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ORIGINAL ARTICLE

Effect of particle size, forging and ageing on the mechanical fatigue characteristics of Al6082/SiC$_p$ metal matrix composites

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Abstract Addition of inexpensive silicon carbide particulates (SiC$_p$) in the aluminium alloy matrix results in materials with properties non-obtainable in monolithic materials. The forging process results in improved properties as well as forms a shape of the final product. The age-hardening processes accelerate the coarse hardening process of the composites and improve strength and ductility. The size, morphology and volume fraction are the key controlling factors that control the plasticity and the thermal residual stresses in the matrix and thereby it's mechanical and fatigue properties. This research paper focuses on the effect of particle size, forging and ageing on the mechanical and fatigue properties of the cast, forged and age-hardened aluminium 6082 (AI6082) reinforced with SiC$_p$. Al6082 reinforced with three different particle sizes of SiC$_p$ (average particles size of 22, 12 and 3 μm) in the forged and ageing conditions were studied. The samples were characterised by optical microscopy, hardness, tensile and fatigue tests. The forged microstructure shows a more uniform distribution of SiC$_p$ in the aluminium matrix. The addition of SiC$_p$ results in improved tensile strength, yield strength and elastic constants of the composites with reduction in ductility. It also increases the fatigue strength of the composites by increasing the number of cycles required for fatigue failure of the composites for the given value of stress. The results also show considerable improvements in mechanical fatigue properties due to forging and ageing heat treatment of the metal matrix composites

Keywords Metal matrix composites · Particle size · Forging · Ageing tensile and fatigue behaviour

1 Introduction

The great potential of application of metal matrix composites (MMCs) in automotive, aerospace and other industries have started reaching its widespread importance. The addition of relatively inexpensive silicon carbide particulates (SiC$_p$) results in material having a very low coefficient of thermal expansion and high specific strengths, wear resistance and heat resistance than conventional Al alloys.

Varieties of techniques are used to manufacture MMCs to the useful engineering shapes [1] such as (1) liquid phase techniques (solidification processing), (2) semi-solid phase techniques and (3) solid phase techniques. Most of the methods are expensive and require skilled, complicated operations [2]. The liquid phase routes are more similar to conventional casting and are economical for the manufacture of MMCs. Solidification processing as in conventional casting leads to casting defects that include porosity and inclusions [3–5]. The characteristics of composites are greatly influenced by these defects.

The improvements in strength and ductility are observed with the application of plastic-forming processes like forging, extrusion etc. [6]. These alterations in properties are attributed to the factors which control the mechanical properties of these materials. Forming process alters structural parameters, which influence the characteristics, as they are sensitive to the reinforcement, production and

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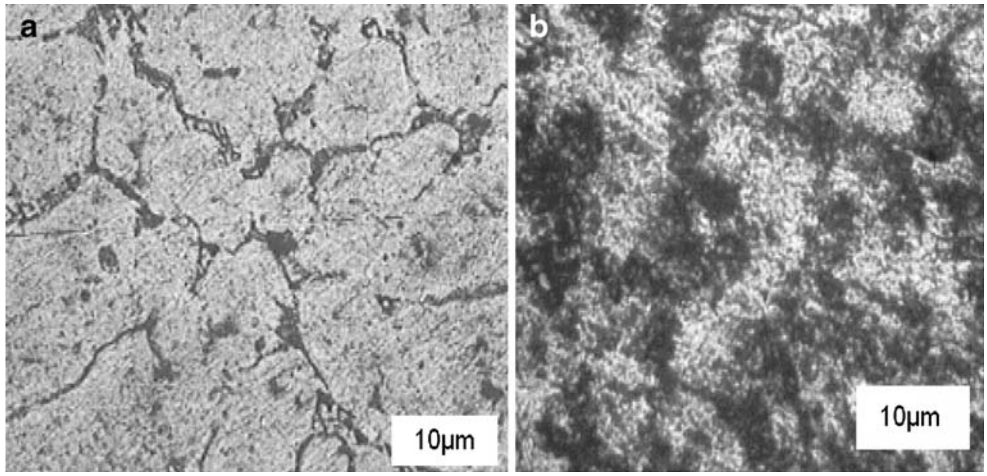


