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REVIEW ARTICLE Open Access

Properties of ceramic-reinforced aluminium matrix composites - a review

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Abstract

A review of various properties of ceramic-reinforced aluminium matrix composites is presented in this paper. The properties discussed include microstructural, optical, physical and mechanical behaviour of ceramic-reinforced aluminium matrix composites and effects of reinforcement fraction, particle size, heat treatment and extrusion process on these properties. The results obtained by many researchers indicated the uniform distribution of reinforced particles with localized agglomeration at some places, when the metal matrix composite was processed through stir casting method. The density, hardness, compressive strength and toughness increased with increasing reinforcement fraction; however, these properties may reduce in the presence of porosity in the composite material. The particle size of reinforcements affected the hardness adversely. Tensile strength and flexural strength were observed to be increased up to a certain reinforcement fraction in the composites, beyond which these were reduced. The mechanical properties of the composite materials were improved by either thermal treatment or extrusion process. Initiation and growth of fine microcracks leading to macroscopic failure, ductile failure of the aluminium matrix, combination of particle fracture and particle pull-out, overload failure under tension and brittle fracture were the failure mode and mechanisms, as observed by previous researchers, during fractography analysis of tensile specimens of ceramic-reinforced aluminium matrix composites.

Keywords: Aluminium matrix composites; Optical; Physical; Mechanical; Properties

Review

Introduction

Ceramic-reinforced aluminium matrix composite materials are well known for their high strength-to-weight ratio, superior tribological properties and corrosion resistance behaviour, for which they are replacing their monolithic alloys in the field of automobile, marine and aviation engineering. Since the last three decades, researchers have shown their interest in these materials and are trying to improve their property to make them suitable for use in complex areas.

The strength of composite materials depends upon composition, grain size, microstructure and the fabrication process. The objective of this paper is to review the effect of the fabrication process on particle distribution and the effect of reinforcement fraction, particle size, heat treatment and extrusion process on physical and mechanical properties of ceramic-reinforced Al matrix composites, as experienced by previous researchers.

Optical and physical properties

Srivatsan and Prakash (1995) observed a near-uniform distribution of the silicon carbide (SiC) particles in the three orthogonal directions and seldom an agglomeration of the SiC particles, during optical microscopy of Al 2080/SiC composites, produced by dry blending techniques. The size of SiCp reinforcement phase was nearly uniform, and very few of the particles were irregularly shaped and these were dispersed randomly throughout the matrix. The degree of agglomeration was found to be largely unaffected by an increase in the particle reinforcement phase. Manoharan and Gupta (1999) observed the presence of equiaxed grains in both as-cast and extruded AA 1050/SiC composite samples, produced by disintegrated melt deposition (DMD) technique. Pronounced refinement in the grain size, significant reduction in the porosity levels, more uniform distribution of the SiC particulates and improvement in matrix-reinforcement interfacial

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integrity were observed in extruded samples as compared to that in the as-processed condition. Cocen and Onel (2002) reported that the microstructures of the Al/SiC as cast composites, produced by melt stirring technique, exhibit a fairly uniform distribution of SiC particulates with some regional clusters and contain some porosity; however, for extruded samples, the clusters of SiC particulates disappeared and the porosity content was substantially reduced to very low levels. Some pores were observed with a light microscope in high reinforcement-containing composites. The extruded materials possessed reduced number of the particles of eutectic Si and other phases, indicating the coarsening of particles to a certain extent. Borrego et al. (2002), while investigating the microstructure of extruded Al 6061 alloy and SiC whisker-reinforced Al 6061 composite samples, synthesized by powder metallurgy route, through optical and scanning electron microscopies, observed that the grains in the un-reinforced alloy were slightly elongated due to extrusion process and were also aligned in bands which are parallel to the extrusion axis. A very homogeneous distribution of $SiC_{whisker}$ was obtained at high extrusion temperature, whereas some trend to clustering was observed at lower extrusion temperature. X-ray texture measurement indicated equiaxed grain morphology in the transverse sections, which confirmed the alignment of the aluminium grains with the extrusion axis. The texture of the aluminium phase of these materials comprised two well-defined fibre texture components, i.e. <111> and <100>. Kalkanli and Yilmaz (2008), through optical micrographs, observed a homogeneous distribution of SiC particulates, some agglomeration and no evidence of porosity in SiCp-reinforced AA 7075 matrix composites, fabricated using vertical pressure casting or squeeze casting technique. Figure 1 shows the optical micrographs of 10, 15 and 20 weight fractions of SiC particles (average particle size of 29 μm) in Al 7075 alloy matrix.

Rao et al. (2010) observed dendrites of aluminium and precipitates along the inter-dendritic regions in the as-cast Al-Zn-Mg-Cu alloy. A uniform distribution of SiC particles in the Al matrix was observed in the scanning electron micrograph of Al 7009/SiC composites, prepared through solidification processing (stir casting) route. The interface bonding between the aluminium matrix and SiC particles was observed with a higher magnification micrograph. Major peaks of aluminium and minor peaks of the α-moissanite form of SiC particles and those of intermetallic phases such as $MgZn_2$ and $AlZn_2$ were observed in the X-ray diffractogram of the composite (Figure 2).

Veeresh Kumar et al. (2010) observed a uniform distribution of reinforcing particles in Al 6063-SiC and Al 7075-Al_2O_3 composites, processed through liquid metallurgy route (Figure 3).

A uniform distribution of SiC particles was observed in AA 7075/SiC composite, fabricated using stir casting method, at a stirring speed of 650 rpm and stirring time of 10 min (Bhushan and Kumar 2011). Vanarotti et al. (2012) observed a homogeneous distribution of SiC particles in

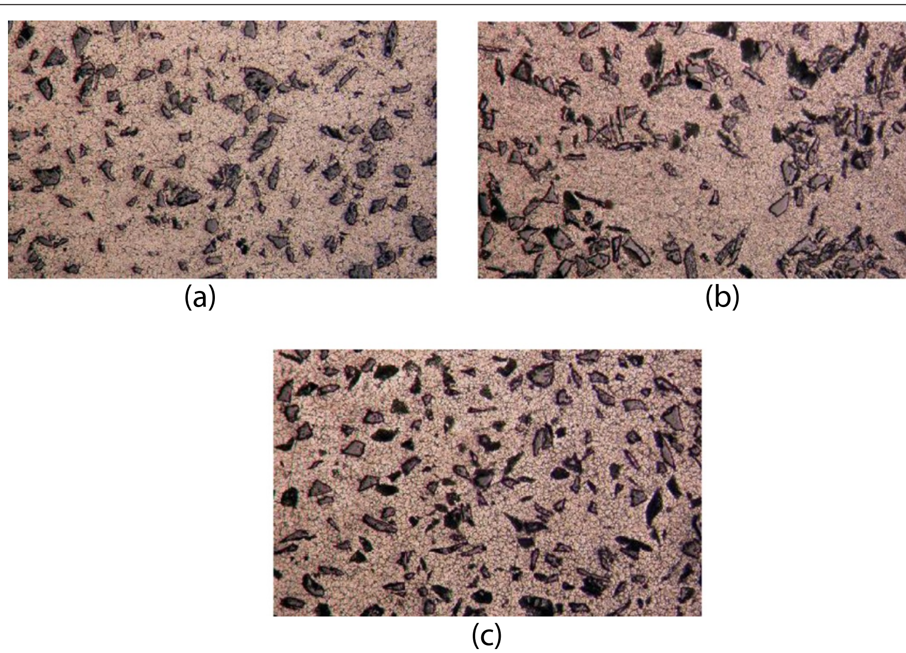

Figure 1 Optical micrographs of SiCp reinforced Al 7075 matrix composites with the weight fractions of (a) 10%; (b) 15%; and (c) 20% (Kalkanli and Yilmaz 2008).

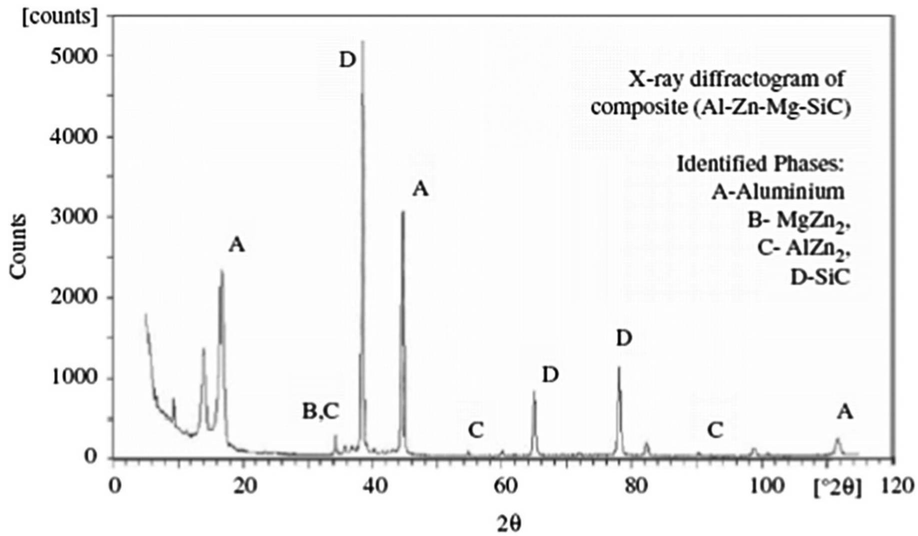

Figure 2 X-ray diffractogram of Al 7009/SiC composite (Rao et al. 2010).

