Morphological and Mechanical Characterization of Al-4032/SiC/GMP Hybrid Composites

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Research Article

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Abstract

The pattern of metal matrix composites can be enhanced by integrating the concept of hybrid composite to produce newer engineering materials. The morphological and mechanical characteristics of Al-4032/SiC/GMP hybrid composites have been investigated. The aluminium alloy (Al-4032) based hybrid composites have been fabricated through the bottom pouring stir casting set up, by reinforcing the silicon carbide (SiC) and granite marble powder ceramic particles as the reinforcement material at various fraction level i.e. 0, 3, 6, 9 weight% in equal proportion. The reinforcement particle size is up to 54 μm. The microstructural characterization of the hybrid composite samples has been carried out using optical microscope, SEM and XRD. The study reveals that the reinforcement hybrid particles (SiC + GMP) are almost uniformly distributed throughout the matrix phase. The mechanical properties (tensile strength, impact strength and microhardness) of the composite samples have been obtained and found to be better than the unreinforced alloy.

1. Introduction

Material scientists have been working for development of advanced materials for satisfying the need of the engineering sector to improve efficiency, and reducing costs of the industrial sector, for decades. Aluminium and its alloy based composites (AMCs) are the most demanding material in various industrial sectors (aeronautical, automobile, sports etc.) for having substantially superior properties involving high specific strength, specific modulus, and damping capacity than conventional Al-alloys. The interest has been arising in AMCs for low density and good mechanical, wear and anti-corrosion properties with low fabrication cost. The AMCs seem to be quite significant for both, industrial application and research [1].

The AMCs are used extensively in various fields due to their low density, high strength-to-weight ratio, good damping properties and better chemical properties. The hybrid metal matrix composite, having two or more reinforcement materials simultaneously in equal or different proportions, is the new concept in this field for the research. It is the fourth-generation composite of have significant potential in the materials world [2]. If a waste or cheaper reinforcement is used, it may yield a relatively cheaper composite, while maintaining reasonably good mechanical properties.

Recent investigation has shown that agro/industrial waste materials such as rice husk ash, red mud powder, fly ash, graphite etc., can be effectively used as a matching reinforcement in AMCs [3, 4]. The properties of the hybrid ceramic reinforcements (different material) can be merged/combined to attain improved material properties than single reinforced composites. Also, using of stir casting technique for mixing the reinforcement material to Al-alloy (matrix) for fabricating AMCs lessens the cost the composites, because its economical, simple and highly productive method [5, 6].

The Al-4032 is the aluminium-silicon alloy having composition of silicon about 12%, is broadly used as the material for components in automobile, aeronautics and other sectors. The research on Al-4032 alloy matrix-based composites is going on to reduce weight and improve the mechanical, chemical &

tribological properties of components used in industrial machinery. In the current study, the fabrication of the aluminium alloy (Al-4032) based hybrid composites have been done through bottom pouring vacuum stir casting technique, using different weight fractions of SiC and GMP reinforcement. The ceramic particles (reinforcement materials) have been used in equal proportion, making the net hybrid reinforcement at 0, 3, 6, 9 weight%. The morphological and mechanical properties of the AMHCs have been investigated to assess the effect of composition, and usefulness for industrial application.

Presentation of the contents has been arranged as follows. The next section presents brief review of recent research on the AMHCs, especially on study of morphological and mechanical properties. Sections 3 provides the brief introduction to the testing techniques. In Sect. 4, the processing/fabrication of the AMHCs has been discussed. Section 5 includes the results and discussion on the characterization (morphological and mechanical) of the AMHCs. The last section presents the conclusion and future scope of the research.

2. Literature Review

Fabrication of AMHCs and testing of their properties with a view to develop improved materials for industrial applications has been an interesting topic for research for decades. The AMCs with one or more (multiple/hybrid) reinforcement are getting more interest than single reinforced composites because of improved properties. The very first research on the AMCs appears to have been taken up by S. Ray in 1968 as Masters' dissertation at IIT Kanpur [7]. But, the concept of hybrid composites appeared in early 1990s [8]. Review of relevant research reported in literature has been presented below.

Lee et al. (2004) fabricated the Al-alloy based metal matrix composite by reinforcing the 20% of metallic amorphous (Ni–20.6Nb–40.2Ta) phase into Al-356 metal matrix using infiltration casting process, under argon pressure. The study reveals that the reinforcing metallic amorphous into Al-alloy improves the mechanical properties (compressive strength, hardness). The composite samples exhibit higher compressive yield strength (163 MPa) than that of the monolithic sample (129 MPa). The metallic amorphous phase ribbons are consistently distributed in the Al-alloy [9].

Dolata & Wieczorek (2007) fabricated the AMHCs using chromium carbide (Cr_3C_2) and titanium carbides (TiC) with 5–10% (by weight) through centrifugal casting and tested the wear behavior. The reinforced composites show the uniform wear mechanism than the base alloy. The composites with higher weight fraction (10%) of the carbide reinforcement shows the better wear behavior than the composite with 5% reinforcement. An increase in the reinforcing phase fraction allowed the elimination of the phenomena connected with adhesion wear [10].

Mahendra & Radhakrishna (2010) fabricated the hybrid composites using Al-4.5%Cu alloy as base matrix and combination of fly ash & SiC (5-10-15% by weight equal proportion) as the hybrid reinforcement, through stir casting. The mechanical properties (tensile strength, compression strength, and impact strength) and wear properties increase with increase in hybrid reinforcement, while decrease in the density of AMHC has been observed [11].

Boopathi el al. (2013) fabricated the hybrid composite using aluminium as base matrix and combination of SiC & fly-ash as the hybrid reinforcement through stir casting method. The weight fraction of fly ash (5% by weight) remains constant while SiC used as 5–10% (by weight) in hybrid reinforcement. It was observed that the tensile strength and hardness of the hybrid composites tends to increase while density and elongation of the composites decreases than base matrix. It was also observed that the hybrid composites of SiC and fly-ash shows improved properties than the single reinforced composites [12].