Fig. 1 The microstructure of the composite Al6082/SiC/10p in the **a** as-cast **b** forged conditions

fabrication methods [4]. Recent widespread publicity on the increasing use of light metals in the transport sector replacing steel has possibly overlooked the tried and proven technology of forging aluminium in a wide range of applications. So, it becomes important to establish a relationship between the factors that affect the properties of the materials. Great improvements in mechanical properties of Al alloys can be achieved by suitable solution treatment and ageing conditions [6–9]. A lot of works have been carried out to study the effect of ageing on the mechanical properties of the composites, but there is little work on the effect of forged metal matrix composites with ageing and their relationship.

A study has been made to understand the effect of particle size, forging and ageing on the mechanical and fatigue properties of Aluminium 6082 (Al6082) reinforced with three different sizes of SiC_p. Porosity, hardness, tensile and fatigue tests are conducted on the cast, forged and age-hardened specimen to characterise the mechanical and fatigue properties of the composites.

2 Experimental details

Stir-cast metal matrix composites Al6082/ SiC_p were used for the study. The matrix material used in this work was Al6082 containing 1.0%Si, 0.5%Fe, 0.1%Cu, 0.8%Mn, 1.0%Mg, 0.2%Zn, 0.1% Ti and remainder Al. The density of the aluminium alloy is 2.70 g/cm^3. The alloy is reinforced with SiC particles of abrasive grade. The metal matrix composites of aluminium 6082 reinforced with SiC_p are prepared in a crucible furnace. Three different sizes of SiC_p with average particle size of 22, 12 and 3-μm sizes were fabricated. The composites were henceforth called as Almmc22, Almmc12 and Almmc3, respectively. The composites were fabricated by adding pre-oxidised (at 650°C for 2 h) SiC_p into the liquid matrix alloy at constant rate and at constant stirring. The SiC particles were added to 10% weight fraction of Al6082. The stirred melt is then poured into the permanent iron die mould to obtain composites of size 17-mm diameter and 230-mm length. Magnesium is added to increase the wettability of the particulates. No evidence of macro-casting defects was seen. The matrix metal was also cast in the same process to standardise the casting process.

Optical micrographs were examined to study the effect of SiC_p percentage on the microstructure and its distribution. The cast MMCs are then forged in a closed die forging at a temperature of 500°C. The porosity, hardness and tensile tests were carried out on the as-cast and forged specimens to compare the resultant effect on the MMCs. The samples were artificially aged to T6 condition by solutionising at 550°C for 1 h followed by precipitation heat treatment at 178°C for 8.5 h [27]. Hardness and tensile tests were also conducted on the aged specimens to study their characteristics.

Table 1 The densities and porosity content of the matrix alloy and the composites in the as-cast and forged conditions

Material	Calculated density (g/cm^3)	Experimental density, as-cast (g/cm^3)	Experimental density, forged (g/cm^3)	Percentage of porosity, as-cast (%)	Percentage of porosity, forged (%)
Al Matrix	2.7	2.6474	2.672	1.9481	1.037
Al mmc22	2.748	2.66	2.704	3.2023	1.6011
Almmc12	2.748	2.655	2.6997	3.384	1.757
Al mmc3	2.748	2.6548	2.69	3.3915	2.110

