

Fabrication and Investigation of Mechanical Properties of SiC Particulate Reinforced AA5052 Metal Matrix Composite

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ABSTRACT

In this present research particulate reinforced aluminium metal matrix composite is developed by using sand mould and liquid stir casting processing route in which AA5052 reinforced with 5 wt. % SiC particulates of 63 μ m particle size. The density, porosity, micro-hardness, and compressive strength of SiC particulate reinforced AA5052 MMC were investigated and compared these properties with similar properties of unreinforced AA5052. The microstructure of the developed composite was also analysed by using optical microscopy, SEM, and XRD. Developed particulate reinforced Al metal matrix composite gives improved hardness and compressive strength as compared to the unreinforced AA5052. The addition of 5 wt. % SiC particulates increases the density of AA5052.

Keywords: MMC, SiC, AMMC, compressive strength, hardness, density.

1 Introduction

Metal Matrix Composite (MMC) is an engineering material of present era which is developed by the macroscopic composition of reinforcement and metal matrix material. Ceramic materials i.e. alumina (Al₂O₃), silicon carbide (SiC), boron carbide (B₄C) etc. are mostly used for reinforcement element in MMC to improve the mechanical as well as tribological properties the used metal matrix. MMCs have outstanding mechanical, tribological and excellent corrosive resistance properties as compared to presently used conventional materials [1–4]. Aluminium Metal Matrix Composite (AMMC) is a lightweight which have high strength to weight ratio and are mainly used for aerospace, automobiles, marine etc. [5–10]. AMMCs are isotropic in nature and rolling, forging, extrusion forming process can also be performed in it [7,11,12]. Particulate reinforced AMMCs give a good combination of mechanical, tribological and corrosion resistance properties at

low cost which make it more attractive than conventional materials [13–16].

Cocen and Onel [17] have investigated the ductility and tensile strength of extruded SiC-p reinforced MMCs. By extrusion application in stir cast fabricated MMCs, disappear the cluster of SiC-p, reduce the porosity to very low levels and the yield tensile strength values are improved 40% approximately. The ductility of the as-cast composites is decreased with the increasing amounts of SiC-p, but yield strength and tensile strength of the as-cast composites increase with the volume fraction of SiC-p upto 17% then decrease with further additions of reinforcement. Sahin [18] has prepared and analysed the mechanical properties of squeeze cast SiC-p reinforced AMMCs. He observed hardness, density and porosity of AMMCs are increase when the wt. % of SiC-p increases. The functionally graded centrifugal cast Al/SiC-p MMCs fabricated and characterized by El-Galy et al. [19]. They observed in the cast tubes, SiC-p concentrations and hardness in the outer zone

reach its maximum value and followed by a gradual decrease in concentrations and hardness in the direction of inner diameter. With increase in wt. % of SiC-p, proportionally increase in outer zone hardness but beyond 10 wt. % SiC-p the increasing rate is decreases slightly. They found that the ultimate tensile strength is proportional to the percentage of SiC-p and inversely proportional to the size of the particles. The tensile strength is increases linear up to 10 wt. % SiC-p and the increase rate is lower afterwards up to 15 wt. % SiC-p. Venkataraman and Sundararajan [20] have investigated the tensile strength behaviour of SiC-p reinforced AMMCs and they also reported that the tensile strength increases but tensile density decreases when the volume fraction of SiC-p is increase in Al matrix. Ozben et al. [21] have examined hardness and density of AMMCs increased with increase in reinforcement ratio, but impact toughness decreased. They also find tensile strength increased upto 10 wt. % of SiC-p reinforced and decreased when 15 wt. % of SiC-p reinforcement used. Rao [22] has done an experimental investigation on mechanical properties of Al7075/SiC-p MMC and he also found that by increase in SiC-p size and wt. % considerably enhanced the tensile strength and hardness of the AMMC but the ductility of the AMMC is decreased.