Moorthy et al. (2015) studied the tribological behavior using artificial neural network (ANN) modelling technique of the aluminium alloy (Al-2218) based hybrid composites by imparting the fly-ash (5, 10, 15 wt%) with 4 wt% of talc. The hybrid composites were fabricated through stir casting technique. It was noticed that the hybrid composites show the better wear characteristics than the base matrix. With adding fly-ash content, the wear performance also improves. The mixing of talc (4%) to form hybrid reinforcement plays significant role and displays better lubricity, which lower the wear rate [13].

Rao et al. (2017) examined the mechanical properties of Al-7075 based hybrid metal matrix composite using non-dominated sorting genetic algorithm (NSGA-II). The composite was fabricated by mixing the silicon carbide (SiC) and titanium dioxide (TiO2) particles in different weight fraction (%) combinations such as (0, 10), (2.5, 7.5), (5, 5), (7.5, 2.5) and (10, 0) respectively through stir casting. The optimum combination of SiC and TiO2 obtained under the best compromise solution has been found to be 9.513% and 0.487%, respectively. The results also indicate that among the two, SiC and TiO2, the fraction of SiC particle is the most influencing parameter to all the three mechanical properties [14].

Vinod et al. (2019) characterized the mechanical properties of the aluminium alloy (Al-356) based hybrid composites, in which combination of rice husk ash (RHA) & fly ash has been reinforced. The double stir casting process has been adopted for processing. It is observed that the hybrid reinforcements are homogeneously distributed through matrix and improves the mechanical properties of composites. Lower porosity is also observed in composites due to imparting of ceramic hybrid particles [15].

These studies highlight that the utilization of hybrid reinforcements in aluminium matrix hybrid composites generate better mechanical, physical and tribological properties. Al-4032 is a famous cast (Al–Si) alloy with high wear resistance, corrosion resistance and improved mechanical properties. In this study, the Al-4032 alloy-based hybrid composites have been fabricated through bottom poring stir casting machine. The mixture of SiC and granite marble powder (GMP) has been used as hybrid reinforcement with 0-3-6-9 weight% in equal proportion. The morphological (microstructure, SEM, XRD) and mechanical (tensile strength, impact strength and micro-hardness) characterization of the AMHC has been carried out. The mechanical properties of the AMHCs have been observed to be better than the unreinforced alloy.

3. Background Theory - Characterization Of The Amhc

The characterization of the AMHC sample has been carried out under two heads – viz. morphological characterization, and mechanical characterization

3.1 Morphological characterization

The morphological characterization describes to the wide-ranging process by which a material's structure and properties (grain structures, grain boundaries, grain size etc.) are assessed. It is an important step for scientific understanding of engineering materials. Microstructure characterization of materials includes analysis of surface topography, porosity, crystal defects, and interfaces. SEM offers the capability to visually inspect the surface morphology for detection of pores, fissures, and other surface materials/deposits. X-ray diffraction (XRD) is a rapid investigative technique mainly used for phase identification of a crystalline material.

The morphological characterization of the AMHCs has been done through optical microscope, X-ray diffraction (XRD) and scanning electron microscope (SEM). Before characterization, the samples are processed by some traditional method of polishing. To analyze the microstructure, a specimen of size ϕ15mm×5 mm cut from the cast composite. Polishing of the samples has been done using the emery paper ranging from 100 to 3000 grit size i.e. 100, 200, 400, 600, 800, 1000, 1200, 1500, 2000, 2500, 3000 grits. After the polishing on emery papers, the diamond paste has been used for attaining the ultrafine mirror like finishing using the velvet cloth. This follows the application of the Keller's etchant (for the aluminium or aluminum base alloy/composites) for etching. These polished samples are tested on different microstructural machines – optical microscope, X-ray diffraction and scanning electron microscope.

3.2 Mechanical characterization

Mechanical characterization of the AMHCs is carried out to study the effect of the reinforcing material on the mechanical properties of the base material. If the bonding between the matrix and the reinforcement is good, the mechanical properties of the composite obtained will also improve. The mechanical characterization includes the testing of tensile strength, microhardness, and impact strength of the AMHC samples.

(a) Tensile test

The tensile test has been conducted to obtain the ultimate tensile strength and ductility of the material (percentage elongation). The tensile tests were performed on Digital Universal Testing Machine and specimens were prepared as per the ASTM E-08 standards. The standard and actual sample (prepared through wire-cut electron discharge machine) for tensile test shown in Fig. 1. The tensile tests were performed on the. An average of three readings has been taken to reduce the variability in the results.

(b) Micro-hardness Test

ASTM E-92 has been approached to conduct the micro-hardness tests for fabricated aluminium matrix composites. The samples were polished up to 1500 grit size to make the surface free from irregularities. A Vickers's micro hardness tester has been used. An average of five readings has been taken along the length of the specimen as the final hardness value of the AMHCs.

(a) Impact Test

To conduct the impact test, the Charpy impact tester has been used. A sample size 10x10x55 mm^3 was machined with a V-notch of depth of 2 mm at 45^0 according to the ASTM A-370 standards for AMCs. Figure 2 (a & b) shows the standard sample and actual prepared sample for the Charpy impact test. The impact test for each type of composition has been five times and the average has been taken as the final impact strength for the composition.

4. Experimental Work

The experimental work involves fabrication/processing of the Al-4032/SiC/GMP hybrid composites, preparation of samples, followed by morphological and mechanical characterization. The details of the experimental work are given below.

4.1 Processing of the hybrid composites

The aluminium matrix hybrid composite (AMHC) has been fabricated with the Al-4032 as the base matrix and the combination of SiC (conventional reinforcement) and granite marble powder (industrial waste particles) ceramic particles as the reinforcement material in equal proportion. The hybrid reinforcement has been used at various weight fraction i.e. 0, 3, 6, 9 %. The reinforcement particles size has been up to 54 µm. The chemical composition of the Al-4032 alloy is shown in Table 1. Silicon present in the base alloy imparts high fluidity and low shrinkage, which results in good cast ability and weldability. The presence of silicon also improves casting characteristics by improving feeding and hot tear resistance [16].

Table 1
Chemical composition (fraction—percentage by weight) of the Al-4032 alloy

Component	Si	Cu	Mg	Cr	Ni	Zn	Mn	Al
Weight%	11.53	0.9	1.00	0.10	0.8	0.25	0.415	Rest

Stir casting process with the bottom pouring vacuum stir casting set up has been adopted for mixing the reinforcement with the molten metal using mechanical stirrer blades [17]. Following are the steps for fabrication of the AMHCs followed in the experiment.