the cast Al 356/SiC (5 and 10 wt.%) composites, fabricated by stir casting technique, under a metallurgical microscope. The particles showed a strong tendency to accumulate in the colonies which froze in the last stage of solidification and contained eutectic phases, and the SiC particles were also observed to be accommodated on the grain boundaries. During microstructural investigation of SiC-reinforced Al 6063 matrix composites using a metallurgical microscope, Alaneme and Aluko (2012) observed that the volume percent of SiC did not influence its pattern of distribution either in the as-cast condition or in the heat-treated (solution treatment followed by age hardening) condition. Microstructural features of bamboo leaf ash (BLA)- and SiC-reinforced Al-Mg-Si alloy hybrid composites, fabricated by a two-step stir casting process, revealed good distribution of the reinforcing particles in the matrix with minimal particle clusters (Alaneme et al. 2013). Boopathi et al. (2013) observed non-uniformity in the distribution of reinforced particles in the case of Al-SiC and Al-fly ash composites; however, their uniform distributions were observed in the micrographs of Al-SiC-fly ash hybrid composite, fabricated by stir casting technique. Umanath et al. (2013) observed a uniform distribution of ceramic reinforcements in Al 6061/SiC/Al_2O_3-T6 heat-treated hybrid metal matrix composites, processed by stir casting method.

Sahin and Murphy (1996) determined the density of SiC-coated unidirectional boron fibre-reinforced Al 2014 matrix composites by the Archimedean method and observed that the density decreased linearly with the increase in volume percentage of reinforcement (Figure 4).

Manoharan and Gupta (1999) measured the density of SiC-reinforced AA 1050 as-cast and extruded composite samples by the Archimedes principle and observed that the density increased with the weight percentage of reinforcement. Theoretical densities were calculated using the rule of mixtures and then these were compared with the experimental densities, from which the volume fractions of porosity were calculated. Porosity was found to be maximum (1.2%) for the composite with 8 wt.% of SiC.

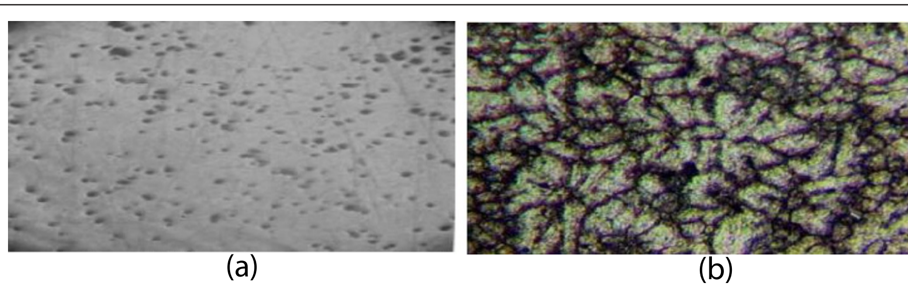

Figure 3 Microphotographs at ×200 magnification for (a) Al 6061-6% SiC and (b) Al 7075-6% Al_2O_3 composites (Veeresh Kumar et al. 2010).

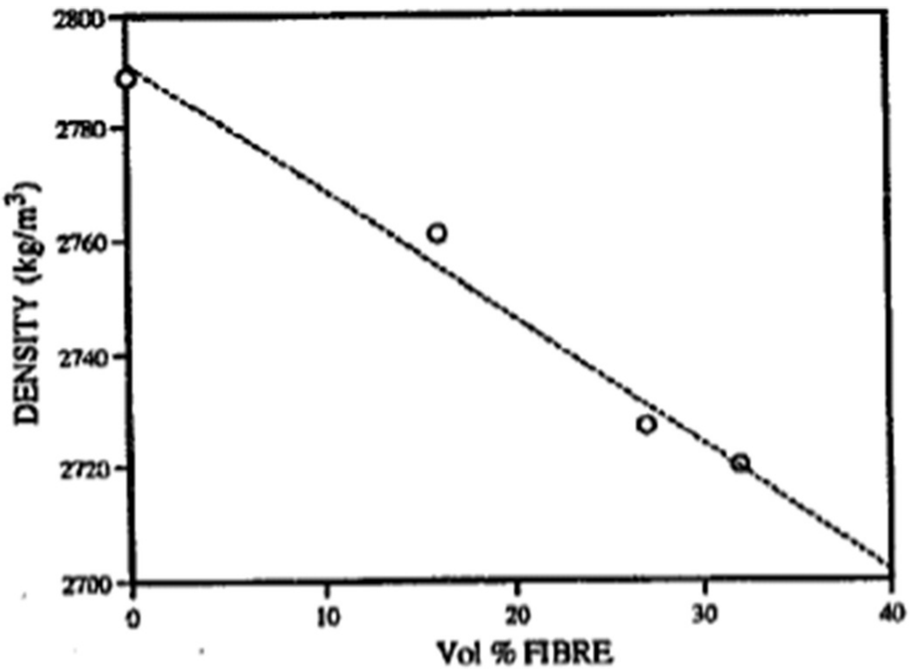

Figure 4 Variation of density with vol.% fibre (Sahin and Murphy 1996).

Table 1 represents the results of the density and porosity of SiC-reinforced AA 1050 matrix composites.

Cocen and Onel (2002) evaluated the porosity content of a SiC/Al-5%Si-0.2% Mg composite sample from the difference between the calculated density and experimentally observed density. It was reported that the composite in the as-cast condition contained some porosity, which was reduced in the extruded condition. Demir and Altinkok (2004) evaluated the density and porosity of a dual-ceramic (Al_2O_3 and SiC)-reinforced Al composite by the Archimedes principle and reported that the relative density increases with both infiltration temperature and pressure. The density of aluminium matrix composites increased with reinforcement fraction, and the density of Al 7075-Al_2O_3 composites was observed to be more as compared to that of Al 6063-SiC composites for the same reinforcement content (Veeresh Kumar et al. 2010). Figure 5 represents a comparison of experimental densities of Al 6061-SiC and Al 7075-Al_2O_3 composites for different fractions of filler contents.

Rao et al. (2010) observed that the density of the Al 7075 alloy was higher than that of the SiC-reinforced Al 7075 composite even though the density of SiC is higher than that of the alloy, which may be due to increased porosity in the composites. Purohit et al. (2012) reported that the theoretical densities of Al-SiCp composites increased with the weight fraction of SiCp from 5% to 30% because the SiC particulates possess higher density than aluminium. However, the measured density of Al-SiCp composites did not increase with the weight fraction of SiCp because of the increase in porosity. Figure 6 represents a comparison between measured and theoretical densities of un-sintered Al-SiCp composites.

Table 1 Density and porosity of SiC-reinforced AA 1050 matrix composites (Manoharan and Gupta 1999)

Material	Density (g cm^{-3})	Porosity (vol.%)
Al-6 wt.% SiC	2.71 ± 0.03	0.9
Al-8 wt.% SiC	2.72 ± 0.02	1.2
Al-17 wt.% SiC	2.75 ± 0.07	0.8

Veeresh Kumar et al. (2012) observed that the density of Al 7075-SiC composites increased with SiC contents and was in line with the values obtained by the rule of mixtures. Alaneme et al. (2013) evaluated the percent porosity of BLA- and SiC-reinforced hybrid Al composites by comparing their theoretical and experimental densities. The experimental density was determined by dividing the measured weight of the test sample with its volume, while the theoretical density was evaluated by using the rule of mixtures. The density of the cast composites was observed to be reduced with the increase in BLA content; however, the percent porosity did not show any significant trend with the increase in BLA content. For all the cast composites, the percent porosity was within the acceptable limiting value of 4%. Boopathi et al. (2013) reported that in the presence of silicon carbide and fly ash in aluminium, the density of hybrid composites decreased. Umanath et al. (2013) observed more porosity around Al_2O_3 particle reinforcement as compared to the location around SiC

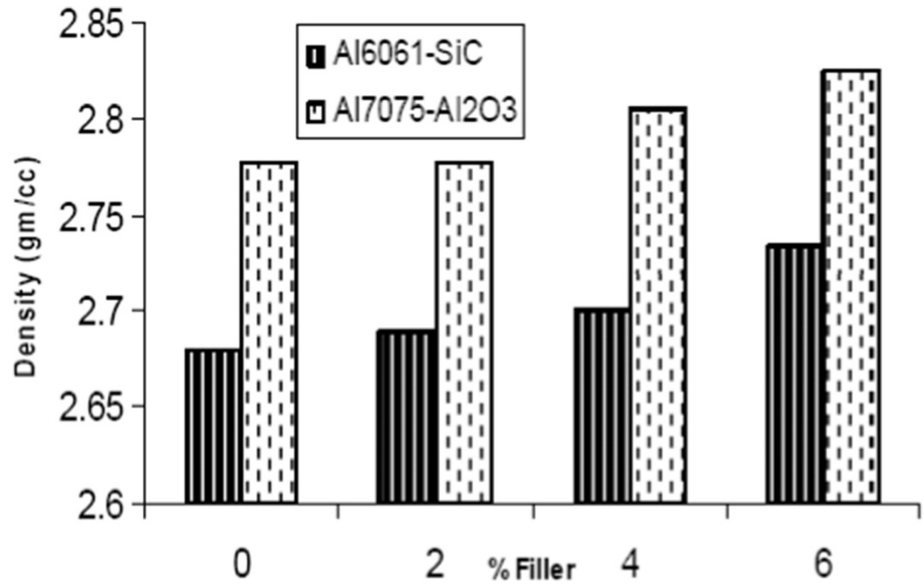

Figure 5 Density of Al6061-SiC and Al7075-Al2O3 composites (Veeresh Kumar et al. 2010).

particle reinforcement in Al 6061/SiC/Al_2O_3-T6 heat-treated hybrid metal matrix composites. It was also reported that the porosity of the specimens increased with increasing volume fractions of the particulate reinforcement.

