Tensile fracture behaviour of 7072/SiC_p metal matrix composites fabricated by gravity die casting process

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The use of gravity die casting process has been studied to fabricate 7072/SiC_p metal matrix composites. The tensile properties have been evaluated. In tensile testing, the composites having volume fraction of 10% silicon carbide gave the maximum values of fracture and yield strengths. The hardness increased with increasing silicon carbide addition to 7072 matrix alloy. The ductility decreased with increasing volume fraction of SiC_p in the composite. Clustering/agglomeration of silicon carbide particulates was observed in some of the tensile test specimens. The fracture mode is ductile and brittle in nature.

Keywords: Gravity die casting, 7072, SiC, Tensile, Hardness

Introduction

Metal matrix composites (MMCs) reinforced with ceramic particles exhibit high specific strength and specific stiffness at room and elevated temperatures. It is well known that the elastic properties of MMC are strongly influenced by the microstructural parameters of the reinforcement, such as shape, size, orientation, distribution and volume fraction.

Aluminium alloy based MMCs are attractive and viable candidate for automobile and aerospace applications.[1,2] Silicon carbide (SiC) is the commonly used reinforcement material because of its high modulus, broad availability and affordable.[3] Particulate reinforced MMCs are much easier to fabricate than continuous reinforced composites. Consequently, production of the material is possible at lower costs as compared to that of MMCs with fibres. The high density of dislocations both at and near the reinforcement/matrix interfaces is aroused as a result of the mismatch in the coefficient of thermal expansion between the SiC particle and the aluminium alloy matrix.[4] Clustering leads to a non-homogeneous response and lower macroscopic mechanical properties. Particle clusters act as crack or decohesion nucleation sites at stresses lower than the matrix yield strength, causing the MMC to fail at unpredictable low stress levels.[5,6] Possible reasons resulting in particle clustering are chemical binding, surface energy reduction and particle segregation.[7]

Among all the liquid state processes, stir casting technology is considered to be the most potential method for engineering applications in terms of production capacity and cost efficiency.[8] A two-step stirring was developed for homogeneous particle distribution to prepare particulate MMCs.[9]

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The motivation for this work was to study the influence of microstructure (as cast and heat treatment conditions), volume fraction of SiC_p reinforcement on the tensile and fracture behaviour of 7072 aluminium alloy MMC reinforced with silicon carbide particles (SiC_p).

Experimental procedure

The chemical composition of 7072 matrix alloy is given in Table 1. The volume fractions V_f of SiC_p reinforcement are 10, 20 and 30%. The particle size of SiC_p reinforcement is 10 μm.

Preparation of melt and MMCs

Al alloys were melted in a resistance furnace. The crucibles were made of graphite. The melting losses of alloy constituents were taken into account while preparing the charge. The charge was fluxed with coverall to prevent dressing. The molten alloy was degasified by tetrachlorethane (in solid form). The crucible was taken out of the furnace and modified with sodium. Then the liquid melt was allowed to cool down just below the liquidus temperature to bring the melt semisolid state. At this stage, the preheated (1000°C for 1 h) SiC particles were added to the liquid melt. The molten 7072 alloy and SiC particles are thoroughly stirred manually. After sufficient manual stirring, the semisolid liquid melt was reheated to a fully liquid state in the resistance furnace followed by automatic mechanical stirring using a mixer to make the melt homogenous for about 15 min at 200 rev min^{-1}. The temperature of the melt was measured using a dip type thermocouple. The dross removed melt was finally gravity poured into the preheated cast iron mould (Fig. 1).

Heat treatment

Before machining of the composite samples, a solution treatment was applied at 550°C for 15 min, quenched in cold water and aged at 150°C for 100 h.

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1 Mould used to prepare test samples

Tests

The as cast and heat treated samples were machined to get specimens for tensile test. The shape and dimensions of the tensile specimen are shown in Fig. 2. The computer interfaced universal testing machine was used for the tensile test. The specimens were loaded hydraulically. The loads at which the specimen has reached the yield point and broken were noted down. The extensometer was used to measure the elongation. Three samples were used for each trial.