5. Result And Discussion

The Al-4032 alloy-based hybrid composites have been fabricated, using SiC and GMP as hybrid reinforcement at 0-3-6-9% by weight in equal proportion, using bottom pouring stir casting method. The morphological and mechanical characterization of the AMHC samples has been attempted to investigate the effect of hybrid reinforcement. The results obtained from the characterization have been discussed in this section.

5.1 Morphological characterization

5.1.1 Microscopic characterization

The microstructure study of the Al-4032/SiC/GMP composites has been carried out through Optical microscope at 200x (Fig. 4). The study reveals that the base matrix contains typically Al-Si eutectic mixture and primary silicon phase (Fig. 4a). It is observed that the hybrid ceramic particles are almost uniformly distributed throughout the Al-matrix and form a good bonding. The significant microstructural differences have been observed in the three samples of different weight fraction AMHCs. As the weight percentage of the hybrid ceramic particles increases beyond 6%, the coagulation/cluster formation starts (Fig. 4d). It is due to the increase of particulate interaction and settling velocity that result in non-homogeneous distribution of ceramic particles. The cluster formation takes place during the mixing and stirring processes [18].

5.1.2 SEM characterization

The SEM characterization study of the Al-4032 matrix-based hybrid composites has been conducted using JUIL (JSM) IT-100 scanning electron microscope, situated at NITTTR, Chandigarh. The presence of dendritic pro-eutectic α-Al and plate like structured eutectic-Si has been observed through SEM characterization for the base matrix. The density of the GMP material is similar to that of the base matrix and this might be the possible reason for insufficient bonding at the interface of the matrix and ceramic particulates leaving voids [16]. The agglomeration of particulates while solidifying may create intra-particulate voids because of insufficient bonding with the matrix material [19]. Clear interface between matrix and reinforcement can increase the load bearing ability of the AMHCs. These hybrid ceramic particles have high melting point, so, no further reaction has been noticed with the matrix material. The GMP particles appear to be surrounded by the α-Al phase (Fig. 5).

From the SEM characterization, it is observed that almost uniform distribution of the reinforcement throughout the matrix has been achieved. But at higher weight percentage, the homogeneity of the samples appears to be disturbed due to the clustering and agglomeration of the ceramic particles at some points. The wettability also affects the bonding between the matrix and ceramic particles. The dispersion of these reinforcing particles is influenced by the wettability of the hybrid ceramic particles, and interfacial bonding between these particles and Al−4032 alloy. It is also observed that the increasing the weight percentage of the hybrid particles above 6% creates the slurry and disturbs the homogeneity of the composite material.

5.3 X-Ray Diffraction (XRD) characterization

Figure 6 shows the XRD patterns attained for the Al-4032/SiC/GMP hybrid composites. The XRD reports confirm the presence of SiC and GMP reinforcement within the matrix alloy. Different peaks have been observed for different samples at 3, 6, 9 % reinforcement by weight. As the weight percentage of both, SiC and GMP particles increases, height of the peaks of the ceramic also increases (Fig. 6). But on the other hand, the peaks of Al-4032 slightly reduce in height.

5.2 Mechanical Characterization

5.2.1 Tensile test

The result of the tensile test conducted on the AMHC samples is presented in the Table 2. With increase in the reinforcement ratio of the hybrid ceramic particles, the UTS value of the AMC samples tend to increase up to the weight fraction 6%. But, after that, it starts decreasing. The maximum value of the UTS is 146 MPa, obtained at the 6%. With increasing weight fraction, more load is transferred to the reinforcement material which results in a higher yield strength of the composite material. During loading, ceramic particles absorb the load and enhances the strength of fabricated composite.

On the other hand, the percentage elongation shows the opposite behavior than the UTS. Elongation percentage of any material represents its ductility behavior. As the UTS value increases, the brittle behavior of the AMHCs sample also increases and causes the decrease in the percentage elongation value of AMHCs. The increasing-decreasing trend of the UTS and percentage elongation for AMHC is shown in Figure (7–8).

Table 2
Tensile test of the AMHCs

Sr. No	Samples	UTS (MPa)	% Elongation
1	Base matrix	69.4	18.4
2	Al-4032/SiC/GMP (3%)	103	13.2
3	Al-4032/SiC/GMP (6%)	146	7.8
4	Al-4032/SiC/GMP (9%)	118	11.7

5.2.2 Micro-hardness test

The effect of reinforced particulate weight fraction on the Vickers micro-hardness value has been investigated and the results have been presented in Table 3 and Fig. 9. The micro-hardness of the AMHC samples has been found to improve with addition of the hybrid ceramic particles. It may be because of the higher hardness of the ceramic particles than the base matrix, and the good bonding interface between the reinforcement and the matrix ([20]; also confirmed by SEM studies, Sect. 5.1.2). Figure 9 shows that the Vickers microhardness of the AMHCs is a function of the reinforcement weight fraction.

However, with addition of the reinforcement beyond 6% of weight fraction, the micro-hardness follows a decreasing trend. This may happen due to coagulation of reinforcement occurring at the high weight fraction, resulting in voids at the interface [21]. The maximum value of micro-hardness obtained corresponding to 6% weight fraction of reinforcement is 190.2 HV.

Table 3
Micro-hardness test of AMHCs

Sr. No	Samples	Microhardness (HV)
1	Al-4032 (Base matrix)	131.4
2	Al-4032/SiC/GMP (3%)	160.4
3	Al-4032/SiC/GMP (6%)	190.2
4	Al-4032/SiC/GMP (9%)	173.3

5.2.3 Impact test

The effect of hybrid ceramic particle reinforcement on the impact strength has been investigated. The results obtained have been presented in Table 4 and Fig. 10. Addition of the hybrid reinforcement ceramic particles appears to improve the impact strength of the AMC samples, with the maximum value 34.3 J occurring at 3% weight fraction.

Beyond 3%, the toughness energy follows a decreasing trend. This may be due to the brittle nature of the reinforced ceramic particulates. Also, the tendency of segregation of the reinforcement particles at some specific locations at higher reinforcement fractions may not improve the strength significantly. On application of load, decohesion at the interface between hybrid ceramic particles and ductile matrix may be a reason for lower impact strength at higher weight fraction of reinforcement [18].