Mechanical properties

Hardness

While investigating the effect of thermal ageing temperature on hardness of SiCp-reinforced 6061 Al and 2014 Al matrix composites, Song et al. (1995) observed an increase in hardness with ageing temperature, and maximum hardness was reached at 150°C to 200°C, and the composites containing 2014 Al were much harder than those with 6061 Al. A significant loss of hardness in all composites was observed upon increasing the ageing temperature up to 250°C. Sahin and Murphy (1996) measured the Brinnell hardness of Al 2014 alloy and that of SiC-coated unidirectional boron fibre-reinforced Al 2014 matrix composites and reported that the hardness increased linearly with increased volume percentage of reinforcements. Fang et al. (1997) observed that an *in situ* formed Al composite had low Vickers hardness owing to some reaction contamination and higher porosity. Jayaram and Biswas (1999) reported that porosity was the major influencing factor for the hardness of Al_2O_3 and SiC-reinforced Al composites. The hardness of the composite was observed to be decreased with the increase in porosity. While comparing Vickers hardness for both the as-cast and heat-treated SiC

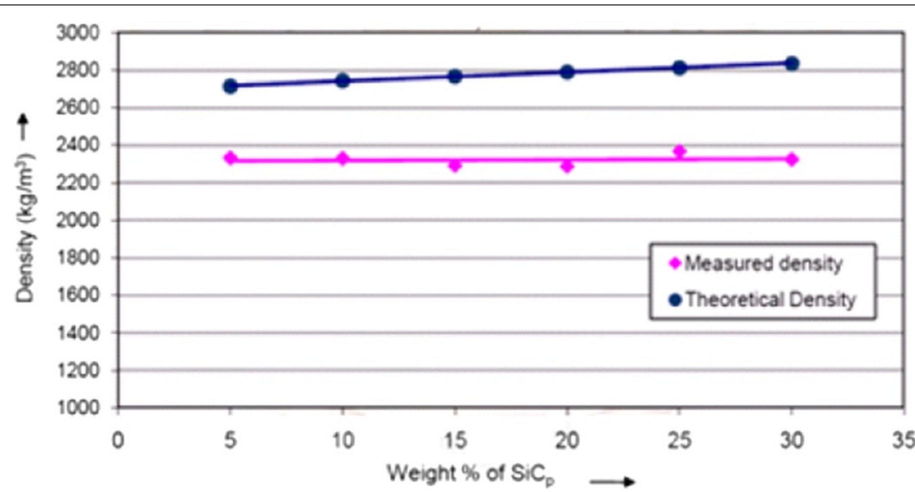

Figure 6 Comparison between measured and theoretical densities of un-sintered Al-SiCp composites (Purohit et al. 2012).

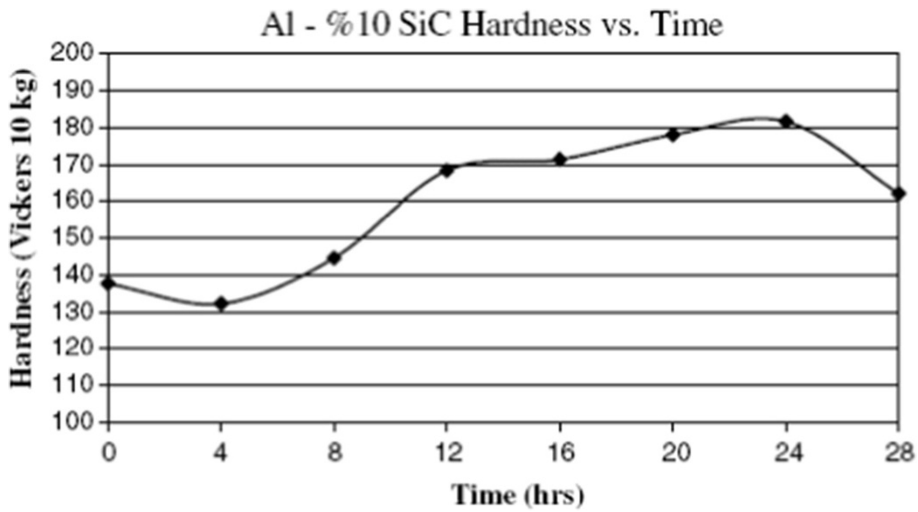

Figure 7 **Variation of hardness values of Al-10 wt.% SiCp composite with artificial ageing time (Kalkanli and Yilmaz 2008).**

(average particle size of 29 μm)-reinforced Al 7075 composites containing different weight percent of reinforcements, Kalkanli and Yilmaz (2008) reported the maximum hardness obtained for the composite with 24-h precipitation heat treatment at 120°C with 10 wt.% SiC. Figure 7 represents variation of Vickers hardness values of Al-10 wt.% SiCp composite with artificial ageing time.

Veeresh Kumar et al. (2010) reported that the micro-hardness (HV) of Al 6063-SiC and Al 7075-Al_2O_3 composites increased with the percentage of filler addition and that of Al 7075-Al_2O_3 composites was observed more as compared to that of Al 6063-SiC composites. Figure 8 shows a comparison of the micro-hardness of Al 6061-SiC and Al 7075-Al_2O_3 composites.

Rao et al. (2010) observed that Vickers hardness of both Al-Zn-Mg (Al 7009) alloy and SiC-reinforced Al-Zn-Mg (Al 7009) composite improved by heat treatment and with the increase in percentage of SiC reinforcement in the matrix alloy. (Bhushan and Kumar 2011) reported that hardness increased by 10.48% with the increase in percentage of SiC reinforcement from 5 to 15 wt.% in AA 7075/SiC composite. Purohit et al. (2012) observed that the Rockwell hardness of Al-SiCp composites increased with the increase in weight fraction of SiCp from 5 to 30 wt.% of SiCp. Figure 9 shows the Rockwell hardness of Al-SiCp composites fabricated using un-ball-milled and ball-milled powders.

Suresha and Sridhara (2012) observed that the Brinell hardness of LM 25-SiC-Gr hybrid composites increased up to 2.5% of combined equal percentage of reinforcement and then decreased (Figure 10). The increase was due to the addition of SiC particulates, overriding the effect of Gr

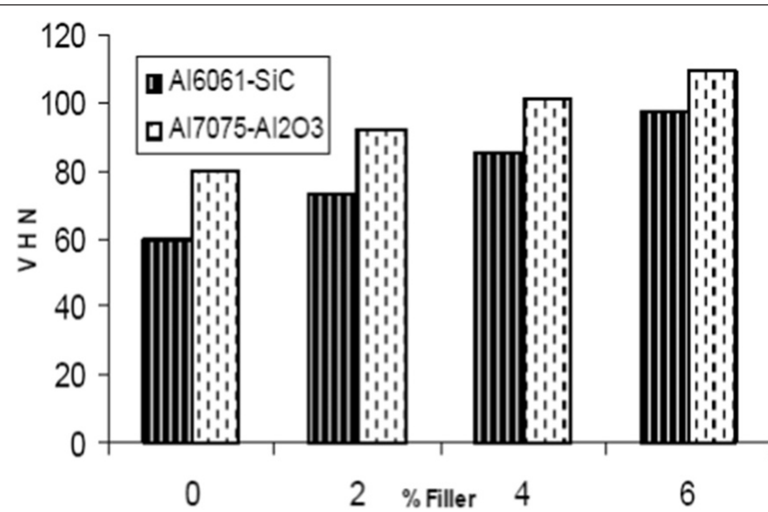

Figure 8 **Micro-hardness of Al6061-SiC and Al7075-Al_2O_3 composites (Veeresh Kumar et al. 2010).**

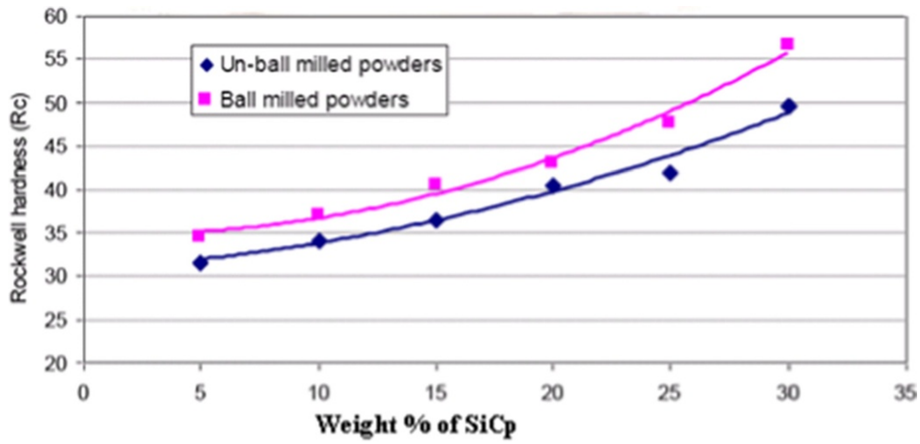

Figure 9 Rockwell hardness of isostatically pressed Al-SiCp composites (Purohit et al. 2012).

particulates, and the decrease was due to the overriding effect of Gr particulates, the addition of which reduced hardness as a consequence of the increase of porosity. However, Uvaraja and Natarajan (2012) reported that the Rockwell hardness of Al 7075/SiCp/B_4C hybrid metal matrix composite (MMC) increased with the volume fraction of the particle reinforcement.