Ozden et al. [23] have investigated the impact behaviour at different temperature i.e. -176°C, 21°C, 100°C, 200°C and 300°C of SiC-p (167µm and 511µm) reinforced AMMCs with hot extrusion ratio of 13.63:1 and 19.63:1. They observed impact toughness of ductile Al alloy matrix decreases with the addition of SiC-p as reinforcement. The impact toughness of the AMMC slightly improved with increased particle size and the hot extrusion ratio, but artificial ageing decreased the impact toughness of the both Al alloys and AMMCs. The test temperature were not affected the impact behaviour of unreinforced Al alloy and SiC-p reinforced AMMCs. Meena et al. [24] have investigated the mechanical properties of the developed stir cast Al/SiC-p MMCs. They observed proportionality limit, upper & lower yield point, ultimate tensile strength, breaking strength, hardness and density

increases with the increase in SiC particulate size (220 mesh, 300 mesh, 400 mesh) and weight fraction (5%, 10%, 15% and 20%) of SiC-p, but % elongation and % reduction in area decreases with the increase in particulate size a& wt. % of SiC-p. Impact strength decreases with the increase in SiC-p size and increases with the increase in wt. % of SiC-p. For fabrication of AA5052/SiC-p MMC, the friction stir processing (FSP) route is used by Dolatkah et al. [25]. In this investigation, 5µm & 50nm SiC-p were used to fabricate surface layer composite. They reported that the SiC-p reinforcement, higher number of FSP passes, shifting the direction of tool rotation between passes and decrease of SiC particles size, enhance the hardness and wear resistance properties of the AA5052.

In this study the microstructure of the stir cast AA5052/SiC-p MMC, effect of SiC-p on the density, porosity, micro-hardness and compressive strength of the AA5052 have been investigated and the microstructure of the developed MMC is also characterized using optical microscopy, SEM and XRD.

2 Experimental Studies

2.1 Materials and Method

The materials chosen for the present work is 5xxx series of Al alloy in which principal alloying element is Mg. The 5xxx series is mainly used in marine applications due to its high corrosion resistance property, but when the Mg content present in the Al is greater than 3% then problem of stress corrosion cracking occurs at temperature above the 63°C [26]. So in this present work AA5052 has been chosen for the experiment due to its excellent corrosion resistance property to seawater and industrial atmosphere with Mg content less than 3%. It has very good weldability and good cold formability property. AA5052 is used for hospital and medical equipment, fan blades, hydraulic tubes, fuel tanks, pressure vessels, rivets etc. One of the major drawbacks of these alloys is their low strength. By improving the strength of these alloys, the functionality of these alloys can be broadened and used in many more applications. For the present work 5 wt. % of SiC particles are

used as reinforcement material due to their high hardness, high modulus of elasticity to improve the mechanical properties of AA5052. The particle size of the used SiC-p is 63 μ m. The chemical compositions of AA5052 are listed in Table 1. The stir casting processing route is used for the synthesis of AMMC for present work. The required amount of AA5052 was taken in graphite crucible and set in a resistance heating furnace then the alloy was melt at 800°C as shown in Figure 1.



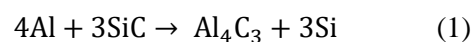
Figure 1: Melting of AA5052 in resistance furnace

Dross product formed and floating over the molten alloy was firstly removed, then the molten AA5052 was degassed by using solid hexachloro ethane (C₂Cl₆) tablet, because the molten AA5052 reacts with atmospheric oxides and degrades properties by oxidation [27,28]. The calculated quantity of SiC-p (5 wt. %) was preheated at 900°C for 1 hr in another electric resistance furnace to (i) reduce the temperature

gradient and increase wettability between the molten alloy and particle by removing the adsorbed gases and moisture from the particles and (ii) to facilitate formation of thin SiO₂ layer on the SiC-p surface [8]. The preheating of SiC is necessary; because without preheating, SiC would react with Al and form Al₄C₃ at the interface of Al and SiC. This would degrade the reinforcement strength and increase the corrosion susceptibility the Al alloy [29].

The reactions occur with or without preheating of SiC with Al are given in the equation (1) and equation (2) respectively.

Reaction of without preheated SiC with Al:



Reaction of preheated SiC with Al, in which a thin SiO₂ layer formed on the SiC surface:



The preheated SiC particulates are packed in Al foil then added into the molten AA5052. With the help of graphite stirrer, stirred the composite slurry for 10min. at 600rpm after that the composite slurry in Gr crucible was taken from the furnace with the help of tong and poured into prepared cavities in sand mould of required shape as shown in Figure 2(a), poured composite slurry into the sand mould is shown in Figure 2(b) and the developed SiC-p reinforced AA5052 MMC is shown in Figure 2(c).