Table 4
Result of impact strength test for AMHCs

Sr. No	Samples	Impact energy (J)
1	Al-4032 (Base matrix)	22.4
2	Al-4032/SiC/GMP (3%)	34.3
3	Al-4032/SiC/GMP (6%)	29.8
4	Al-4032/SiC/GMP (9%)	24.8

Conclusions

In this work, Al-4032/SiC/GMP composites have been fabricated through stir casting route for different reinforcement ratios (0-3-6-9%) by weight. The SiC (conventional reinforcement) and granite marble powder (industrial waste ceramic particles) has been utilized to form the Al-alloy based hybrid composites. The morphological and mechanical characterization have been conducted to study the effect of addition/ variation of the hybrid ceramic particles on the properties of the AMHCs. Following conclusion can be drawn from the study.

- The hybrid ceramic particles are almost uniformly distributed all over the matrix phase, for AMHC samples up to 6% reinforcement. However, localized coagulation of the reinforcement (causing adverse effect on the homogeneity) has been noticed at 9% weight fraction, indicating the formation of the composite is satisfactory only up to 6% reinforcement.
- Addition of the hybrid ceramic particles to the matrix in general results in improvement in mechanical properties of the AMHC. The tensile strength and microhardness of the AMC sample increases with increase in the reinforcement ratio up to 6% (by weight). Beyond this, the properties start decreasing, possibly be due to coagulation of the reinforcement, and weak interfacial bonding at higher weight fractions.
- The impact strength of the AMHCs appears to be higher than that of the Al-alloy matrix. The highest value of the impact strength occurs corresponding to 3% weight fraction of the reinforcement. The impact strength follows a decreasing trend beyond this value, possibly due to increase in brittleness of the composite with increase in the reinforcement fraction.

In this work, the fabrication of the hybrid AMC (SiC + GMP in equal proportions) has been attempted using 0-3-6-9% (by weight) reinforcement ratio. The work can be extended for other weight fractions of the reinforcement (in the range 2-8%) for more useful results. Inclusion of torsion and fatigue test of the AMCs may be beneficial for industrial application.

Declarations

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

Deepak Kumar: Data curation, Investigation, Formal analysis, Conceptualization, Project administration and experimentation, Writing – original draft, Validation, Visualization, Funding acquisition.

Pradeep K Singh: Conceptualization, Resources management, Supervision, Project administration, Writing – review & editing.

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Compliance with ethical standards

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue

Consent for Publication

I, Pradeep K Singh, on the behalf of all co-authors, hereby given consent for publication of this manuscript.

Availability of data and material

Not applicable

Consent to participate

Not applicable

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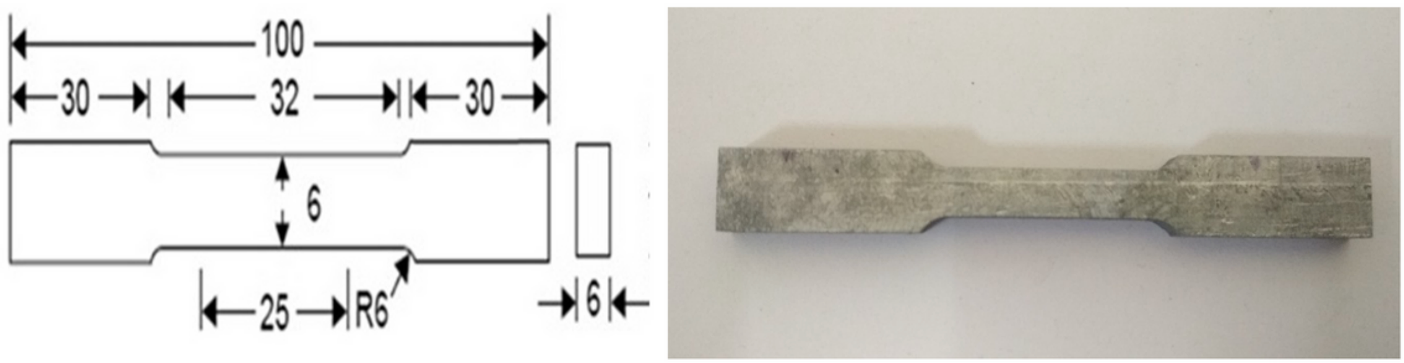
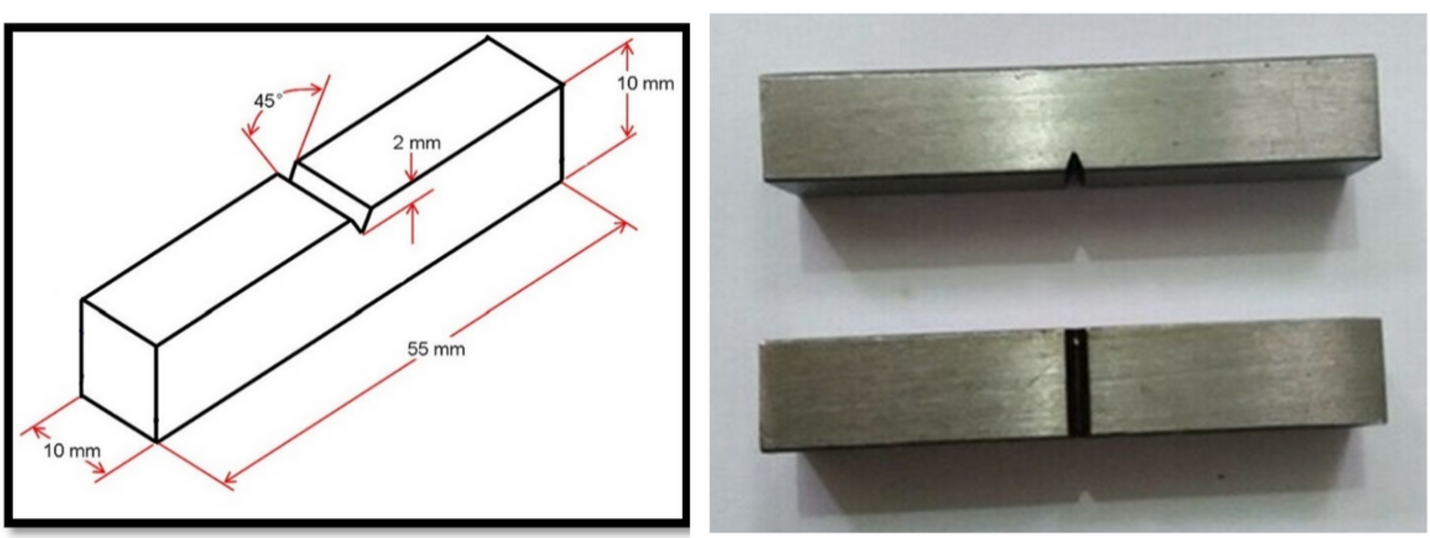
Figures