Ravesh and Garg (2012) reported that the hardness of fly ash-SiC-reinforced hybrid aluminium composites increased with increasing volume fraction reinforcements. The Rockwell hardness on the C scale was observed to be 61, 70, 81 and 93 for 2.5%, 5%, 7.5% and 10% of SiC, respectively, with a constant 5% fly ash-reinforced hybrid Al 6061-T6-treated hybrid matrix composites. The hardness of the Al 7075-SiC composite was found to be increased with the increased volume percentage of ceramic particles (Veeresh Kumar et al. 2012). Deshmanya and Purohit (2012) observed that the hardness of Al 7075-Al_2O_3 composites consistently decreased with the increase in size of reinforcement (Figure 11a), which is due to the fact that a higher grain size results in a less dense distribution of Al_2O_3 particulates in the aluminium matrix. The hardness of the composite was reported to be reduced initially with the increase in percent of reinforcement; however, there was a substantial improvement of hardness after about 8% of reinforcement addition (Figure 11b), and a maximum value of hardness (140 VHN) was observed for the composite containing 15% of Al_2O_3.

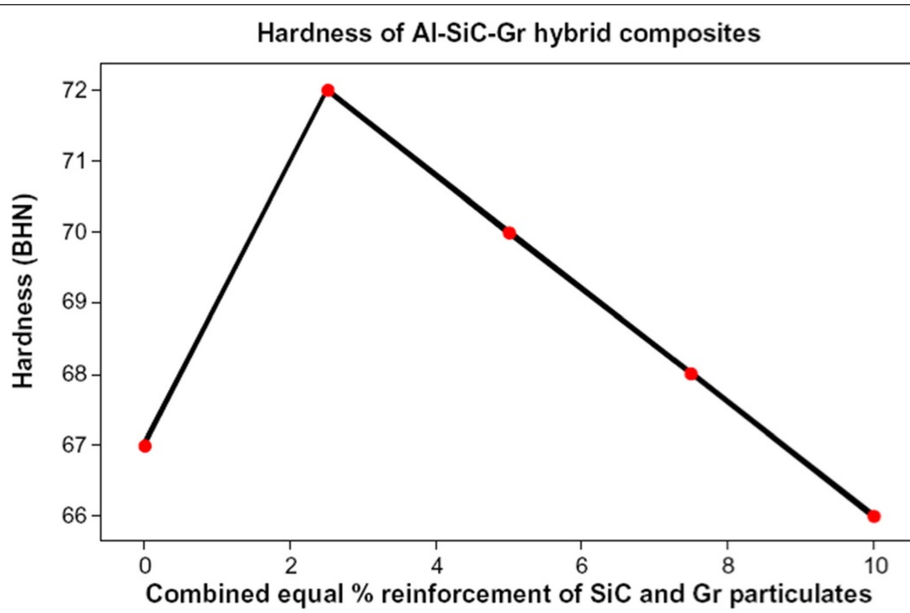

Figure 10 Effect of percentage of reinforcement on the hardness of Al-SiC-Gr hybrid composites (Suresha and Sridhara 2012).

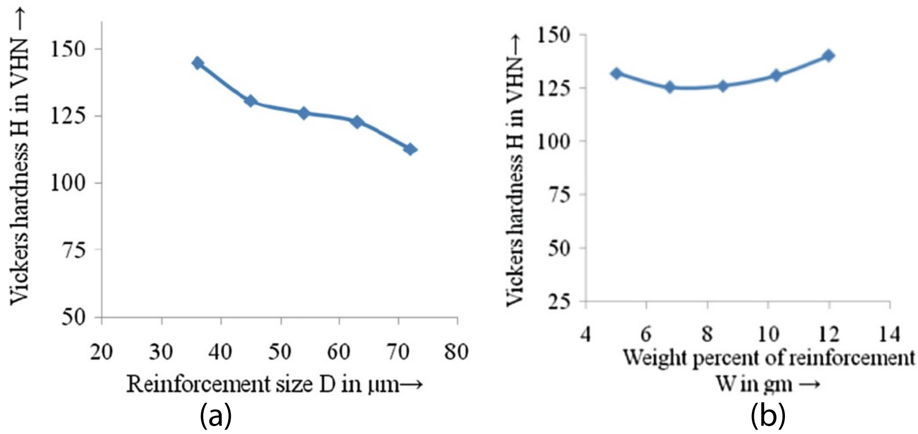

Figure 11 Variation of the hardness of Al 7075-Al_2O_3 composites with (a) reinforcement size and (b) weight percent (Deshmanya and Purohit 2012).

With the increase in reinforcement content, the ratio of reinforcement-to-matrix becomes richer, which imparts increased hardness to the composite.

Vanarotti et al. (2012) observed that the Brinell hardness number of Al 356/SiC composite increased with the increasing weight fraction of SiC reinforcement in the matrix alloy. The BHN was observed to be 70 and 78 for 5 and 10 wt.% of SiC reinforcement, respectively. Alaneme et al. (2013) reported that the hardness of SiC- and bamboo leaf ash-reinforced Al alloy hybrid composites decreased with the increase in BLA content. Boopathi et al. (2013) evaluated the Brinell harness number of Al-SiC, Al-fly ash and Al-SiC-fly ash metal matrix composites and reported that aluminium in the presence of 10% of SiC and 10% of fly ash was the hardest instead of Al-SiC and Al-fly ash composites.

Tensile strength and ductility

Young's modulus, yield stress, ultimate tensile strength and fracture stress of heat-treated SiCp-reinforced Al 2080 matrix composites were improved; however, percent elongation, percent reduction of area and tensile ductility were reduced with increasing reinforcement content, as reported by Srivatsan and Prakash (1995). Fractography analysis revealed that the presence of the hard and brittle SiC particles in the soft and ductile metal matrix caused initiation of fine microcracks at low values of applied stress. The microcracks had grown rapidly, resulting in macroscopic failure and low tensile ductility. Sahin and Murphy (1996) observed that the tensile strength of SiC-coated unidirectional boron fibre-reinforced Al 2014 matrix composites was in the range of 312 to 524 MPa, whereas that of the alloy was 172 MPa. Xu et al. (1997) reported that the ductility of as-cast SiCp-reinforced Al 359 matrix composites increased greatly by the hot isostatic pressing (HIP) treatment but the yield stress reduced drastically. The reduction of internal defects due to HIP treatment was the major cause for the improvement of ductility. The T6 heat-treated and hot-isostatic-pressed specimens were better with respect to both strength and ductility, as compared to the as-cast specimens. Lu et al. (1999) observed a maximum flow stress value of 450 MPa during dynamic tensile tests of SiCp/Al-5% Cu composites at the strain rate of 1×10^3 s^{-1}. Fractured surface studies indicated that the failure of the composite was controlled by ductile failure of the aluminium matrix, which was due to the nucleation, growth and coalescence of voids. Manoharan and Gupta (1999) reported that the ultimate tensile stress was increased and fracture strain was reduced with the increase in reinforcement content in the as-processed and extruded SiC-reinforced AA 1050 matrix composites. The yield strength first improved and then reduced with the increase in SiC content in the composite (Table 2).

Ravi Kumar and Dwarakadasa (2000), while investigating the effect of matrix strength on the tensile properties of SiC-reinforced Al-Zn-Mg alloy matrix composites, observed that the yield strength increased in the solution-annealed condition (485°C/90 min), but decreased in both peak-aged (135°C/16 h) and over-aged (170°C/36 h) conditions with the increase in volume percent of reinforcement. The ultimate tensile strength (UTS) and percent elongation reduced with the increase in volume fraction of SiC

Table 2 Room temperature mechanical properties of the extruded SiC/AA 1050 composite samples (Manoharan and Gupta 1999)

Material	YS (MPa)	UTS (MPa)	Experimental fracture strain	Calculated fracture strain
Al-6 wt.% SiC	93.8 ± 6.2	104.4 ± 5.1	0.17 ± 0.08	0.165
Al-8 wt.% SiC	97.4 ± 3.6	113.3 ± 2.8	0.16 ± 0.02	0.154
Al-17 wt.% SiC	80.5 ± 2.3	120.3 ± 7.9	0.10 ± 0.01	0.106

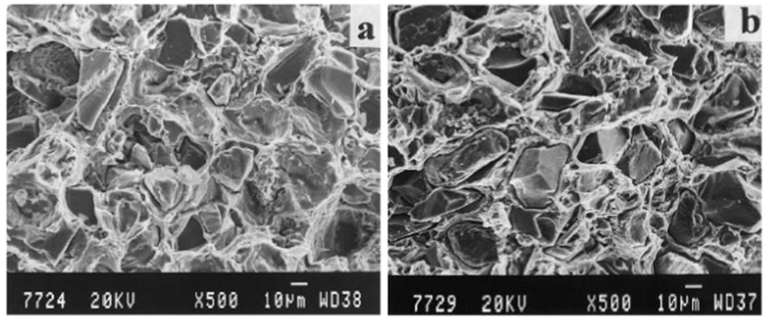

Figure 12 Secondary electron micrographs of tensile fracture in 18% composite in different tempers: (a) solution annealed and (b) peak aged (Ravi Kumar and Dwarakadasa 2000).

for all the three conditions, i.e. SA, PA and OA. Both yield strength and ultimate tensile strength reduced with the increase in SiC particle size for the T6-conditioned composite. Combination of particle fracture and particle pull-out was reported to be the fracture mechanism. The lack of interfacial strength was due to factors such as Al-SiC reaction, partial wetting of particles and the presence of constituent particles at the interface. Figure 12 presents secondary electron micrographs of tensile fracture in 18% composite in solution-annealed and peak-aged conditions.