Table 1: Chemical composition of AA5052 by weight percentage

Elements	Mg	Cr	Fe	Mn	Si	Cu	Zn	Al
% by weight	2.5	0.25	0.35	0.1	0.2	0.1	0.1	Remaining

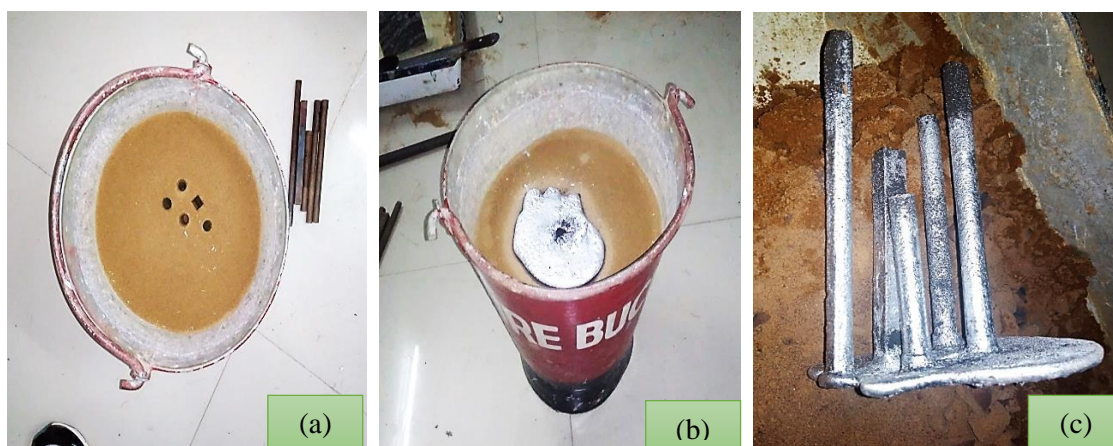


Figure 2: (a) Cavities prepared for casting (b) Poured composite slurry in cavities (c) Developed AA5052 + 5 wt. % SiC-p MMC

The fabricated as-cast AA5052 and AA5052 + 5 wt. % SiC-p MMC are shown in Figure 3.



Figure 3: Developed as-cast AA5052 and AA5052/SiC-p MMC

2.2 Microstructure Characterization

For the microstructural characterization of the AA5052 + 5 wt. % SiC-p MMC, 10×10×3 mm³ test samples was prepared from the middle section of the casted compositions as shown in Figure 4. The test samples were metallographically polished upto 2000 grade emery paper and cleaned with acetone to carry out microstructural characterization using ZEISS AxioCam ERc 5s Optical microscopy at 5x magnification, ZEISS EVO 18 SEM equipped with the Oxford EDS system (INCA 250 EDS with X-MAX 20mm Detector) and X'pert Powder - Multifunctional XRD from PANalytical.

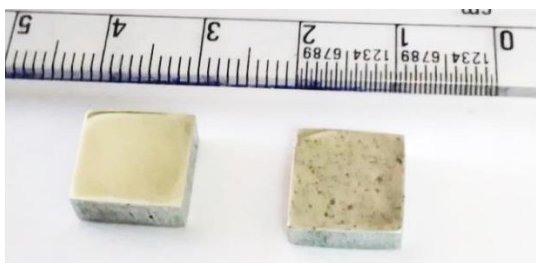


Figure 4: Test samples for microstructure characterization

2.3 Mechanical Characterization

2.3.1 Density and Porosity Measurement

The theoretical density of the as-cast AA5052 and the developed AA5052 + 5 wt. % SiC-p MMC was calculated from the rule of mixture formula, given by following equation (3) [2]. The density was calculated experimentally by applying Archimedes' principle and finally the density of the sample of casted compositions was calculated

by using equation (4). The percentage of porosity presented in the as-cast AA5052 and the developed AA5052 + 5 wt. % SiC-p MMC was calculated by using the equation (5) [30].

$$\frac{1}{\rho_c} = \frac{W_r}{\rho_r} + \frac{W_m}{\rho_m} \quad (3)$$

$$\rho_c = \frac{m_1}{m_2 - m_3} \times \rho_{H_2O} \quad (4)$$

Porosity (%)

$$= \left[1 - \frac{\text{Measured density}}{\text{Theoretical density}} \right] \times 100 \quad (5)$$