(a) (b)

Figure 1

(a) Tensile test specimen as per the ASTM E-8 standards (b) Machined tensile specimen



(a) (b)

Figure 2

(a) Standard Charpy Impact specimen dimensions as per ASTM A370 (b) Machined Impact specimen

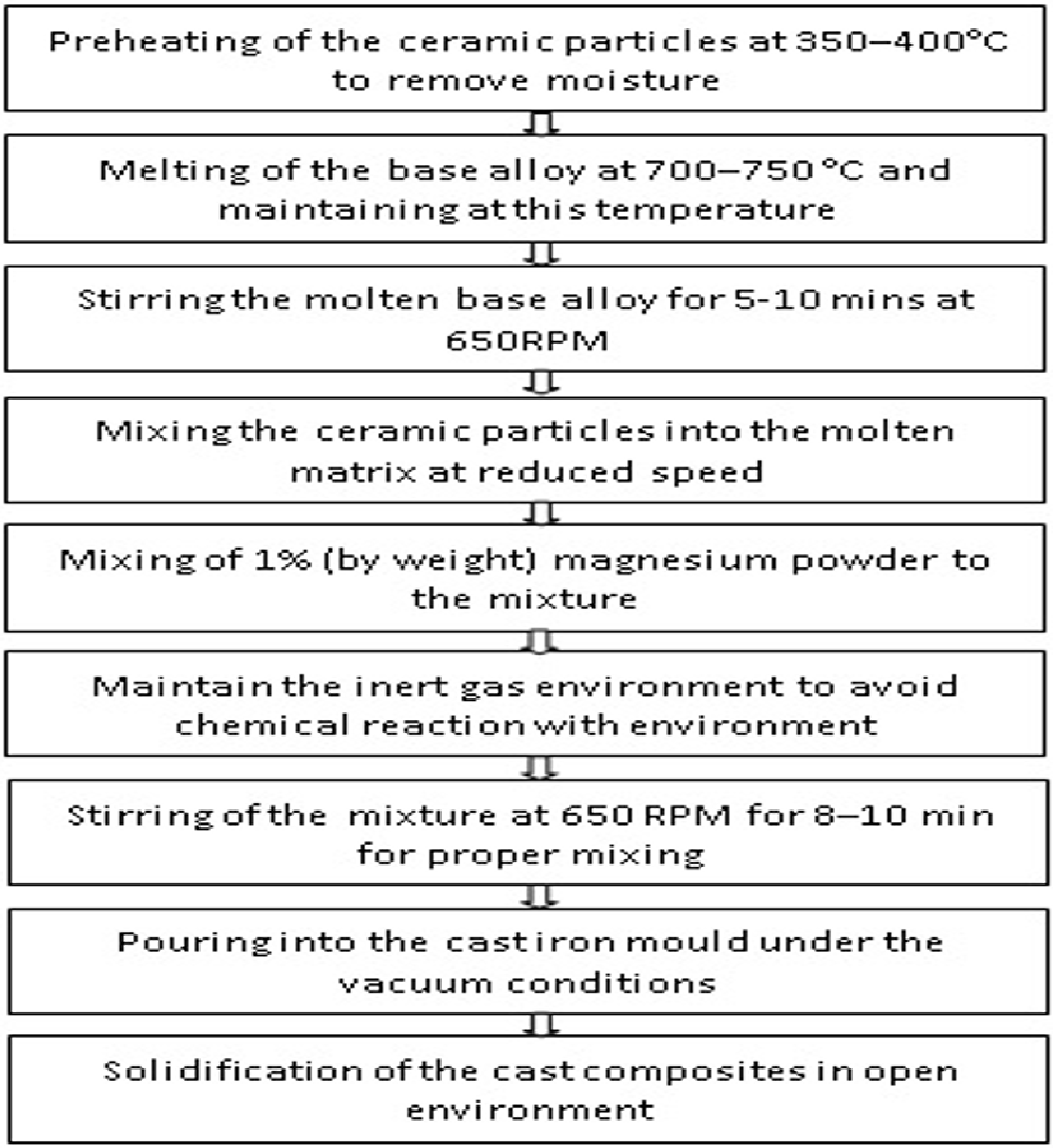


Figure 3

Step for the processing of the AMHC

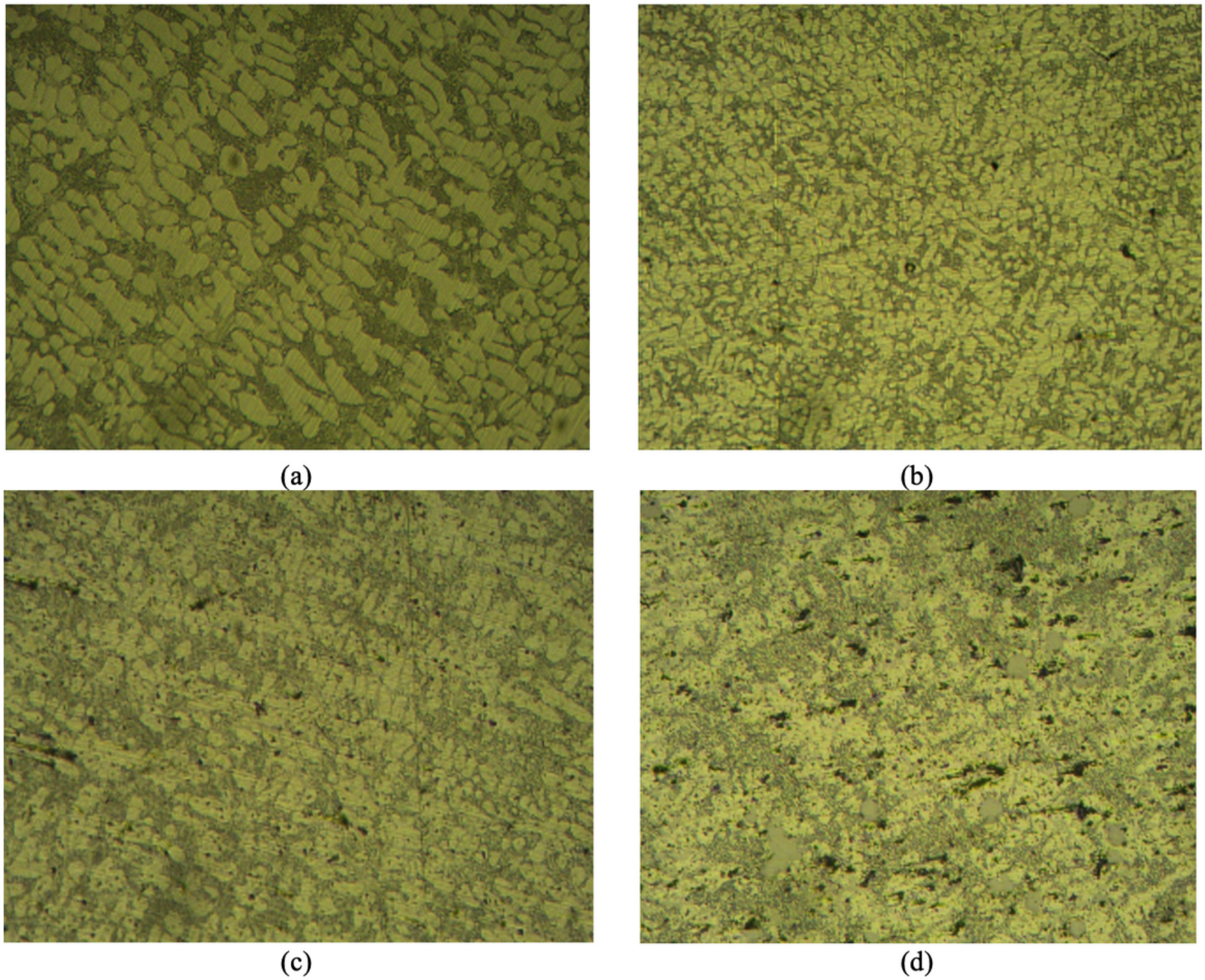