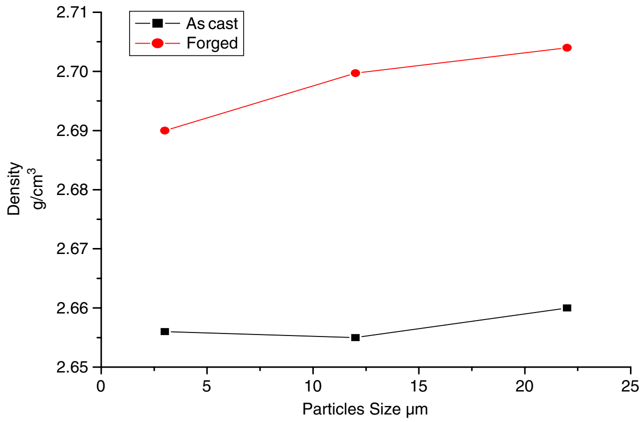


Fig. 2 Variation of porosity of the composite the variation of particle size

3 Results and discussions

3.1 Initial microstructure

The specimens for the metallographic examination were prepared according to ASTM standard E-3-01 (2007). The specimens were cut from the cast, and forged samples were selected in random using abrasive cut-off wheel. The cut samples were then mounted on a Bakelite moulding material for convenience in handling and to protect the edges of the specimen being prepared. The mounted sample surfaces were coarse-grinded to generate an initial flat surface necessary for the subsequent grinding and polishing steps. The samples were washed thoroughly before proceeding from one grinding stage to the next stage. Successive grinding was done using fine emery papers with decreasing grit size of the grinding particles. Distilled water was used as a lubricant for fine grinding and polishing process.

The microstructures of the cast and forged MMCs are shown in the Fig. 1. Keller's reagent was used as etchant. The examinations of the microstructure generally show the uniform distribution of SiC_p in the matrix, but some local clusters of particles exist in the as-cast samples resulting in SiC_p-rich and SiC_p-depleted regions. After the application of the forging process, relatively uniform distribution of SiC_p was found as in earlier works [4]. Although the holding time at 500°C is short, the accelerated coarsening of the phases has occurred to a certain extent, which is expected during annealing and hot working.

3.2 Porosity

Porosity of castings is an important defect, which tends to cause appreciable reduction in mechanical and fatigue properties. Porosity in aluminium casting is caused by the precipitation of hydrogen from liquid solution or by shrinkage during solidification and, more usually, by a combination of these effects. There are other sources of internal voids, mould reactions, high-temperature oxidation, blow holes and entrapped gases resulting in defects that adversely affect mechanical and fatigue properties as well as physical acceptability. The porosity was determined using the Archimedean method. The average porosity content of the produced samples in as-cast and forged conditions was determined. The theoretical density is calculated by using rule of mixtures.

Porosity of the samples was determined using the Archimedean method [3]. In order to estimate the overall porosity content, density measurements were conducted on unreinforced alloy and composites containing three different particle sizes, and the results are given in Table 1.

The variation of porosity and density with the different particle sizes are shown in Fig. 2, and the values are given in Table 2. The density of the samples decreases with the decrease in particle size. The porosity of the samples increases with the decrease in particle size.

The secondary processing increases the density and decreases the porosity of the samples. The decrease in

Table 2 The hardness of the matrix alloy and the composites in the as-cast, forged, age-hardened conditions

Hardness [Vickers] of the samples			
Material	As-cast	Forged	Age-hardened specimens
Al 6082	61.67 (55)	98 (91)	110 (107)
Almmc22	72.8 (68)	108.23 (102)	122.26 (115)
Almmc12	76.2 (74)	113.34 (111)	128 (125)
Almmc3	78.69 (76)	117.39 (115)	132.21 (130)

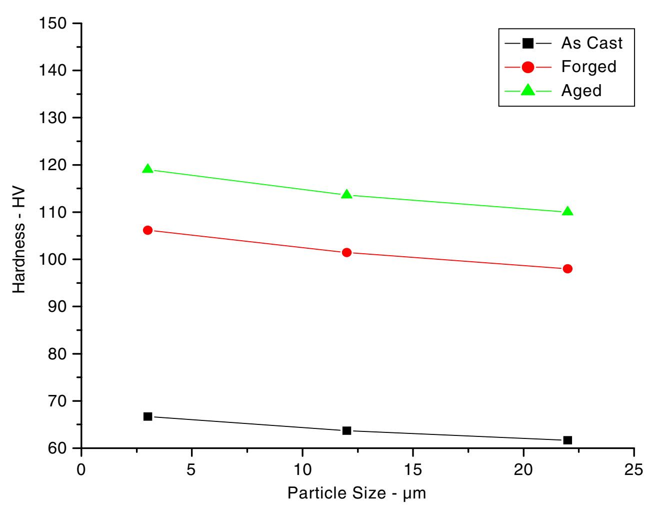


Fig. 3 Hardness of the composites with the variation of SiC particle size

Table 3 The tensile strength of the matrix alloy and the composites in the as-cast and forged conditions