Where: ' ρ_c ', ' ρ_r ' and ' ρ_m ' is the density of composite or alloy, reinforcement and matrix respectively. ' W_r ' & ' W_m ' is the weight fraction of the reinforcement and the matrix respectively. ' m_1 ' is the mass of sample in air ' m_2 ' is the mass of sample in air with stand, ' m_3 ' is the mass of sample in water with stand and ' ρ_{H_2O} ' is the density of distilled water (at 293K) is 0.9982 g/cm³

2.3.2 Micro-hardness Test

Hardness test of test samples of the developed compositions was carried out according to ASTM E384 by using LECO LM248AT Micro hardness Tester as shown in Figure 5. Dimensions of the prepared test samples were 15×10×10 mm³ and were metallographic polished by 600 grit SiC waterproof abrasive paper for conducting the micro-hardness test. Micro-hardness test was performed at room temperature using a highly polished, pointed, square-based pyramidal diamond indenter with face angles of 136° and load of 300 gf applied for dwell time of 10 sec on the polished surface of the test sample. The value of the calculated hardness was shown digitally. Micro-hardness measurement was done on each casted composition by measurements taken at four different points of each sample to assess its reproducibility. The Micro-hardness value is shown by Vickers hardness number (HV) and theoretically the value of Vickers hardness number is calculated by the equation (6)[31].

$$HV = \frac{2P \sin\left(\frac{\alpha}{2}\right)}{d^2} = \frac{1.8544 P}{d^2} \quad (6)$$

Where: 'P' = Applied load in kgf, ' α ' = face angle of the diamond indenter = 136° , 'd' = mean diagonal of impression in mm.



Figure 5: Micro-hardness test carried out according to ASTM E384

2.3.3 Compression Test

The standard test samples were prepared into sizes of 11mm diameter and 26mm length to carry out the compression test. The test samples were fixed in the computerized universal testing machine of INSTRON SATEC 600 kN as shown in Figure 6 to conduct compression test by choosing the compression fixture. The movable jaws were properly adjusted so as to keep gauge length of 26mm. The maximum capacity of the UTM INSTRON SATEC 600 kN was 600 kN. 600 KN Models of INSTRON are ideal for high capacity tension, compression, flex and shear testing [32]. The compressive load is gradually applied with cross head speed of 2 mm/minute along principal material direction. The test sample broke after the applied load reached ultimate value.

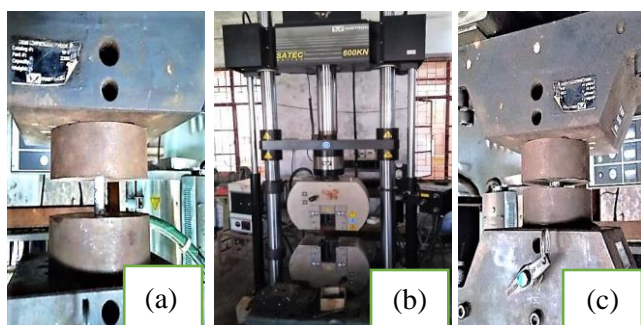


Figure 6: (a) Sample before compression test (b) Used INSTRON SATEC UTM (c) Sample after compression test

3 Results and Discussion

3.1 Microstructure

The optical micrographs of as-cast AA5052 and stir cast AA5052 + 5SiC-p MMC are shown in Figure 7. Figure 7(a) and Fig. 7(b) show the optical microstructure of as-cast AA5052 and stir cast AA5052 + 5SiC-p MMC respectively. Figure 7(c) shows the SEM image of the sample of AA5052 + 5SiC-p MMC. These figures clearly indicate that the voids or pores not present in the developed compositions.



Figure 7: Micrograph of the developed compositions: (a) Optical micrograph of AA5052 (b) Optical micrograph of AA5052/SiC-p MMC (c) SEM image of AA5052/SiC-p MMC

By analysis of Fig. 7(b) & 7(c) it is confirmed the presence of SiC particulates in the AA5052 matrix. The distribution of the SiC-p are fairly uniform but certain places they are agglomerate or clustered as shown in Fig. 7(c), this is due to simultaneously added of SiC-p in the molten AA5052 matrix at the time of stirring. In both as-cast AA5052 and stir cast AA5052 + 5SiC-p MMC no any pores existed due to improved wettability of preheated SiC particulates and well casting. Due to absence of cavities either at interfaces or in matrix, a good bonding between the AA5052 matrix and SiC particulate was obtained.