Hardness data were obtained from the Vickers hardness tester. A load of 10 kg was applied on the square based diamond pyramid indenter. The length of the diagonal of the impression was measured through a microscope fitted with an ocular micrometer. Three readings were taken on both sides of the specimen. The average value of hardness values was calculated.

Optical microscopic analysis

Microstructures of as cast and heat treated aluminium composite samples were examined metallographically. The photographs of samples were taken. Samples were firstly cut and mounted. Then they were grinded, polished and etched with Keller solution which contains 1·5% HCl, 2·5% HNO_3, 1% HF and 95% H_2O.

Scanning electron microscopic analysis

Fracture surfaces of the deformed/fractured (under tensile loading) test samples were examined in a scanning electron microscope (SEM) to determine the macroscopic fracture mode and to characterise the fine scale topography and establish the microscopic mechanisms governing fracture. Samples for SEM observation were obtained from the tested specimens by sectioning parallel to the fracture surface and the scanning was carried in Indian Institute of Chemical Technology (Hyderabad, India) S-3000N Toshiba.

X-ray structure analysis

The second phases that may form during casting and heat treatment were revealed by X-ray structure analysis. X-ray analysis was made by 100 kV Philips twin tube X-ray diffractometer.

Table 1 Chemical composition of matrix alloy 7072

Alloy	Composition determined spectrographically/%								
	Al	Si	Fe	Cu	Ti	Mg	Mn	Zn	Cr
7072	97·8	0·387	0·464	0·013	0·005	0·396	0·008	0·85	0·012

Results and discussion

Three tensile specimens were tested for each trial. The average values of yield strength, fracture strength (ultimate tensile strength) and ductility in terms of tensile elongation are presented in the graphical forms.

Undeformed microstructure

The optical micrographs illustrating the microstructures of heat treated 7072 Al alloy and the as cast and heat treated 7072/SiC_p MMCs are shown in Figs. 3–5. The alloy 7072 Al structure consists of fine and coarse particles of $MgZn_2$ (black) and a few insoluble particles of $FeAl_3$ (light grey) in the aluminium rich solid solution (Fig. 3). Figures 4 and 5 show the random distribution of SiC_p reinforcement particles in the 7072 alloy. The as cast microstructure (Fig. 4) reveals coarse grain structure, whereas the heat treated microstructure (Fig. 5) represents the fine grain structure. At regular intervals, a clustering or agglomeration of SiC_p of varying sizes in high volume fraction composites is observed resulting in SiC_p rich and SiC_p depleted regions (Fig. 6).

X-ray diffractogram of heat treated 7072 Al/SiC_p (V_f=20%) composite is shown in Fig. 7. Aluminium and carbon react to form a second phase of aluminium carbide (Al_4C_3) as shown in Fig. 8. The carbon is exposed to the structure and reduced by aluminium by the reaction $4Al+3SiC=Al_4C_3+3Si$. Thus, the higher level of silicon will result in the composite. It was confirmed that the formation of $A1_4C_3$ was detrimental to the properties of composite.[10] The microstructure also consists of fine and coarse particles of $MgZn_2$, and $AlMg_2Zn$ in the aluminium rich solid solution matrix as shown in Figs. 9 and 10 respectively as a result of heat treatment of the composite.

Tensile properties

The variations of yield strength and fracture strength (ultimate tensile strength) with volume fraction of SiC are shown in Fig. 11. The yield strength, defined as the stress corresponding to a plastic strain of 0·2%, increases with increasing volume fraction of SiC_p. The yield and fracture strengths of heat treated 7072 Al/SiC composite (V_f=20%) are found to be high. As the volume fraction of SiC particles increases beyond 20%, the yield and fracture strengths decrease. The variation in the fracture strength 7072/SiC_p composites is largely affected by the workhardening rate. It was reported that the workhardening rate was a function of lower matrix volume (the matrix volume decreases with increasing volume fraction of reinforcement).[9] This is due to reduction of strain hardening after yield point for composites having volume fraction more than 20% as shown in Fig. 12. A significant strain hardening occurs, which is dependent on the particle diameter and volume fraction. The strain hardening contribution to the yield strength is given by