Cocen and Onel (2002) reported that the yield strength and tensile strength of Al/SiCp composite samples in the as-cast condition increased up to 17 vol.% of SiCp and then reduced. These values improved by 40% for extruded samples and increased continuously with the volume fraction of reinforcement. The ductility of as-cast composites decreased with the increase in volume fraction of SiC, and with application of extrusion, improvement in ductility was observed. While comparing the tensile strength of both as-cast and T6 heat-treated SiC-reinforced Al 7075 composites, Kalkanli and Yilmaz (2008) reported the maximum tensile strength obtained for the T6 heat-treated composite with 10 wt.% SiC. Figure 13 represents a comparison of tensile test results for both the as-cast and heat-treated SiC-reinforced Al 7075 matrix composites.

Veeresh Kumar et al. (2010) reported that the tensile strength of Al 6063-SiC and Al 7075-Al_2O_3 composites increased with the percentage of filler addition and that of Al 7075-Al_2O_3 composites was observed more as compared to Al 6063-SiC composites. The tensile strength of AA 7075/SiC composite was increased by 12.74% with the increase in percentage of SiC reinforcement from 5 to 15 wt.% (Bhushan and Kumar 2011). Purohit et al. (2012) reported that the indirect tensile strength of Al-SiCp increased with the increase in weight percent of SiCp from 5 to 30, which was due to the increase in the modulus of elasticity and the elastic limit of the material. Figure 14 presents a remarkable increase in the indirect tensile strength with the increase in reinforcement content up to 20 wt.%; however, a very small increase was observed beyond 20%. This was

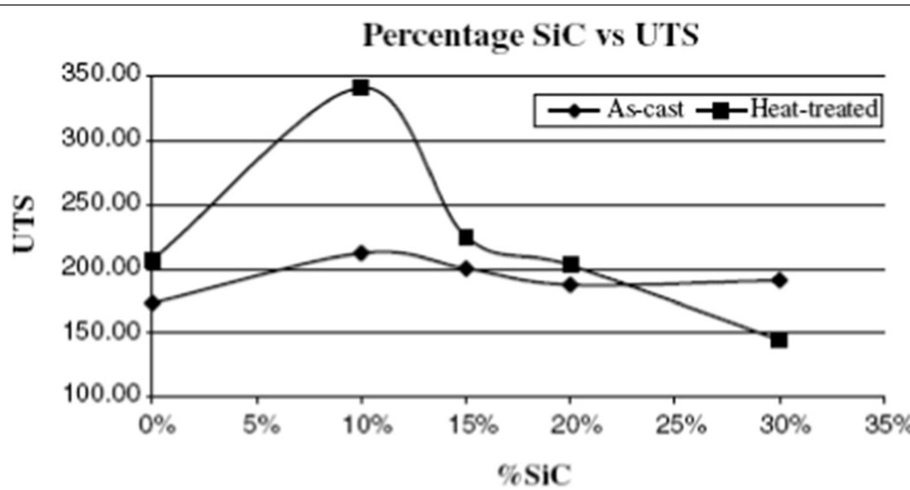

Figure 13 Tensile test results of as-cast and heat-treated SiC-reinforced Al 7075 matrix composites (Kalkanli and Yilmaz 2008).

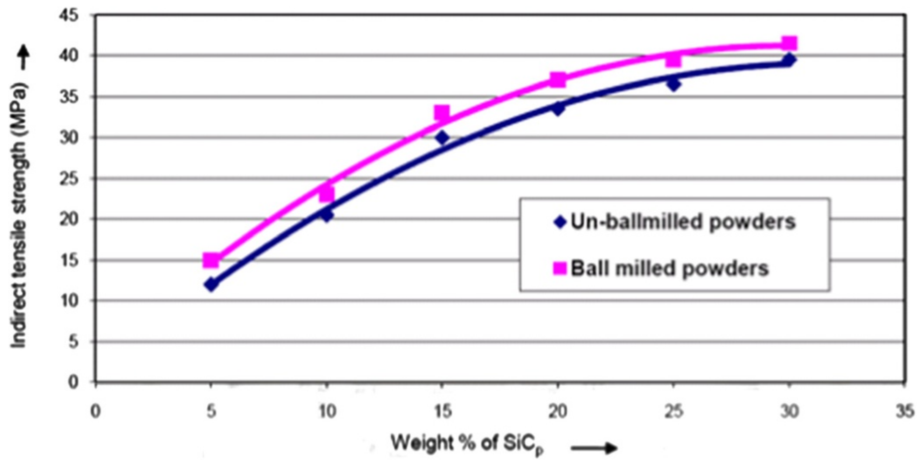

Figure 14 Indirect tensile strength of Al-SiCp composite (Purohit et al. 2012).

due to the brittleness of the material at higher percentage of SiCp.

The tensile strength of Al7075-SiC composites was found to be increased by increasing the volume percentage of ceramic phase at the cost of reduced ductility (Veeresh Kumar et al. 2012). Sanjay Kumar et al. (2012) observed that corrosion environments reduced the mechanical strength of Al 6061 alloy and its SiC-reinforced composites and drop in ultimate tensile strength was lower in the composite as compared to the matrix alloy, under the exposure of 3.5% NaCl solution for same duration of time. Ravesh and Garg (2012) reported an improvement in tensile strength and reduction in ductility with the increase in weight percent of SiC in a SiC-fly ash-reinforced hybrid Al 6061 matrix composite. Vanarotti et al. (2012) observed that the UTS increased and percent elongation reduced with increasing weight fraction of reinforcement in the SiC/Al 356 matrix composite. The presence of dimples in the matrix alloy and 5 wt.% SiC-reinforced composite, during fractographic observations, indicated overload failure under tension, and the fractured surface displayed a dendritic structure, typical of castings. Inter-dendritic cavities were observed in a higher weight fraction (10%) of SiC-reinforced composites. Featureless regions in fractographs indicated brittle mode of fracture in localized regions possibly due to high hardness of the material. Alaneme and Aluko (2012) reported that the tensile strength and yield strength of SiC-reinforced Al 6063 composites increased with SiC content in both as-cast and age-hardened conditions (Figure 15), and ageing treatment improved its tensile strength (Figure 16). The strain to fracture was less affected by the volume fraction of SiC reinforcement and ageing treatment.

Alaneme et al. (2013) reported that ultimate tensile strength, yield strength, specific strength and percent elongation of SiC- and BLA-reinforced Al-Mg-Si alloy hybrid composites decreased with the increase in BLA content, and this trend was due to the presence of silica in the BLA, which has lower hardness and strength values in comparison with SiC. Boopathi et al. (2013) observed that

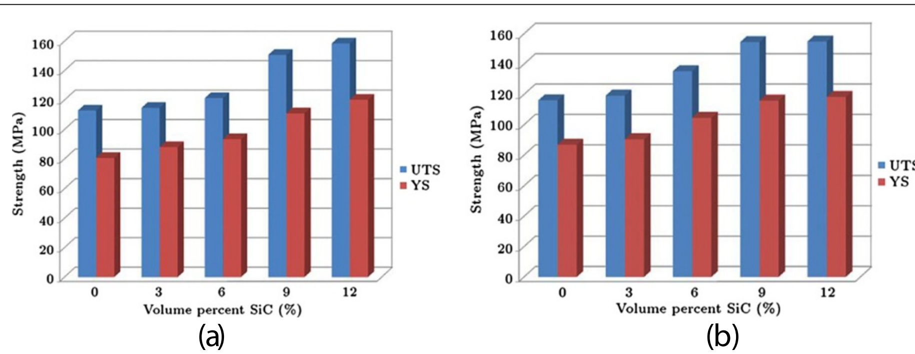

Figure 15 Effect of volume fraction of SiC on UTS and YS of SiC/Al 6063 composites in (a) as-cast and (b) age-hardened conditions (Alaneme and Aluko 2012).