An X-ray diffraction pattern of developed AA5052 + 5SiC-p MMC is shown in Fig. 8. XRD of these composites was carried out using CuK α radiation ($\lambda = 1.54056\text{\AA}$). The diffraction angle varies from $0^\circ - 100^\circ$. XRD data of AA5052 + 5SiC-p MMC was analysed by 'MAUD 2.8' software with the help of 'Crystallography Open Database (COD)'. The profile of the Al, SiC, and Al_2O_3 constituents are matching with the profile of XRD and the type of crystal system, density and percentage amount of these constituent are tabulated in the Table 2. From XRD analysis of the developed composite, confirmed that the presence of SiC.

Table 2: XRD analysis of AA5052 + SiC-p MMC

S. N.	Element/Compound	Crystal System	Calculated Density (g/cm^3)	Amount (%)
1.	Aluminium	Cubic	2.715	92.639
2.	Silicon Carbide	Cubic	3.240	5.212
3.	Aluminium Oxide	Trigonal	3.991	2.148

3.2 Density and Porosity

It is noted that from Fig. 9 both measured and theoretical density increase with the addition of SiC particulates into the AA5052 matrix. This is due to the higher density of SiC (3100 kg/m^3) as compared to the density of AA5052 (2680 kg/m^3). From the Figure 9, it may also be concluded that both the measured as well as theoretical density of the casted compositions are in-line with each other and indicates the suitability of stir casing. The measured density of AA5052/SiC-p MMC is 0.8% higher than the unreinforced AA5052 matrix. A similar increases in density with the addition of SiC particulates in Al alloys was found by Sahin [18], Meena et al. [24], Ozben et al. [21] and Sujan et al. [33].