$$\sigma_s = k_s G V_p \left(\frac{2b}{d}\right)^{1/2} \varepsilon^{1/2}$$

where k_s is a constant, G is the shear modulus, V_p is the particle volume fraction, b is the Burgers vector, d is the particle diameter and ε is the elongation. The effect on the strain hardening is on account of formation of the aluminium silicide (Al_4C_3) and other second-phases. The amount of aluminium silicide increases with increasing volume fraction of SiC. The decrease in the fracture

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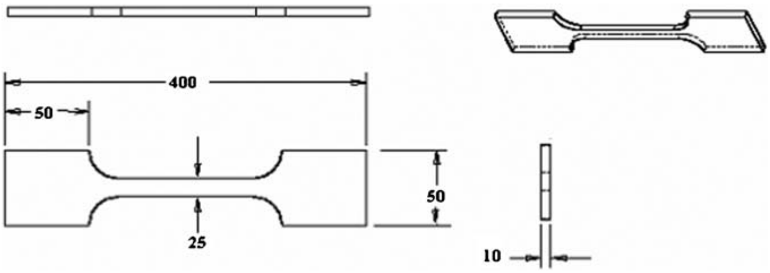
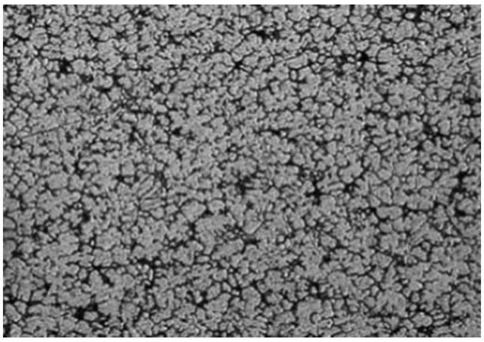


2 Tensile specimen: all dimensions are in millimetres



3 Microstructure of heat treated 7072 Al alloy

strength and yield strength is also due to the formation of clusters of SiC in the composite at high volume fractions of SiC$_p$. The fracture strength is only marginally higher than the yield strength.

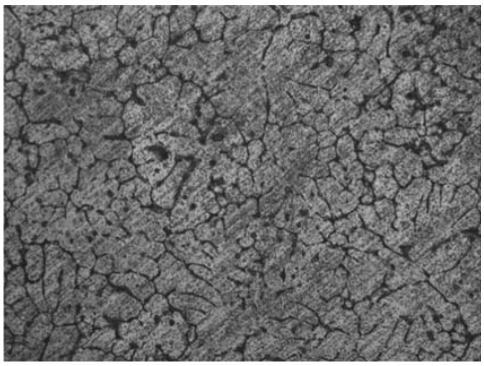
The influence of volume fraction of SiC$_p$ on the ductility (measured in terms of tensile elongation) and hardness is shown in Fig. 13. It can be seen that the tensile elongation decreases with increasing volume fraction of SiC, whereas the hardness increases with increasing volume fraction of SiC. The increase in hardness is influenced by the precipitation hardening during the heat treatment. The influence of change in grain size during heat treatment is given by

$$\sigma_g = k_g D^{-1/2}$$

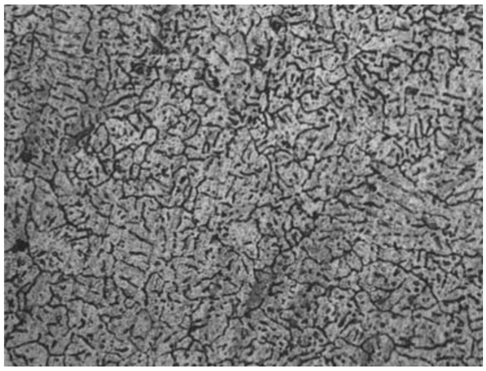
with

$$D = d\left(\frac{v_m}{v_p}\right)^{1/3}$$

where K_g is a constant, D is the resultant grain size, V_p the volume fraction of reinforcement and V_m the volume fraction of matrix. The influence of change in grain size on the precipitation hardening is shown in Fig. 14. The precipitation hardening increases with increasing volume