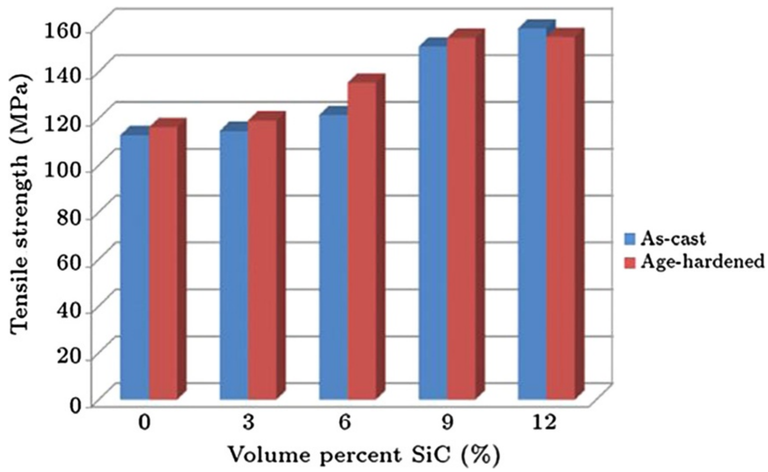

Figure 16 Effect of age hardening on the tensile strength of SiC/Al 6063 composites (Alaneme and Aluko 2012).

the presence of SiC and fly ash in Al 2024 alloy improved its tensile strength and yield strength, however reduced its ductility.

Compressive strength, flexural strength and toughness

Lu et al. (1999), during dynamic compression tests of SiCp/Al-5% Cu composites, reported that the yield stress increased from 180 to 220 MPa as the strain rates increased from 1×10^{-3} to 2.5×10^{3} s^{-1} (Figure 17).

Ravi Kumar and Dwarakadasa (2000), while investigating the effect of matrix strength on the compressive properties of SiC-reinforced Al-Zn-Mg alloy matrix composites, observed that the yield strength increased in both solution-annealed (485°C/90 min) and over-aged (170°C/36 h) conditions, but reduced in the peak-aged (135°C/16 h) condition with the increase in volume percent of reinforcement. Purohit et al. (2012) reported that the compressive strength of Al-SiCp composites, fabricated using ball-milled and un-ball-milled powders, increased with the increase in weight percent of SiCp (Figure 18).

Jayaram and Biswas (1999) determined rupture strengths of SiC (of particle sizes 8, 25, 35, 67, 129 and 218 μm)-reinforced Si-Zn-Mg-based Al matrix composite samples by the three-point bend test, which did not show any trend with the increase in particulate size, and it was found to be maximum (200 MPa) for the composites with SiC particle size of 25 and 67 μm. Demir and Altinkok (2004), during three-point bend tests of highly porous dual-ceramic (Al_2O_3/SiC)-reinforced Al matrix composites, produced by liquid aluminium infiltration and gas pressure infiltration technique, reported that the bending strength increased with dual-ceramic reinforcement up to 13 vol.%, beyond which it reduced (Figure 19). Also, it increased with infiltration temperature and pressure, and maximum

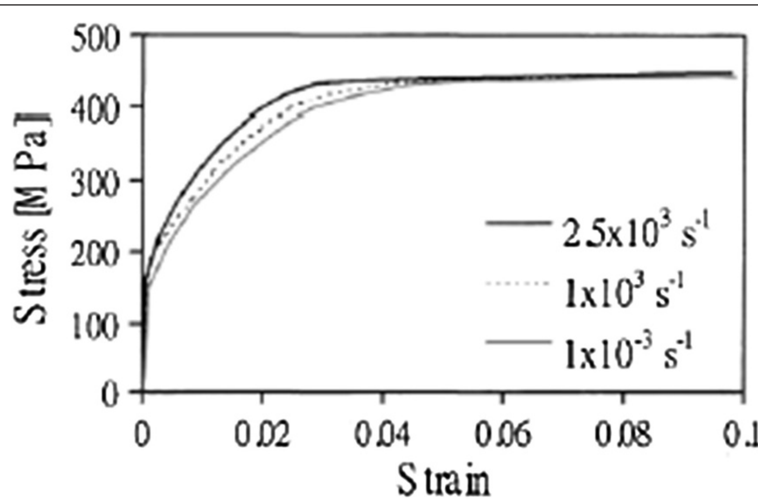

Figure 17 Compressive stress-strain responses of the SiCp/Al-5Cu composite at various strain rates (Lu et al. 1999).

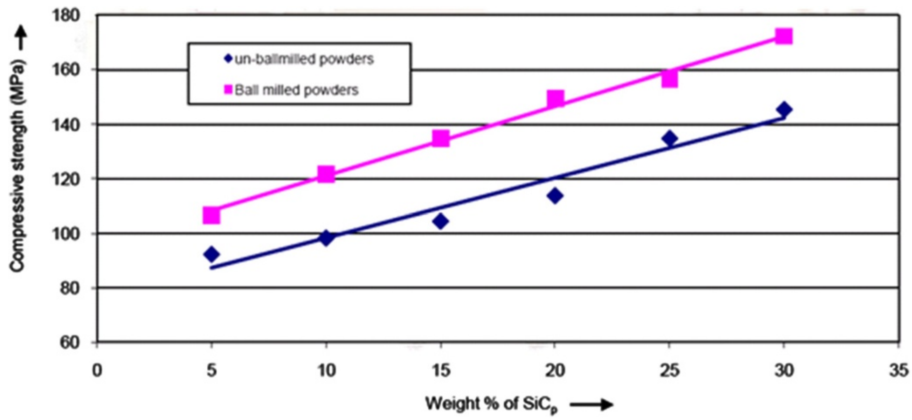

Figure 18 Compressive strength of Al-SiCp composites prepared using ball-milled and un-ball-milled powders (Purohit et al. 2012).

bending strength (558 MPa) was obtained for 13 vol.% dual-particle-reinforced Al matrix composites at the infiltration temperature and pressure of 800°C and 3 MPa, respectively (Figure 20).

Kalkanli and Yilmaz (2008), while studying the fracture behaviour of SiC-reinforced Al 7075 composites by the three-point bend test, reported that the flexural strength increased with increasing reinforcement content up to 10 wt.%, beyond which it reduced. At 10 wt.% reinforcement, the flexural strength of the composite was about 580 MPa, which reduced to 300 MPa for 30 wt.% SiC-reinforced composites (Figure 21).

(Ravesh and Garg 2012) reported that the toughness (impact strength, measured by the Izod impact test) of SiC-fly ash-reinforced hybrid Al 6061 matrix composites increased with the increase in weight percent of SiC (Table 3), which may be due to proper dispersion of reinforcements into the matrix or strong interfacial bonding between the matrix and reinforcement interfaces. The maximum value of toughness (7.8) was obtained for the composite containing 10 wt.% of SiC and 5 wt.% of fly ash.

Alaneme and Aluko (2012) determined the fracture toughness of SiC-reinforced Al 6063 composites using circumferential notch tensile (CNT) method and reported that the fracture toughness improved either by ageing treatment or by increasing the volume percent of SiC reinforcement (Figure 22).

Alaneme et al. (2013) reported that the fracture toughness of SiC- and BLA-reinforced hybrid Al-Mg-Si alloy composites improved with the increase in BLA content,

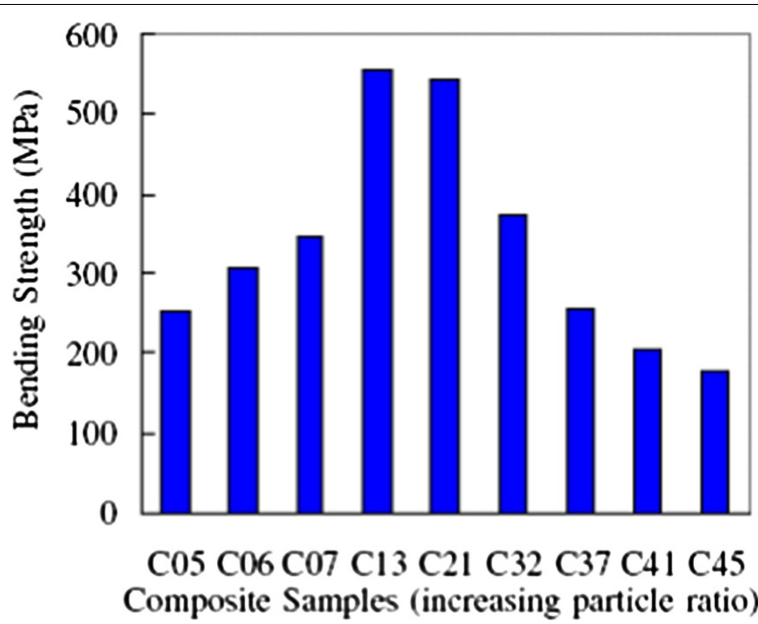

Figure 19 Effect of particle ratio on bending strength (Demir and Altinkok 2004).