Figure 4

Microstructure images by Optical micrographs of AMHC samples at 200x (a) base alloy (b) 3% hybrid (c) 6% hybrid (d) 9% hybrid

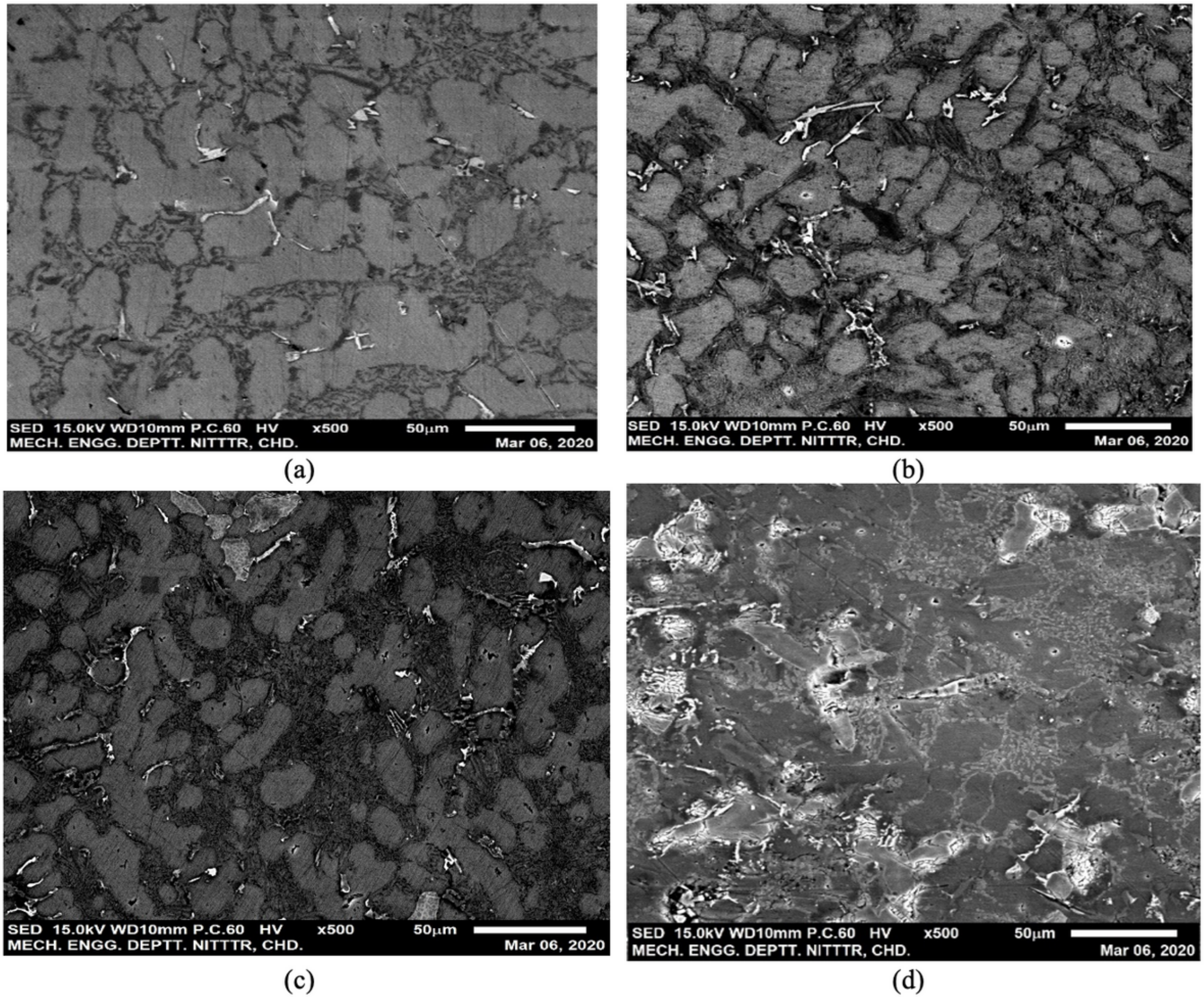


Figure 5

Scanning electron microscope (SEM) characterization at x500- 50μm of the AMC (a) base alloy (b) 3% hybrid (c) 6% hybrid (d) 9% hybrid