Material	As-cast			Forged		
	$\delta_{0.2\%}$ MPa	δ_{Uts} MPa	Percentage of Elongation ε	$\delta_{0.2\%}$ MPa	δ_{Uts} MPa	Percentage of Elongation ε
Al6082 matrix	52	127	2.8	54.5	166.7	9.96
Almmc22	54	83.11	0.6	70.3	173.6	3.3
Almmc12	55.76	86	1.9	73.56	181.73	5.47
Almmc3	57.58	88.94	3.26	75.96	188	7.23

Table 4 The tensile strength and Young's modulus of the matrix alloy and the composites

Material	Aged			Young's modulus GPa		
	δ0.2% MPa	δuts MPa	Percentage of Elongation ε	As-cast	Forged	Aged
Al6082 matrix	300	320	11	63.9	68.7	69
Almmc22	321	346	6	85.205	91	93
Almmc12	335.47	363.19	10.10	92.95	95.42	97.38
Almmc3	343.44	375	14.35	96.84	98.54	100.18

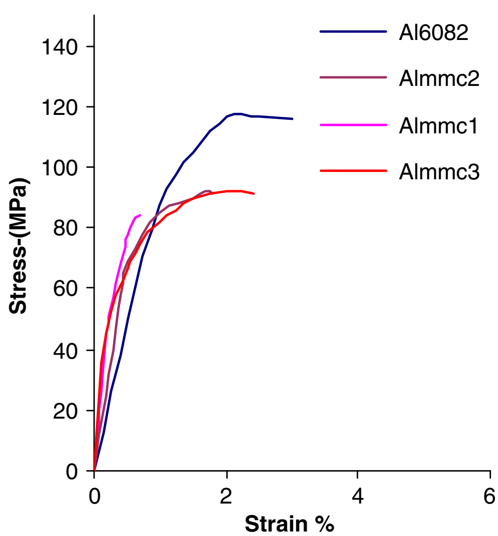


Fig. 4 Stress–strain diagrams of the composites and the metal matrix composites in the as-cast and forged conditions

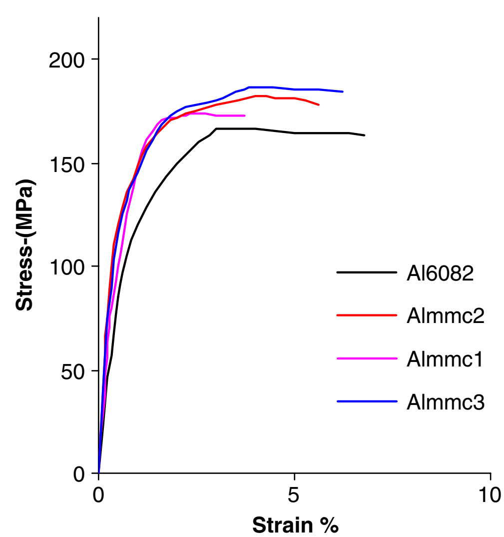


Fig. 5 Stress–strain diagrams of the composites and the metal matrix composites in the as-cast and forged conditions

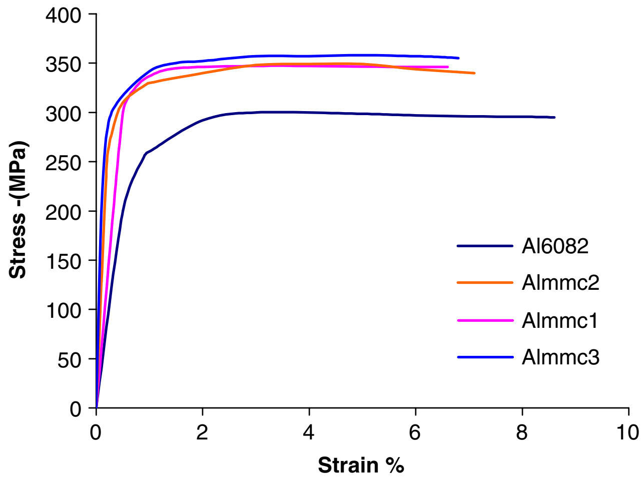


Fig. 6 Stress–strain diagrams of the composites and the metal matrix composites in the age-hardened condition