4 Microstructure of 7072/SiC$_p$ as cast composite (V_f=20%)



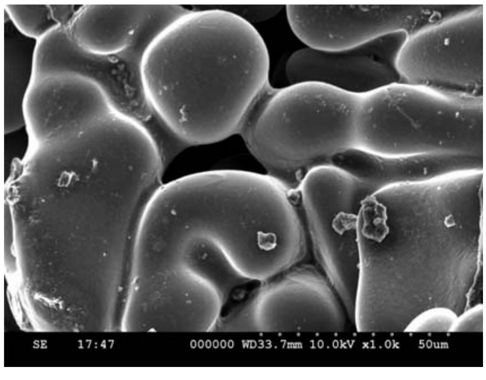
5 Microstructure of 7072/SiC$_p$ heat treated composite (V_f=20%)

fraction of SiC. The increase in the hardness can be attributed to the precipitation process, which is taking place progressively. The increase in hardness may be due to the second phases precipitated during the heat treatment of the composites. The second phases are brittle and hard. The finely distributed particles effectively hinder the motion of dislocations in the matrix alloy and increase the hardness of the composite.

The decrease in the ductility can be attributed to the beginning of void nucleation in advance with increasing amount of SiC$_p$ reinforcement and the stress concentrations at reinforcement particles and reaction/precipitated second phases. It was verified that the microplasticity took place in the MMCs due to stress concentrations in the matrix at the poles of the reinforcement and/or at sharp corners of the reinforcing particles.[10]

Fracture behaviour

The tensile fracture behaviour of heat treated 7072/SiC$_p$ MMCs, which were cast by the gravity die casting



6 Clustering or agglomeration of SiC$_p$ observed in 7072 Al/SiC$_p$ (V_f=30%)

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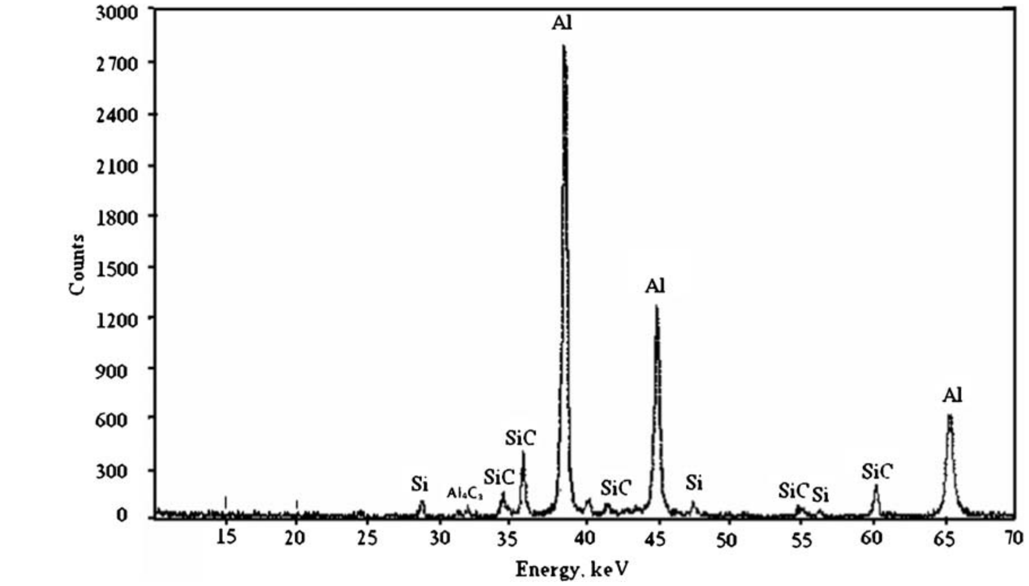
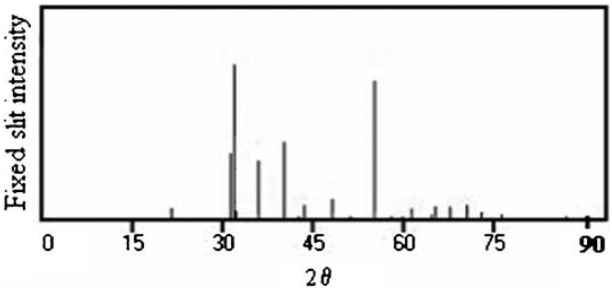
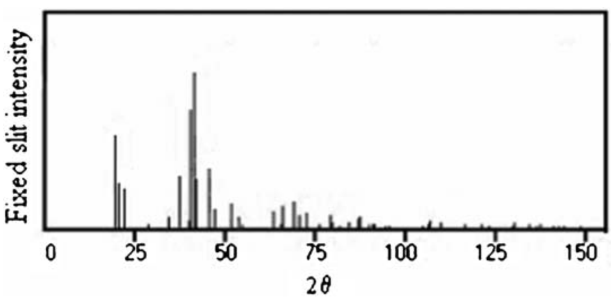