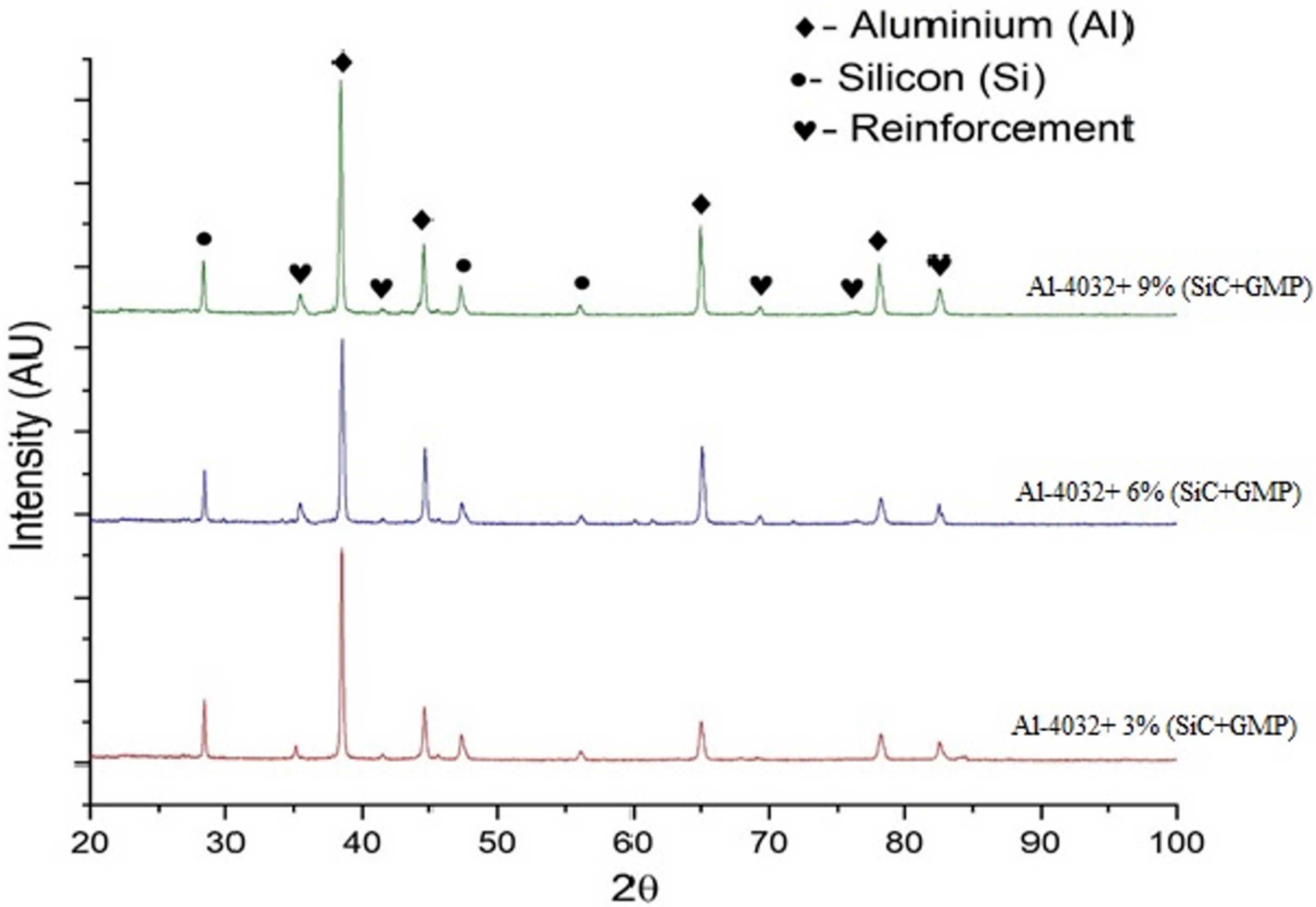


Figure 6

XRD pattern for Al-4032/SiC/GMP hybrid composites

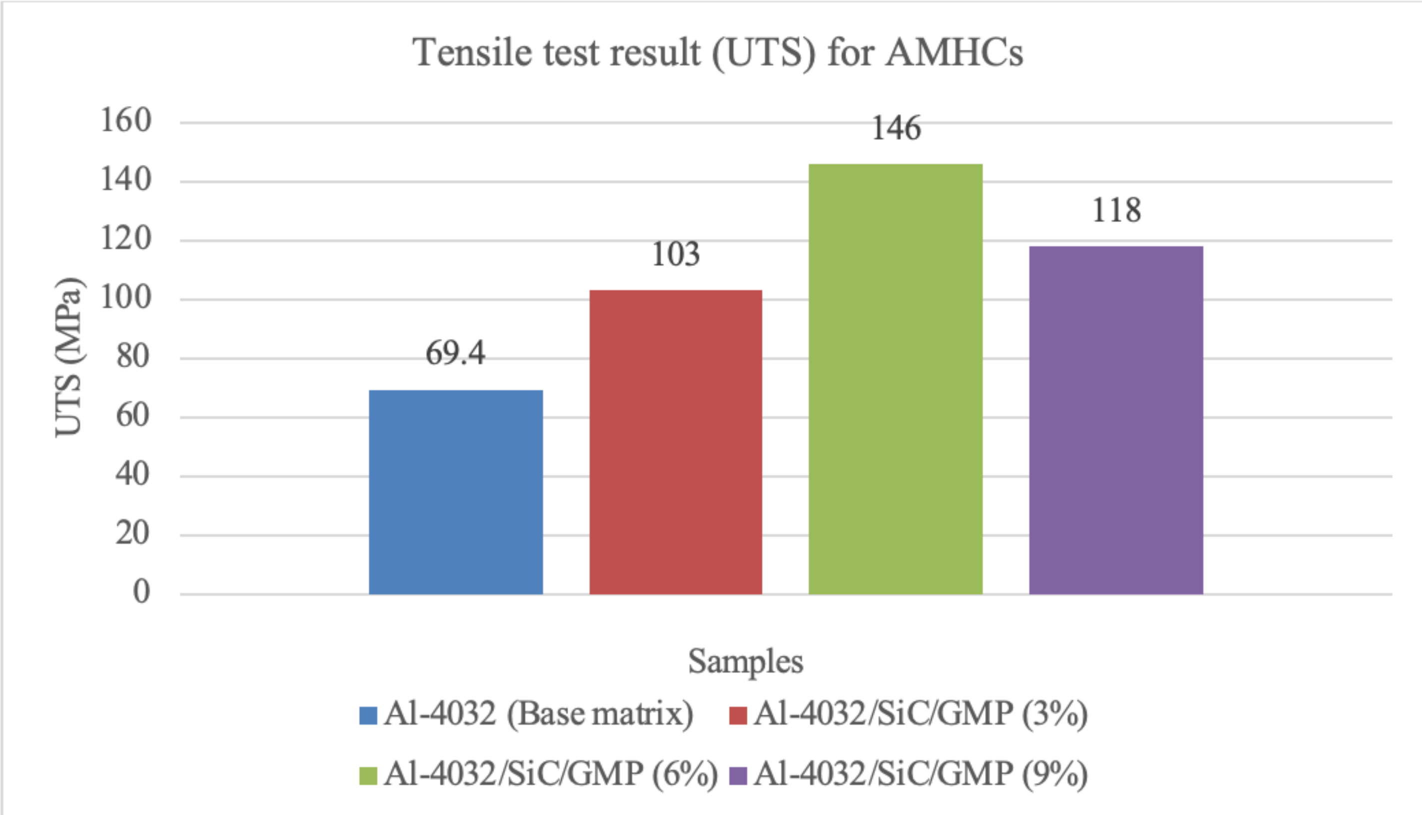


Figure 7