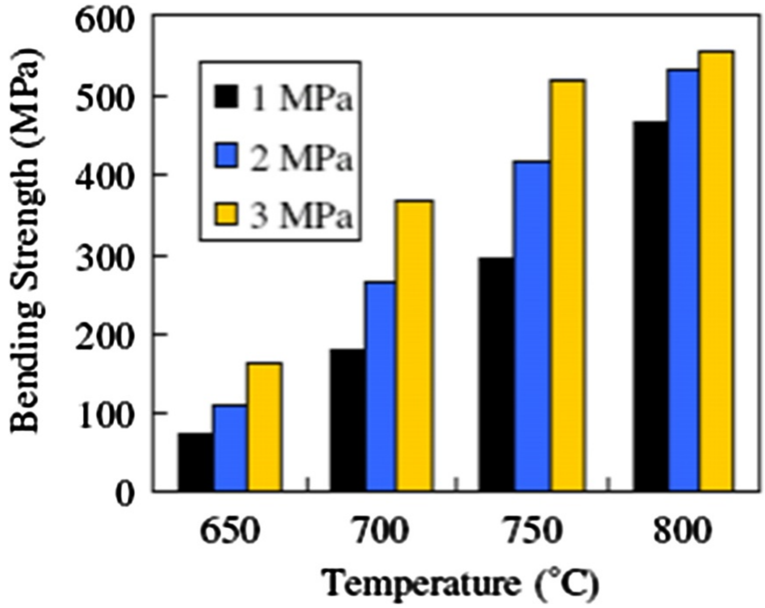

Figure 20 Effect of bending strength on infiltration temperature and pressure (Demir and Altinkok 2004).

which may be attributed to the increased presence of silica which is a softer ceramic in comparison with SiC. The fracture toughness of the hybrid composite was observed to be superior to that of the single reinforced Al-10 wt.% SiC composite.

Discussion

Specimen preparation is an important aspect for microstructural examinations of any metal, alloy or composite. The first step of specimen preparation is metallographic polishing, using emery cloths, ranging from coarse to very fine grades, and then by using diamond paste to get a mirror finish on the surface. For a detailed study of the microstructures and grain boundaries of the matrix or reinforcement, the polished sample is to be etched using some suitable etching agent. Kellor's reagent is used by most of the researchers (Cocen and Onel 2002, Rao et al. 2010 and many more) for etching; however, equal proportions of HNO_3 and HCl were used as etching agent by Alaneme et al. (2013).

Some researchers have observed only the uniformity in distribution of reinforced particles or whiskers in the matrix phase, whereas others have investigated thoroughly for the metallurgical aspects of metal matrix composites through a high-resolution microscope. It is easy to attain uniformity in distribution of reinforced particles in the matrix phase, when the MMC is developed through solid-state processing. However, solid-state processing is not economical and also not suitable for mass production, as compared to the stir casting method of processing of MMCs. One of the major challenges in composite fabrication is the uniformity in distribution of reinforced particles,

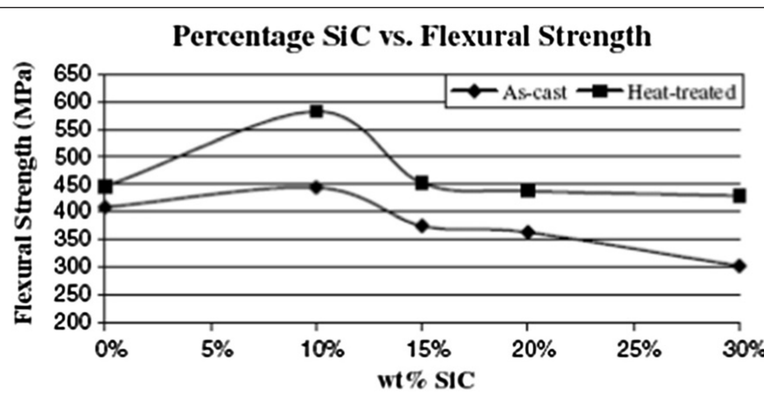

Figure 21 Flexural strength of as-cast and heat-treated SiC-reinforced aluminium matrix composite (Kalkanli and Yilmaz 2008).

Table 3 Izod test results of SiC-fly ash-reinforced hybrid Al 6061 matrix composites (Ravesh and Garg 2012)

Sample	SiC (wt.%)	Fly ash (wt.%)	Izod test result
Sample 1	2.5	5	6.0
Sample 2	5	5	6.6
Sample 3	7.5	5	7.1
Sample 4	10	5	7.8

which affects directly the properties and quality of the composite material (Singla et al. 2009). Some researchers claim the uniform distribution of reinforced particles with localized agglomeration at some places, when the MMC is processed through liquid metallurgy or stir casting method.

Most of the researchers have determined the density of MMCs using the Archimedes principle; however, some have also determined it by dividing the measured weight of the test samples with their volume. Theoretical density has been calculated using the rule of mixtures and percentage of porosity by comparing the experimental density with the theoretical density. In most of the cases, measured (experimental) density was found to be increased with reinforcement fraction (Manoharan and Gupta 1999; Demir and Altinkok 2004; Veeresh Kumar et al. 2012); however, Sahin and Murphy (1996), Purohit et al. (2012) and Alaneme et al. (2013) observed it to be reduced with the increase in reinforcement. Increased porosity in the composites was claimed as the basic reason for reduction of density with the increase in reinforcement content.

Researchers have determined the hardness of ceramic-reinforced aluminium matrix composites in various units, such as HV, HB, HRB and HRC. Most of the researchers observed the hardness to be improved with the increase in reinforcement fraction (Sahin and Murphy 1996; Veeresh Kumar et al. 2010; Rao et al. 2010; Bhushan and Kumar 2011; Purohit et al. 2012; Uvaraja and Natarajan 2012; Ravesh and Garg 2012; and many more); however, Suresha and Sridhara (2012) and Alaneme et al. (2013) observed the hardness to be reduced with the increase in reinforcement content in the composite, and the presence of porosity may be the reason for the reduction of hardness. The particle size of reinforcement had an adverse effect on hardness (Deshmanya and Purohit 2012). The hardness of ceramic-reinforced composites improved by heat treatment (Rao et al. 2010), ageing temperature (Song et al. 1995) and ageing time (Kalkanli and Yilmaz 2008).

From the open literature, it was observed that Young's modulus, yield stress, ultimate tensile stress and breaking (fracture) stress of ceramic-reinforced aluminium matrix composites were higher than those of their monolithic alloys and increased with the reinforcement fraction of ceramic materials; however, the ductility (percent elongation) of the composites reduced. Manoharan and Gupta (1999) observed that the yield strength first improved and then reduced with the increase in SiC content in the aluminium matrix composite. The particle size of reinforcing materials affected the yield strength and tensile strength of the composite adversely (Ravi Kumar and Dwarakadasa 2000). The tensile strength of the composite can be improved by thermal treatment (Xu et al. 1997; Kalkanli and Yilmaz 2008) or extrusion (Manoharan and Gupta 1999; Cocen and Onel 2002). However, ductility increased greatly and the yield stress

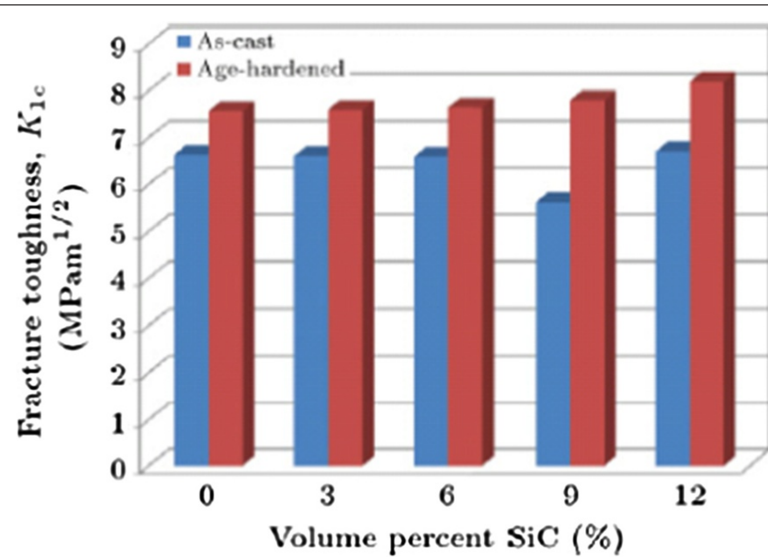

Figure 22 Variation of fracture toughness with the increase in vol.% SiC in the as-cast and age-hardened composites (Alaneme and Aluko 2012).

reduced drastically by HIP treatment of SiCp/Al 359 matrix composite (Xu et al. 1997).

The mechanism and mode of failure during tensile testing of aluminium matrix composites has been reported in various ways by different authors. Srivatsan and Prakash (1995) reported that initiation and growth of fine microcracks lead to macroscopic failure of the composite; however, Lu et al. (1999) observed that the failure of the composite was controlled by ductile failure of the aluminium matrix, and it was due to the nucleation, growth and coalescence of voids. Combination of particle fracture and particle pull-out was reported by Ravi Kumar and Dwarakadasa (2000) to be the fracture mechanism of the AMC. Vanarotti et al. (2012) reported that overload failure under tension was the fracture mechanism of the Al 356 matrix alloy and 5 wt.% SiC-reinforced Al 356 matrix composite; however, brittle fracture was observed for a higher weight fraction (10%) of SiC-reinforced Al 356 matrix composites.

Compressive strength was found to be increased with the increase in reinforcement fraction in the aluminium matrix composites (Ravi Kumar and Dwarakadasa 2000; Purohit et al. 2012) and with increasing strain rate during compression (Lu et al. 1999).

The flexural strength (bending strength) of ceramic-reinforced aluminium composites increased with increasing reinforcement content up to 10 wt.% (Kalkanli and Yilmaz 2008) and up to 13 vol.% (Demir and Altinkok 2004), beyond which it reduced.

The toughness (impact strength) of ceramic-reinforced aluminium matrix composites increased with the increase in reinforcement fraction (Ravesh and Garg 2012; Alaneme and Aluko 2012) or by ageing treatment (Alaneme et al. 2013).