7 X-ray diffractogram of heat treated 7072 Al/SiC$_p$ (V_f=20%) composite

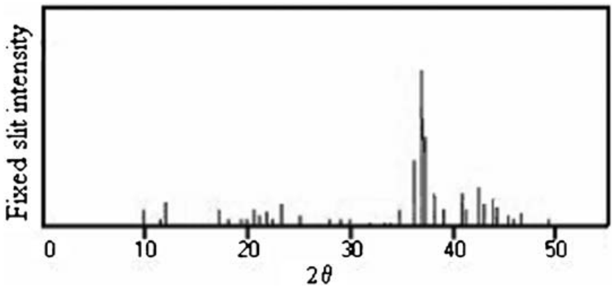


8 X-ray analysis to recognise second phase of Al_4C_3

process, was studied in the present work. Examination of the tensile fracture surfaces (Figs. 15 and 16) reveals features of locally ductile and brittle mechanisms. The factors influencing the ductile and brittle fracture are the non-uniform distribution of SiC particles in the 7072 aluminium alloy metal–matrix, and the formation of second phases during casting and heat treatment. Failures of the reinforcement SiC particles by both decohesion and cracking are evident on the tensile fracture surfaces. The fracture behaviour is governed by two essential mismatches between the reinforcement particles, matrix alloy and the second phases precipitated during the casting and heat treatment. The first mismatch is the difference in the strain carrying capability between the hard and inherently brittle reinforcing SiC$_p$ and the soft and ductile aluminium alloy metal–matrix. The second mismatch is due to differences in the



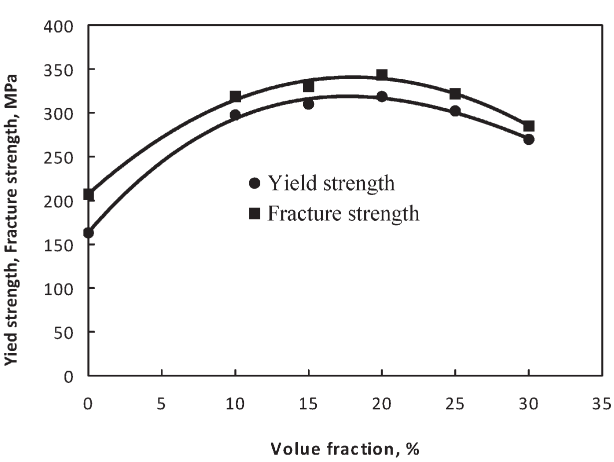
9 X-ray analysis to recognise second phase of $MgZn_2$



10 X-ray analysis to recognise second phase of $AlMg_2Zn$

coefficient of thermal expansion between the SiC particles, the 7072 aluminium alloy matrix and the precipitated phases.

