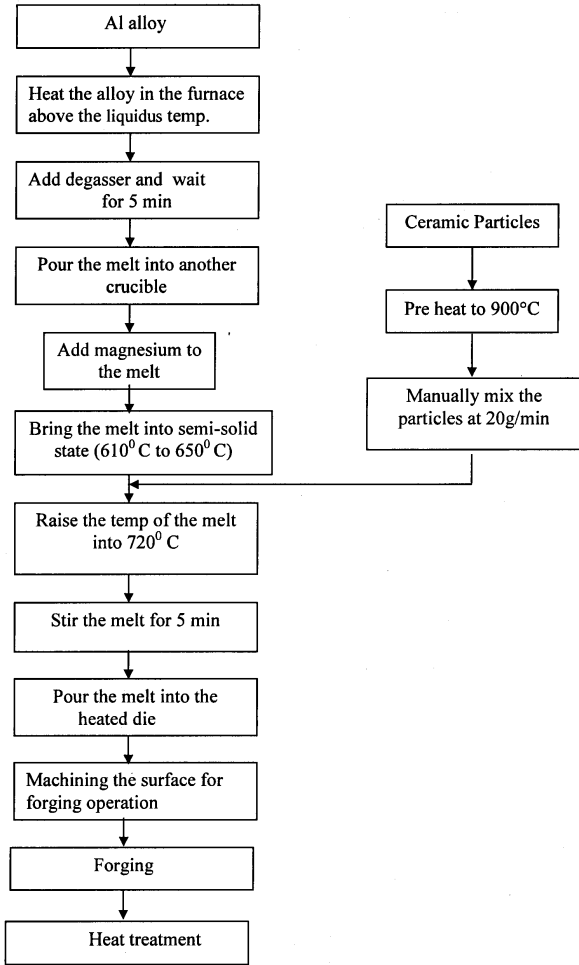


Fig.4 Sequence of MMC Preparation Using Semi-solid State Mixing

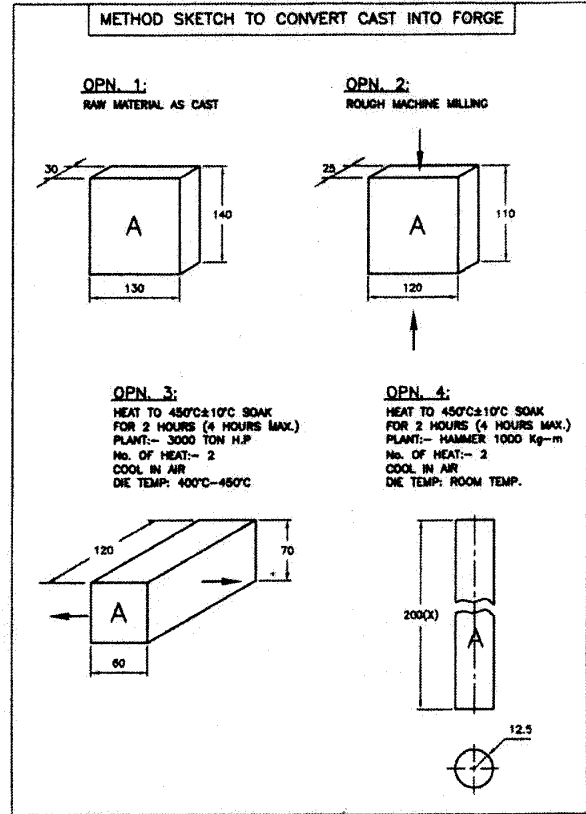


Fig.5 Method Sketch to Convert Cast into Forge

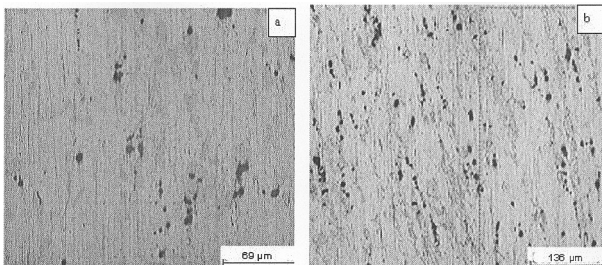


Fig.6(a) and (b) is the Optical Micrograph of Al Alloy Reinforced with 5 and 10% wt. SiC Particles Size 'F' - Liquid State Mixing