particle size after forging also decreases the density and increases the porosity. The decrease in porosity with the decrease in particle size may be attributed to increase in particle availability for bonding with the matrix materials. The increase in particles may lead to a slight increase in porosity due to increase in interspaces between matrix and particulates.

3.3 Hardness

Hardness is the characteristic of a solid material expressing its resistance to permanent deformation. The hardness test was conducted according to ASTM E92-82 (2003). The Vickers test is often easier to use than other hardness tests since the required calculations are independent of the size of the indenter, and the indenter can be used for all materials irrespective of hardness. The hardness tests are conducted on as-cast, forged and age-hardened specimens. Four to six tests are conducted, and average value is taken as the hardness of the specimen. 10 kgf is taken as the load. The hardness values are given in Table 2. The values given in the brackets indicate the minimum values.

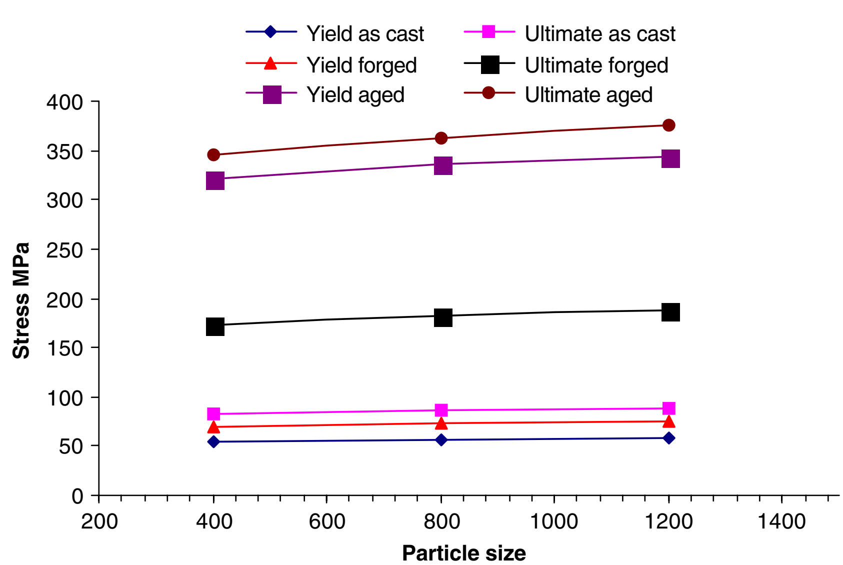
The effect of change in particle size on the hardness of the composites is illustrated in Fig. 3. The hardness test shows marginal increase in hardness with the decrease SiC particulates' size and greater increase with the secondary processing and age hardening of the material. The changes in the properties may be attributed dually to the changes in microstructure and changes in matrix material properties due to forging and ageing.

The increase in hardness with the decrease in particle size may be attributed to the increase in specific surfaces available for the same fraction of SiC particles. The addition of SiC_p particles increases the strain energy in the periphery of the particles distributed in the matrix.

3.4 Tensile strength

The tension tests were conducted according to ASTM standard E8M-08. The tensile test specimens having gauge length of 96-mm and 9-mm diameters were machined from the cast, forged and age-hardened specimens. The room temperature tensile tests were carried out in an auto-make universal testing machine. The decrease in SiC_p size results in increase in percentage elongation to fracture. The effect of forming processes on the structure and properties of metal matrix composites was clearly seen with the improvement in the strength and ductility of the particulate containing composites. The tensile strength of the unreinforced alloy and the composites are given in Tables 3 and 4.