The first mismatch promotes stress concentration near the reinforcement SiC$_p$. This situation generates favourable conditions for the SiC$_p$ particles, second phases (reaction compounds and intermetallics) and clusters to crack and subsequently the separation (decohesion) of SiC$_p$ particles from the adjacent matrix alloy. Simultaneous failure of the reinforcement SiC$_p$, second phase particles in the composite microstructure is governed by the contending influences



11 Variations of yield strength and fracture strength with volume fraction of SiC

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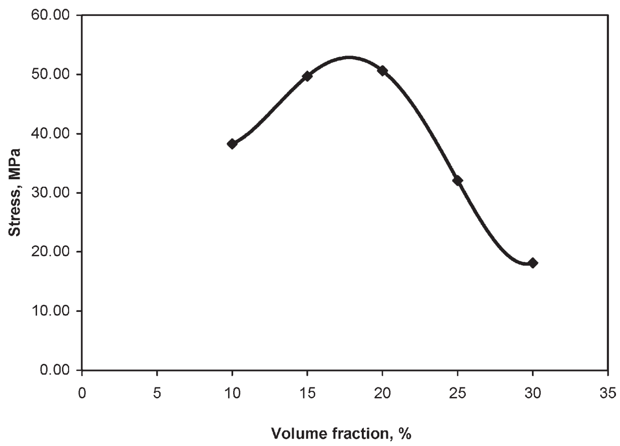
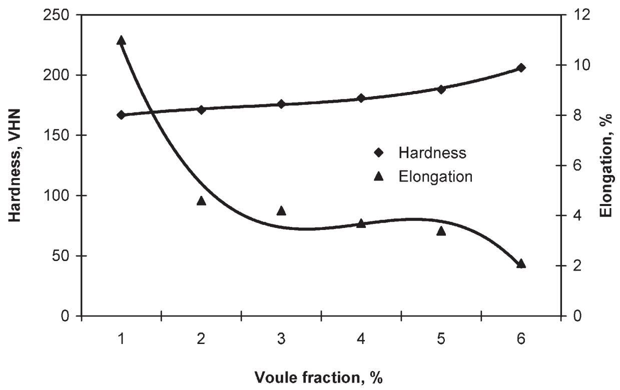


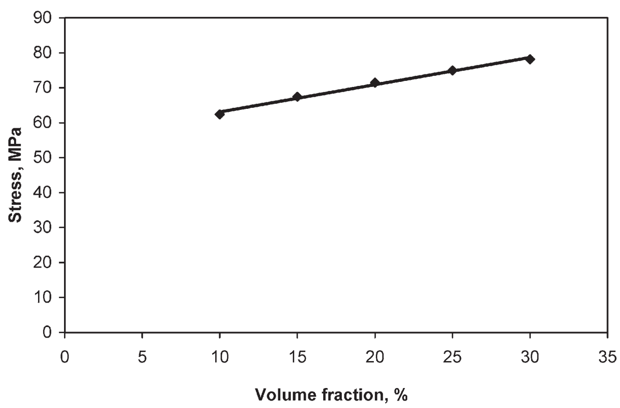
12 Variation of strain hardening with volume fraction of SiC



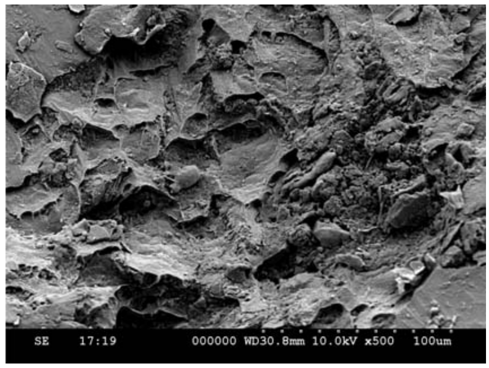
13 Variations of ductility and hardness with volume fraction of SiC particles

of local plastic constraints, particle size and degree of clustering. The local plastic constraints are particularly important for the larger sized particles and particle clusters during composite fracture.[11]