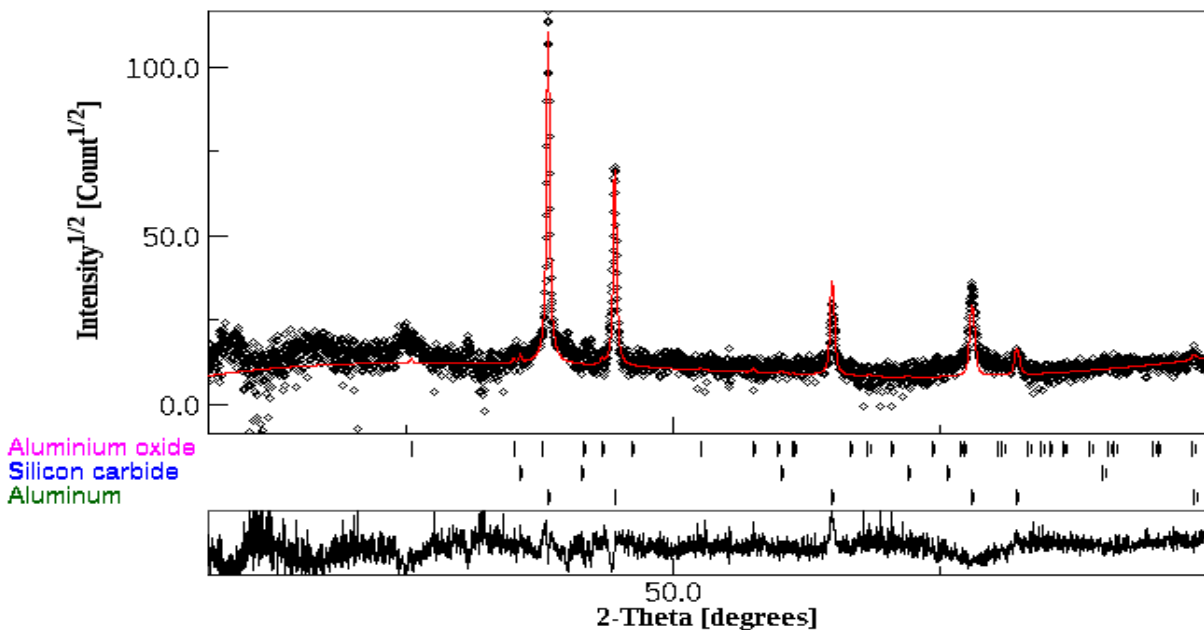


Figure 8: X-ray diffraction pattern of AA5052 + SiC-p MMC

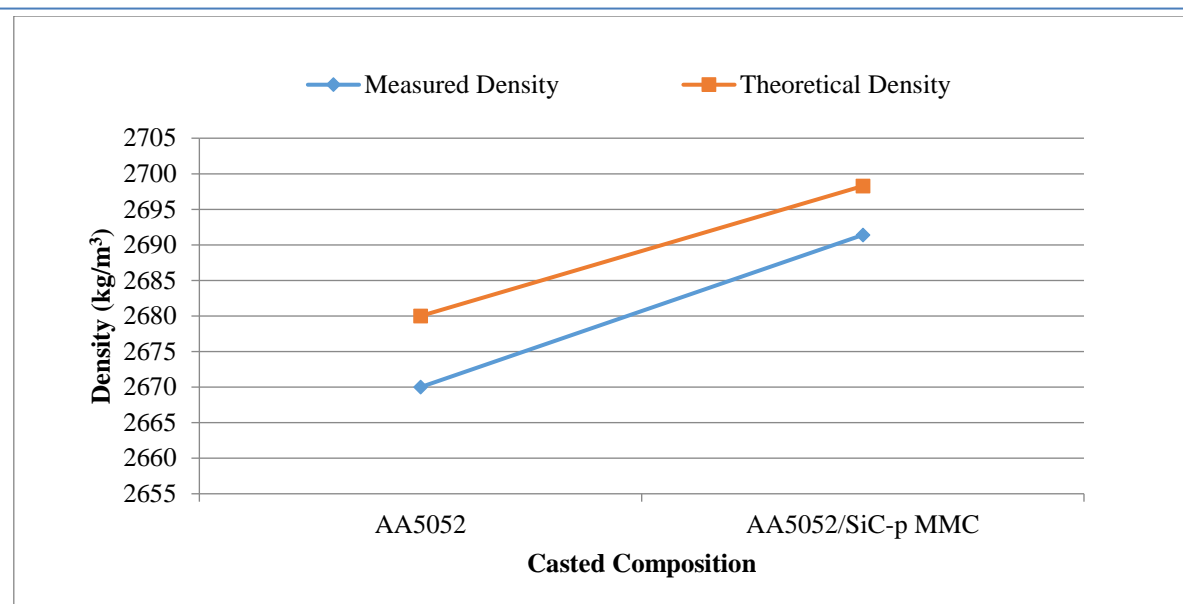


Figure 9: Variation in measured and theoretical density of developed compositions

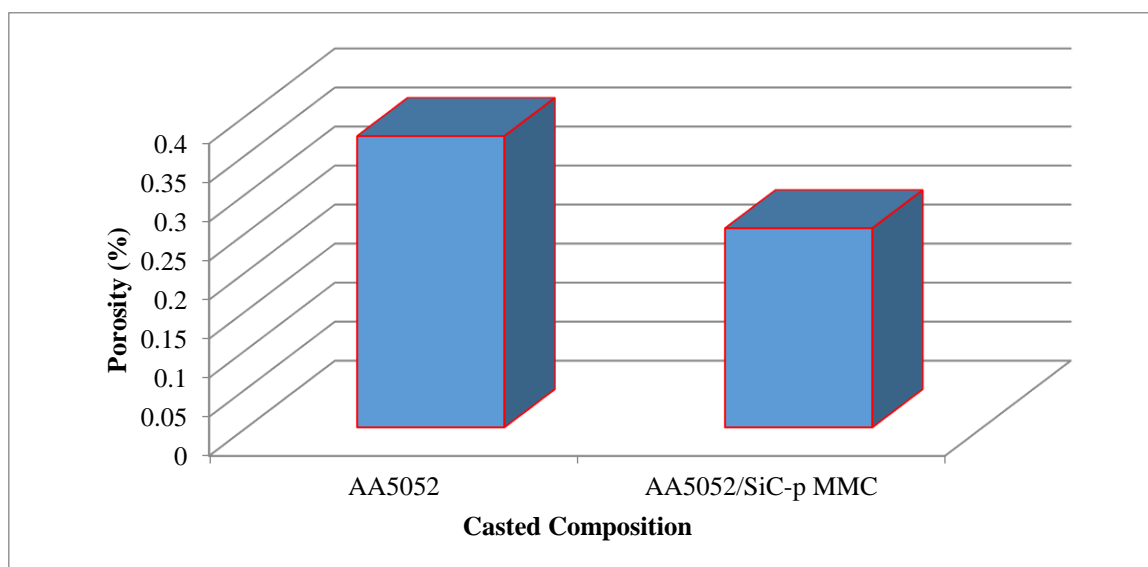


Figure 10: Percentage porosity presented in casted compositions

The percentage porosity presented in both the as-cast AA5052 and AA5052/SiC-p MMC is shown in Fig. 10. The difference between measured and theoretical density indicates that the presence of porosity in the casted compositions and it can also be affecting the performance of cast compositions. It is also concluded that from Fig. 10, the porosity presented in as-cast AA5052 and AA5052/SiC-p MMC is very small ($< 0.5\%$) due to the well casting process.