Fig. 7 Tensile strength of the composites with the variation of percentage of SiC



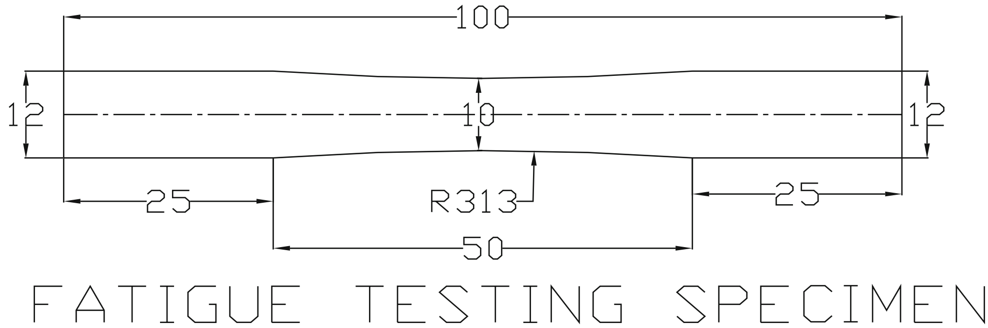


Fig. 8 Fatigue test specimen

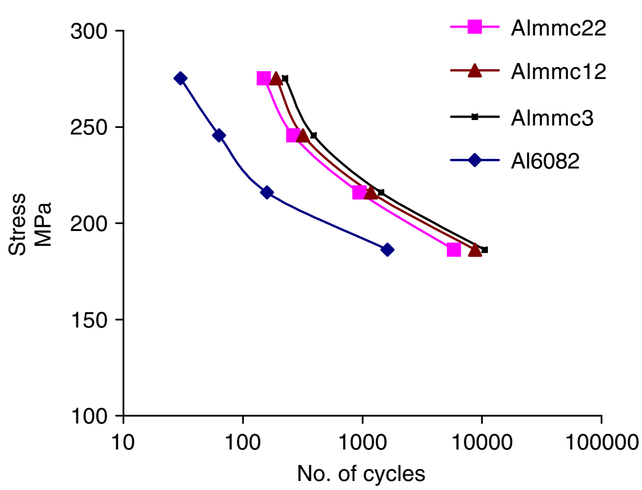


Fig. 9 Fatigue S–N diagram in as-cast condition

The effect of forging processes on the observed samples' increase in yield and tensile strength may be attributed to the changes in microstructure, the reduction of porosity and the alteration of matrix microstructure.

The stress–strain diagrams of the composites and matrix materials are shown in the Figs. 4, 5 and 6. The effect of change in SiC particle size on the tensile strength of the alloy and the composites is illustrated in Fig. 7. The effect of ageing on the composites increases the yield strength and ultimate strength to a larger extent as that of matrix material but with slight increase in the elastic constants of the materials.

The change in the tensile strength is attributed to the changes in the microstructure due to secondary processing and age hardening of the matrix material and the composite. The increase in tensile strength may also be due to increase in strain energy with the decrease in size of the particles and the increase in number of particles available per unit area of the composites.

4 Fatigue strength

The fatigue behaviour of MMCs is very important for many engineering applications involving cyclic or dynamic loading. The applications of MMCs, which include automotive and aerospace components often involving cyclic loading and