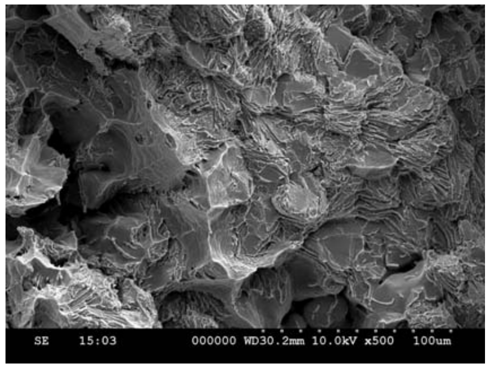
The second thermal mismatch induces dislocations at the reinforcement/matrix interface. The presence of SiC reinforcement particles reduces the average distance in the composite by providing strong barriers to the dislocation motion. The interaction of dislocations with other dislocations, precipitates and SiC particles causes the dislocation motion. The dislocation motion results in dimple structure.



14 Variation of strain hardening with volume fraction of SiC

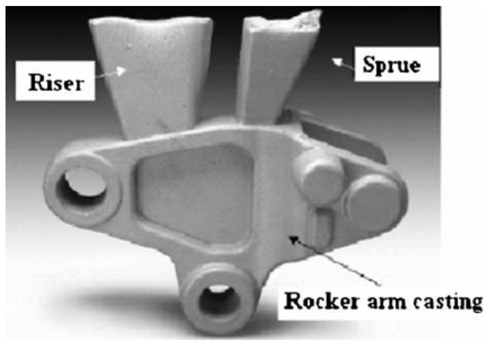


15 Image (SEM) of fracture surface of as cast tensile sample (V_f=30%)



16 Image (SEM) of fracture surface of heat treated fatigue sample (V_f=30%)

Void nucleation occurs at particle/matrix interfaces and can be realized by either interface decohesion or particle cracking. The microscopic voids are associated with failure of the ductile metal matrix between the reinforcement particles, whereas the macroscopic voids are coupled with the reinforcement SiC_p. The sources of macroscopic voids and resultant shallow dimples on the fracture surface are the critical events controlling both the fracture and decohesion of the reinforcement SiC particles. The constraints are induced by the presence of hard and brittle carbide (SiC) particle reinforcements in the soft and ductile 7072 metal–matrix. The voids then grow under both the applied load and the influence of local plastic constraint until a coalescence mechanism is activated, and this is followed by the total failure of the specimen. The void coalescence occurs when the void elongates to the initial intervoid spacing. This leads to the dimpled appearance of the fractured surfaces.



17 Rocker arm casting

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During the later stages of deformation, microscopic cracks initiate and grow in the region of high plasticity and are aided by the local elevation of hydrostatic stresses due to the presence of coarse SiC particles.[12] This confirms the important role played by the local plastic strains in governing damage initiation and propagation in the 7072/SiC_p composite microstructure. The fracture due to tensile loading is ductile and brittle in nature.

Application

A trail die casting of 7072/SiC_p (with 10% of reinforcement) and 7072 Al alloy was applied to the manufacturing of rocker arm as shown in Fig. 17. The 7072/SiC_p MMC reduces the weight of rocker arm casting by $\sim$27% as compared with the casting made from the 7072 Al alloy. The use of 7072/SiC_p MMCs in other commercial applications is also expected to increase due to its high strength to weight ratio.

Conclusions

In tensile testing, the composites having volume fraction of 10% silicon carbide gave the maximum strength. The fracture and yield strengths decreased with increase in volume fraction of SiC beyond 10%. The hardness increased with the increase of silicon carbide addition to 7072 matrix alloy. The ductility decreased with the increase in volume fraction of SiC_p in the composite. Clustering/agglomeration of silicon carbide particulates was observed in some of the tensile test specimens. Heat-treated composites were examined with x-ray analysis to find precipitated phases. In all x-ray diffractograms aluminum and silicon carbide peaks were observed. Pure silicon peaks were observed in 20% and 30% SiC/7072 Al composites. This might be on account of reduced SiC_p. As a result of SiC_p reduction the Al_4C_3 phase might have been formed. The tensile fracture was governed by the ductile and brittle behaviors.

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