3.3 Micro-hardness

Micro-hardness measurement at four different points of the developed compositions is listed in Table 3 and the average hardness value of each composition is also plotted in Fig. 11. From Fig. 11, it is observed that the micro-hardness of the developed composites is higher than the unreinforced AA5052. The presence of hard SiC particulates increases the value of micro-hardness of the composite. 5% SiC-p addition in AA5052 increases the hardness from 66.725HV to

93.225HV. Dolatkhan et al. [25] have been reported that the addition of SiC-p to AA5052 led to increase in micro-hardness upto 55%. With the addition of hard SiC particulates in AA5052 matrix, results in 39.72% improvement in the micro-hardness.

Table 3: Micro-hardness of the developed compositions

S. N.	Cast Composition	Micro-hardness value (HV)				Average (HV)
1.	AA5052	66.0	70.5	70.0	60.4	66.725
2.	AA5052/SiC-p MMC	92.1	93.2	91.1	96.5	93.225

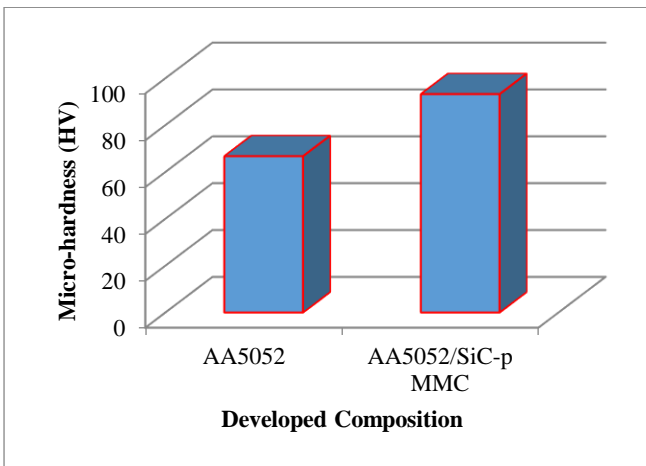


Figure 11: Average micro-hardness of the developed compositions

3.4 Compressive Strength

Compressive strength of particulate reinforced AMMCs are mainly decided by the reinforcement type and their content in matrix. So the variations in compressive strength of AA5052 with the addition of 5% SiC particulate reinforcement obtained from the compression test is plotted in Fig. 12. The ultimate compressive strength of AA5052 increases from 819 MPa to 890 MPa with the addition of SiC-p in it, because SiC has compressive strength of 3.9 GPa, which is approximately 24 times higher than the compressive strength of AA5052, hence SiC impart 8.5% higher compressive strength to the developed AA5052/SiC-p MMC. In the case of SiC-p reinforced AMMC, Mahendra & Radhakrishna [27] also found similar improvement in result. With the addition of 5 wt.

% of SiC-p in AA5083 matrix Idrisi et al. [34] found the compressive strength increases by 4.7%.

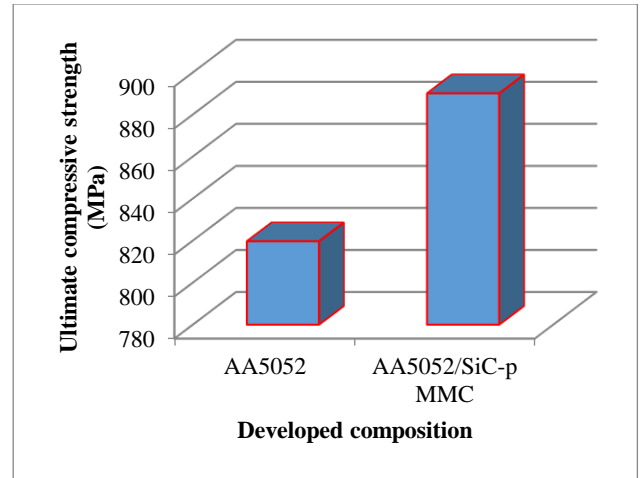


Figure 12: Compressive strength of the casted compositions

Load vs. displacement curve for unreinforced AA5052 is shown in Fig. 13 (a). The maximum load obtained for the sample is 77,894.79N and analogous to this maximum force, compressive strength calculated is 819.66 MPa. Figure 13(b), shows the load-displacement curve for AA5052/SiC-p MMC.