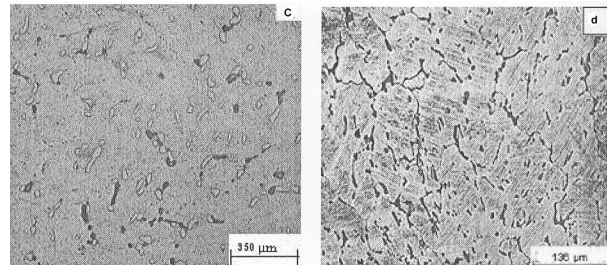


Fig.6(c) and (d) Optical Micrographs Illustrating (c) Non-etched Microstructure of AA 2618 / SiCp / 5 % / C Composites (d) Etched Microstructure of AA2618 / SiCp / 10 % / F Composites - Semi Solid State Mixing

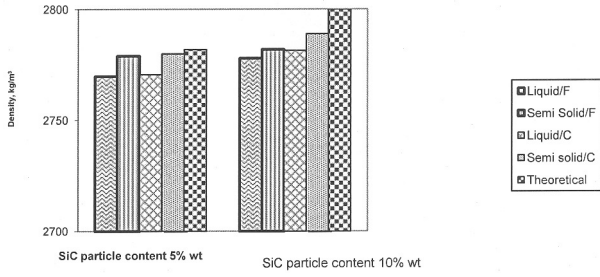


Fig.7 Variation of Theoretical and Experimental Densities with Respect to % Weight of Particles and Size and Process of Mixing

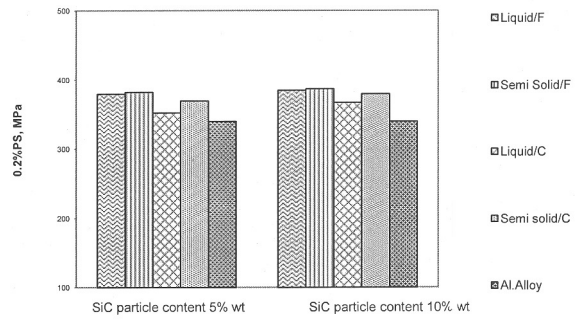


Fig.10 Variation of 0.2% PS with Respect to % Weight of Particles and Size and Process of Mixing

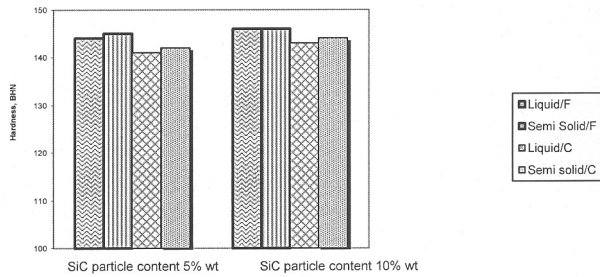


Fig.8 Variation of Hardness with Respect to % Weight of Particles and Size and Process of Mixing

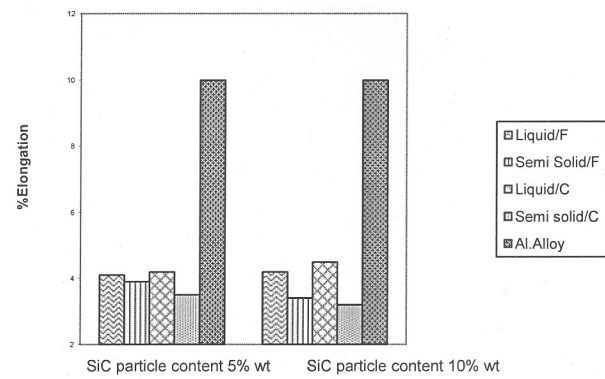


Fig.11 Variation of % Elongation with % Weight of Particles and Size and Process of Mixing

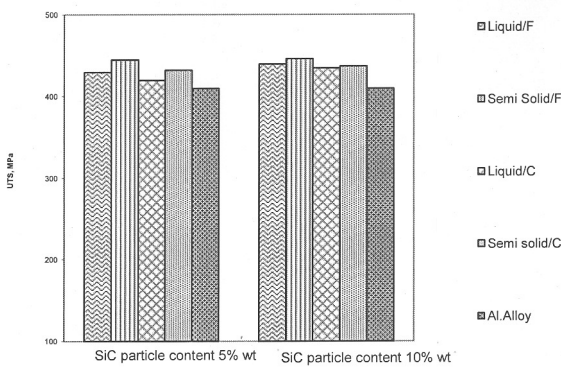


Fig.9 Variation of UTS with Respect to % Weight of Particles and Size and Process of Mixing