Conclusions

- It was difficult to attain a perfectly homogeneous distribution of reinforced particles in the matrix phase, when the aluminium matrix composites were processed through liquid metallurgy or stir casting method.
- Density in the aluminium matrix composite was found to be increased with reinforcement fraction; however, increased porosity levels in the composite caused reduction in density.
- It was observed that the hardness of aluminium matrix composites can be improved with the increase in reinforcement fraction or by reducing the particle size of reinforcement; however, the presence of porosity affects hardness adversely. The hardness of ceramic-reinforced composites can also be improved by heat treatment, ageing temperature and ageing time.
- Young's modulus, yield stress, ultimate tensile stress and breaking (fracture) stress of ceramic-reinforced aluminium matrix composites were higher than those of their monolithic alloys and increased with the reinforcement fraction of ceramic materials; however, the ductility (percent elongation) of the composites reduced.
- Fractography studies revealed that the mechanism and mode of failure during tensile testing of aluminium matrix composites may be due to initiation and growth of fine microcracks leading to macroscopic failure, ductile failure of the aluminium matrix, combination of particle fracture and particle pull-out, overload failure under tension and brittle fracture.
- The compressive strength of ceramic-reinforced aluminium matrix composites was found to be increased with the increase in reinforcement fraction in the aluminium matrix composites and with increasing strain rate during compression.
- The flexural strength (bending strength) of ceramic-reinforced aluminium matrix composites increased up to a certain percentage of reinforcement, beyond which it reduced.
- The toughness (impact strength) of ceramic-reinforced aluminium matrix composites increased with reinforcement fraction or by ageing treatment.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
Dipti Kanta Das performed thoroughly the literature on Mechanical properties of MMCs and carried out mechanical characterization of MMCs by various tests. Purna Chandra Mishra studied optical and physical characterization of MMCs by various techniques including Mechanical tests. Saranjit Singh participated in the sequence alignment and drafted the manuscript. Ratiash Kumar Thakur participated in the sequence alignment and drafted the manuscript. All authors read and approved the final manuscript.

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References

Alaneme, KK, & Aluko, AO. (2012). Fracture toughness (K_{1C}) and tensile properties of as-cast and age-hardened aluminium (6063)–silicon carbide particulate composites. *Scientia Iranica, 19*(4), 992–996. Iran.

Alaneme, KK, Ademilua, BO, & Bodunrin, MO. (2013). Mechanical properties and corrosion behaviour of aluminium hybrid composites reinforced with silicon carbide and bamboo leaf ash. *Tribology in Industry, 35*(1), 25–35.

Bhushan, RK, & Kumar, S. (2011). Influence of SiC particles distribution and their weight percentage on 7075 Al alloy. *Journal of Materials Engineering and Performance, 20*(2), 317–323. Springer, United States.

Boopathi, MM, Arulshri, KP, & Iyandurai, N. (2013). Evaluation of mechanical properties of aluminium alloy 2024 reinforced with silicon carbide and fly ash hybrid metal matrix composite. *American Journal of Applied Sciences, 10*(3), 219–229. Science Publications, Australia.

Borrego, A, Fernandez, R, Cristina, MC, Ibanez, J, & Doncel, GG. (2002). Influence of extrusion temperature on the microstructure and the texture of 6061Al–15 vol.% SiCw PM composites. *Composites Science and Technology, 62*, 731–742. Elsevier, United Kingdom.

Cocen, U, & Onel, K. (2002). Ductility and strength of extruded SiCp/aluminium-alloy composites. *Composites Science and Technology, 62*, 275–282. Elsevier, United Kingdom.
Demir, A, & Altinkok, N. (2004). Effect of gas pressure infiltration on microstructure and bending strength of porous Al_2O_3/SiC-reinforced aluminium matrix composites. *Composites Science and Technology, 64*, 2067–2074. Elsevier, United Kingdom.
Deshmanya, IB, & Purohit, G. (2012). Development of mathematical model to predict micro-hardness of Al 7075/Al_2O_3 composites produced by stir-casting. *Journal of Engineering Science and Technology Review, 5*(1), 44–50. Greece.
Fang, Q, Sidky, P, & Hocking, MG. (1997). Erosive wear behaviour of aluminium based composites. *Materials & Design, 18*(Nos. 4/6), 389–393. Elsevier, United Kingdom.
Jayaram, V, & Biswas, SK. (1999). Wear of Al_2O_3-SiC-(AlSi) melt oxidised ceramic composites. *Wear, 225–229*, 1322–1326. Elsevier, United Kingdom.
Kalkanli, A, & Yilmaz, S. (2008). Synthesis and characterization of aluminum alloy 7075 reinforced with silicon carbide particulates. *Materials and Design, 29*, 775–780. Elsevier, United Kingdom.
Lu, YX, Meng, XM, Lee, CS, Li, RKY, Huang, CG, & Lai, JKL. (1999). Microstructure and mechanical behaviour of a SiC particles reinforced Al-5Cu composite under dynamic loading. *Journal of Materials Processing Technology, 94*, 175–178. Elsevier, United Kingdom.
Manoharan, M, & Gupta, M. (1999). Effect of silicon carbide volume fraction on the work hardening behaviour of thermo mechanically processed aluminium-based metal–matrix composites. *Composites: Part B, 30*, 107–112. Elsevier, United Kingdom.
Purohit, R, Rana, RS, & Verma, CS. (2012). Fabrication of Al-SiCp composites through powder metallurgy process and testing of properties. *International Journal of Engineering Research and Applications, 2*(3), 420–437. ISSN: 2248–9622.
Rao, RN, Das, S, Mondal, DP, & Dixit, G. (2010). Effect of heat treatment on the sliding wear behaviour of aluminium alloy (Al–Zn–Mg) hard particle composite. *Tribology International, 43*, 330–339. Elsevier, United Kingdom.
Ravesh, SK, & Garg, TK. (2012). Preparation & analysis for some mechanical property of aluminium based metal matrix composite reinforced with SiC & fly ash. *International Journal of Engineering Research and Applications (IJERA), IJERA, 2*(6), 727–731. India.
Ravi Kumar, NV, & Dwarakadasa, ES. (2000). Effect of matrix strength on the mechanical properties of Al–Zn–Mg/SiCp composites. *Composites Science and Technology, 31*, 1139–1145. Elsevier, United Kingdom, Part A.
Sahin, Y, & Murphy, S. (1996). Wear performance of aluminium alloy composites containing unidirectionally-oriented silicon carbide coated boron fibres. *Wear, 197*, 248–254. Elsevier, United Kingdom.
Sanjay Kumar, SM, Rao, KP, & Girish, DP. (2012). Corrosion rate and tensile strength of Aluminium/SiC metal matrix composites in seawater. *International Journal of Advanced Engineering Research and Studies, I*(III), 313–315.
Singla, M, Dwivedi, DD, Singh, L, & Chawla, V. (2009). Development of aluminium based silicon carbide particulate metal matrix composite. *Journal of Minerals & Materials Characterization & Engineering, 8*(6), 455–467. Scientific Research Publishing Inc.
Song, WQ, Krauklis, P, Mouritz, AP, & Bandyopadhyay, S. (1995). The effect of thermal ageing on the abrasive wear behaviour of age hardening 2014 Al/Sic and 6061 Al/SIC composites. *Wear, 185*, 125–130. Elsevier, United Kingdom.
Srivatsan, TS, & Prakash, A. (1995). The quasi-static fracture behaviour of an aluminum alloy metal-matrix composite. *Composites Science and Technology, 53*, 307–315. Elsevier, United Kingdom.
Suresha, S, & Sridhara, BK. (2012). Friction characteristics of aluminium silicon carbide graphite hybrid composites. *Materials and Design, 34*, 576–583. Elsevier, United Kingdom.
Umanath, K, Kumar, KP, & Selvamani, ST. (2013). Analysis of dry sliding wear behaviour of Al6061/SiC/Al_2O_3 hybrid metal matrix composites. *Composites: Part B, 53*, 159–168. Elsevier, United Kingdom.
Uvaraja, VC, & Natarajan, N. (2012). Processing of stir cast Al-7075 hybrid metal matrix composites and their characterization. *International Review of Mechanical Engineering, 6*(4), p 724. United Kingdom.
Vanarotti, M, Kori, SA, Sridhar, BR, & Padasalgi, SB. (2012). *Synthesis and characterization of aluminium alloy A356 and silicon carbide metal matrix composite*. Singapore: International Proceedings of Computer Science and Information Technology.
Veeresh Kumar, GB, Rao, CSP, Selvaraj, N, & Bhagyashekar, MS. (2010). Studies on Al 6061-SiC and Al 7075-Al_2O_3 metal matrix composites. *Journal of Minerals & Materials Characterization & Engineering, 9*(1), 43–55. USA.
Veeresh Kumar, GB, Rao, CSP, & Selvaraj, N. (2012). Mechanical and dry sliding wear behavior of Al7075 alloy-reinforced with SiC particles. *Journal of Composite Materials, 46*(10), 1201–1209. SAGE, USA.
Xu, ZM, Loh, NL, & Zhou, W. (1997). Hot isostatic pressing of cast SiCp-reinforced aluminium-based composites. *Journal of Materials Processing Technology, 67*, 131–136. Elsevier, United Kingdom.

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