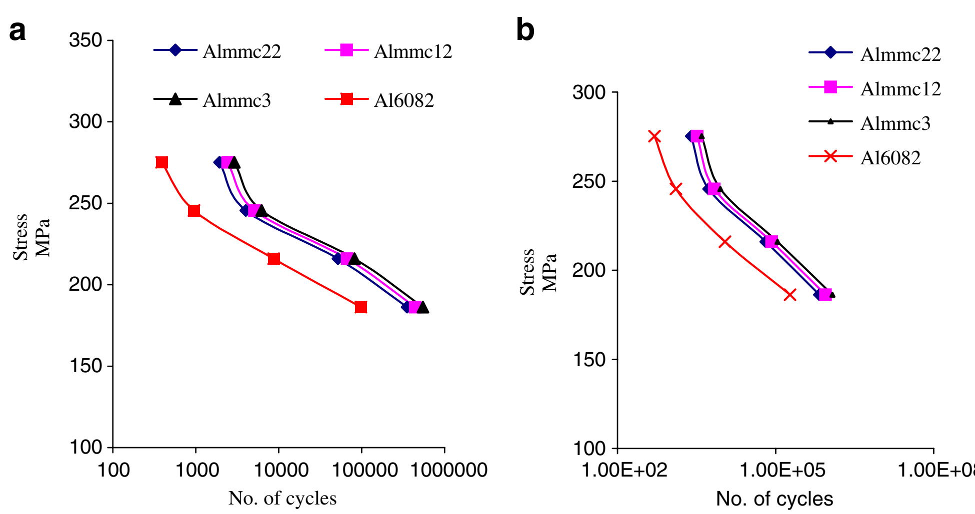


Fig. 10 Fatigue S–N diagrams in **a** forged condition **b** age-hardened condition

hence, fatigue behaviour, is most important. When the composite materials are subjected to a given cyclic stress, the resultant stress–amplitude may change with continued cycling. The cyclic stress response or cyclic hardening and / or softening behaviour is a measure of this transient response and is very useful in designing and developing materials with improved cyclic stress controlled fatigue.

The cyclic stress amplitude-reversals to the fatigue life curve can be viewed as an indication of the resistance of the composite microstructure to microscopic crack formation, potential propagation and coalescence of the cracks culminating in fracture. The fatigue tests were performed under fully reversed bending load (R=−1). The fatigue tests are conducted till the failure of the composites and the numbers of cycles for failure for the applied stress are noted down. The fatigue-testing specimen is as shown in Fig. 8.

The fatigue tests were performed under fully reversed bending loading (R=−1). The fatigue tests are conducted till the failure of the composites and the numbers of cycles for failure for the applied stress are noted down.

Increase in weight fraction results in increase in number of cycles to failure under fatigue loading. The fatigue tests show an improvement in number of cycles to failure in the forged condition and noticeable increase in the aged condition. The decrease in size of the particles increases the number of cycles required for the fatigue failure of the composites [24–32]. The fatigue S–N curves of the composites in the as-cast, forged and in age-hardened conditions are given in the Figs. 9 and 10.

5 Cyclic stress-Strain response

When the composite materials are subjected to cyclic stress amplitude, the resulting strain amplitude may change with continued cycling. Cyclic strain produces a number of damaging process which affect the microstructure and the resulting cyclic strain resistance and low-cycle fatigue The cyclic stress–strain response or cyclic hardening and/or softening behaviour is the measure of this transient response and is very useful in designing and developing materials with improved cyclic strain–amplitude control fatigue.

The cyclic strain amplitude reversals to the failure can be viewed as an indication of the resistance of the composites microstructure to microscopic crack formation, potential propagation and coalescence of the cracks culminating in fracture. The strains are much lower in the composite materials than they would be in the unreinforced material. This is because of the higher elastic modulus and higher proportional limit of the composite material.

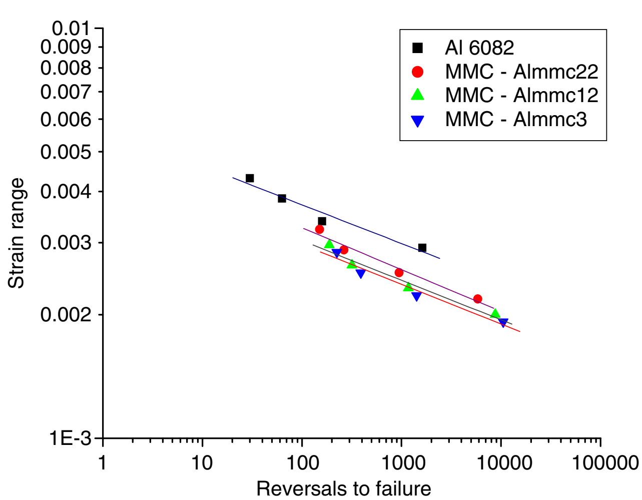


Fig. 11 Cyclic strain–fatigue life response of Al 6082/SiC$_p$ composites in as-cast condition—variation of particle size