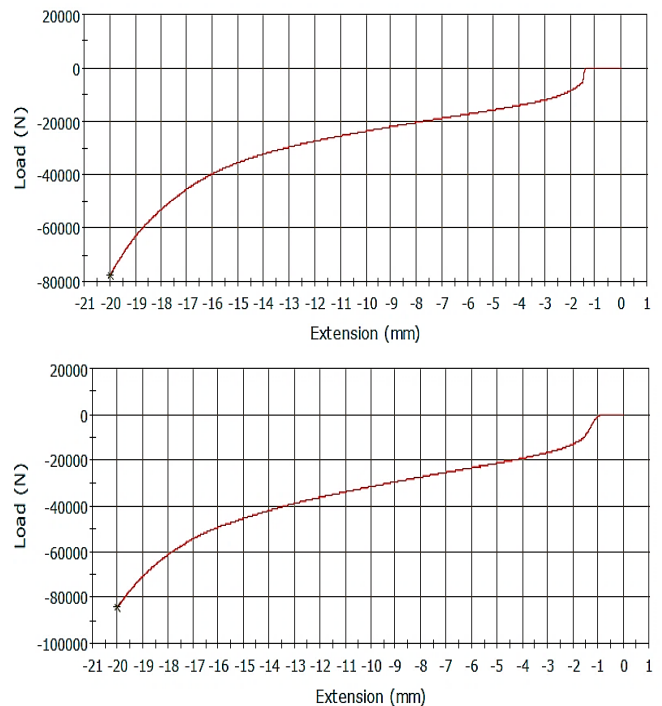


Figure 13: Load vs. displacement curve for (a) AA5052 composition (b) AA5052/SiC-p MMC

The maximum load obtained for the sample is 84,584.84N and analogous to this maximum force, compressive strength calculated is 890.06 MPa. Comparative observation of compressive strength between the sample of AA5052 and AA5052/SiC-p MMC compositions reveals that the dispersion of 5 wt. % SiC-p in AA5052 matrix is responsible for increase in compressive strength.

High hardness of the MMC is also required to improve the wear resistance properties, most of the researchers are also working on to improve the wear resistance properties of AMMCs to implement these materials on the hydraulic field and also try to decrease the density of the AMMCs to implement in the field of aerospace, automobile [35]. Power saving and noise reduction in the field of aerospace and automobile are very essential requirement. Light-weight AMMCs are used for power saving and noise reduction in the field of Automobiles [36, 37]. In this research work the developed AMMC having high hardness and strength and this can be used in the hydraulic field like slurry pump impeller and pump casing.

4 Conclusions

In this research, the AA5052 matrix has been reinforced with 5 wt. % SiC particulates of 63 μ m particle size by using stir casting liquid processing technique and it is concluded that the optical and SEM micrographs of the AA5052/SiC-p MMC show the uniform distribution of the SiC particles and from XRD analysis confirm the presence of SiC in AA5052 matrix. The density of the AA5052 increases up to 0.8% with the addition 5 wt. % SiC particulates. Very less percentage (<0.5%) of porosity present in the developed compositions, which are 0.37% and 0.26% for the as-cast AA5052 and AA5052/SiC-p MMC respectively. With the addition of the SiC particulates into the AA5052 matrix, the micro-hardness and compressive strength of the AA5052 are improved by 39.72% and 8.5% respectively. Due to improved hardness and good compressive strength of the AA5052/SiC-p MMC can be applicable for the various I.C. engines parts i.e. connecting rod, cylinder blocks. The developed MMC can also replace the

conventional Al alloy material used for fan blades, medical equipment due to its advantageous properties. It is also applicable for the aircraft and aerospace industries in the strength points of view but its implementation is limited due their increase in the density with the addition of SiC particulates. With the increase in the weight fraction and particle size of SiC in AA5052 matrix these experiments can also be done in the future.

5 Declarations

5.1 Acknowledgements

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5.2 Competing Interests

No any potential conflict of interest exists in this publication.

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