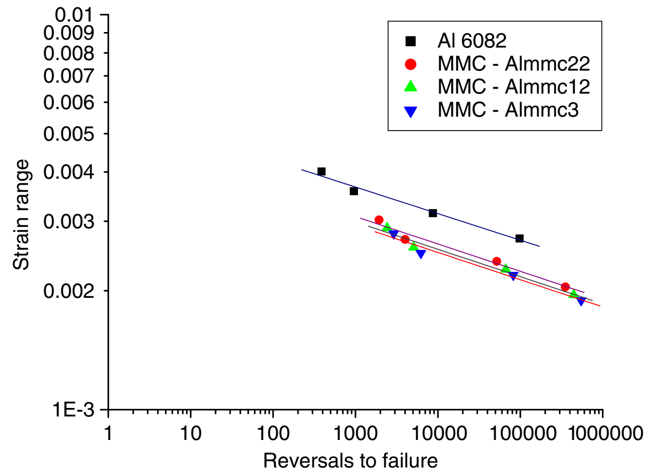


Fig. 12 Cyclic strain–fatigue life response of Al 6082/SiC$_p$ composites in forged condition—variation of particle size

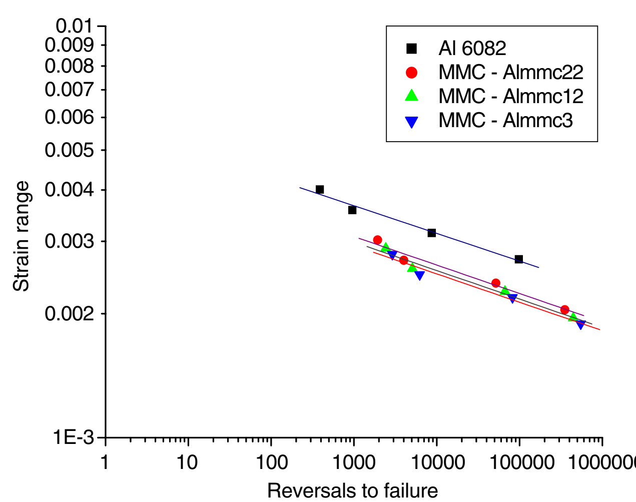


Fig. 13 Cyclic strain–fatigue life response of Al 6082/SiC$_p$ composites in aged condition—variation of particle size

The presence of particulate reinforcements results in the development of localised stresses results from constraints in matrix deformation around the reinforcing particles. The highly localised stresses contribute to the observed work-hardening behaviour of the composites. The concentration of the localised stresses results from constraints in matrix deformation that occur because of the significant difference in elastic modulus of the constituents of the composite, i.e. the discontinuous particulate-reinforcement and continuous phases and the continuous aluminium alloy metal matrix [10–24].

The constraint results in the development of a triaxial stress state and steep stress gradients in the matrix around the reinforcing silicon carbide particles. The localised stress results in localised deformation. As the stress in the composite matrix increases, the volume of material that is deformed increases. The cyclic strain fatigue life of the matrix and the composites is shown in Figs. 11, 12 and 13.

6 Summary and conclusions

The influence of change in SiC_p size on the mechanical and fatigue properties of the forged aluminium6082 metal matrix composites with three different sizes of silicon carbide particles were studied. Based on the analysis, the following points may be concluded

1. The density and porosity of the as-cast samples slightly increase with the decrease in size of the SiC_p particles, and density of the samples is increased with the secondary process forging, and the porosity of the samples is decreased.
2. A slight increase in hardness is found with the decrease in SiC_p particle size and shows a marked increase due to forging and ageing process.
3. The proof stress and elastic constant increases with the decrease in SiC_p particle size, and the forging and ageing increases the strength and ductility of the composites.
4. The number of cycles for the fatigue failure of the composites increases with the decrease in particle size of the SiC_p.

The increase in strength of the composites due to the decrease in size of the SiC_p particles may be attributed to the increase in strain energy of the composites and increase in availability of the particles per unit volume of the composites. The remarkable changes in the properties due to secondary processing may be attributed to the changes in the microstructure of the matrix and the composite material.

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