Graphical representation of ultimate tensile strength of AMHCs

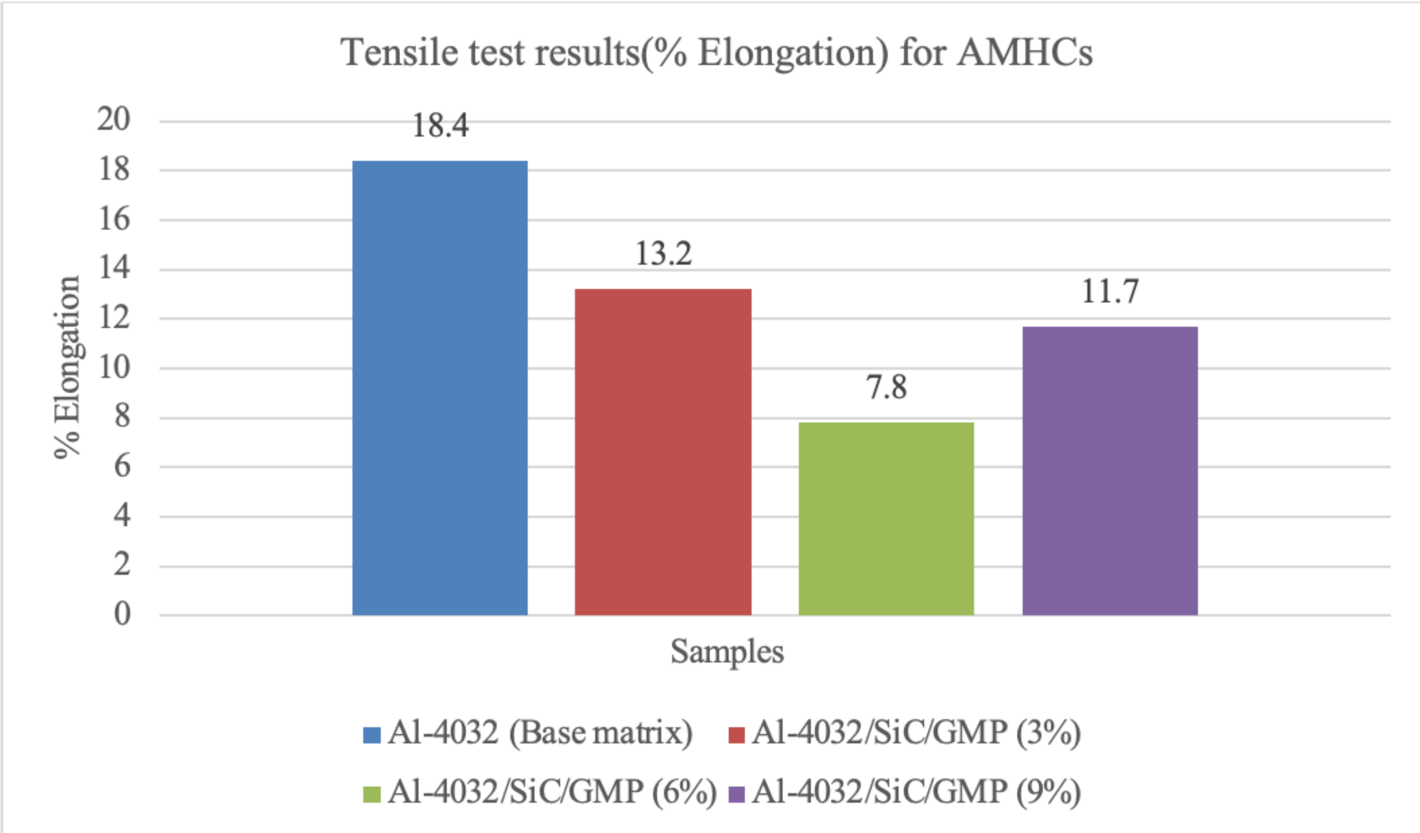


Figure 8

Graphical representation of % Elongation of AMHCs

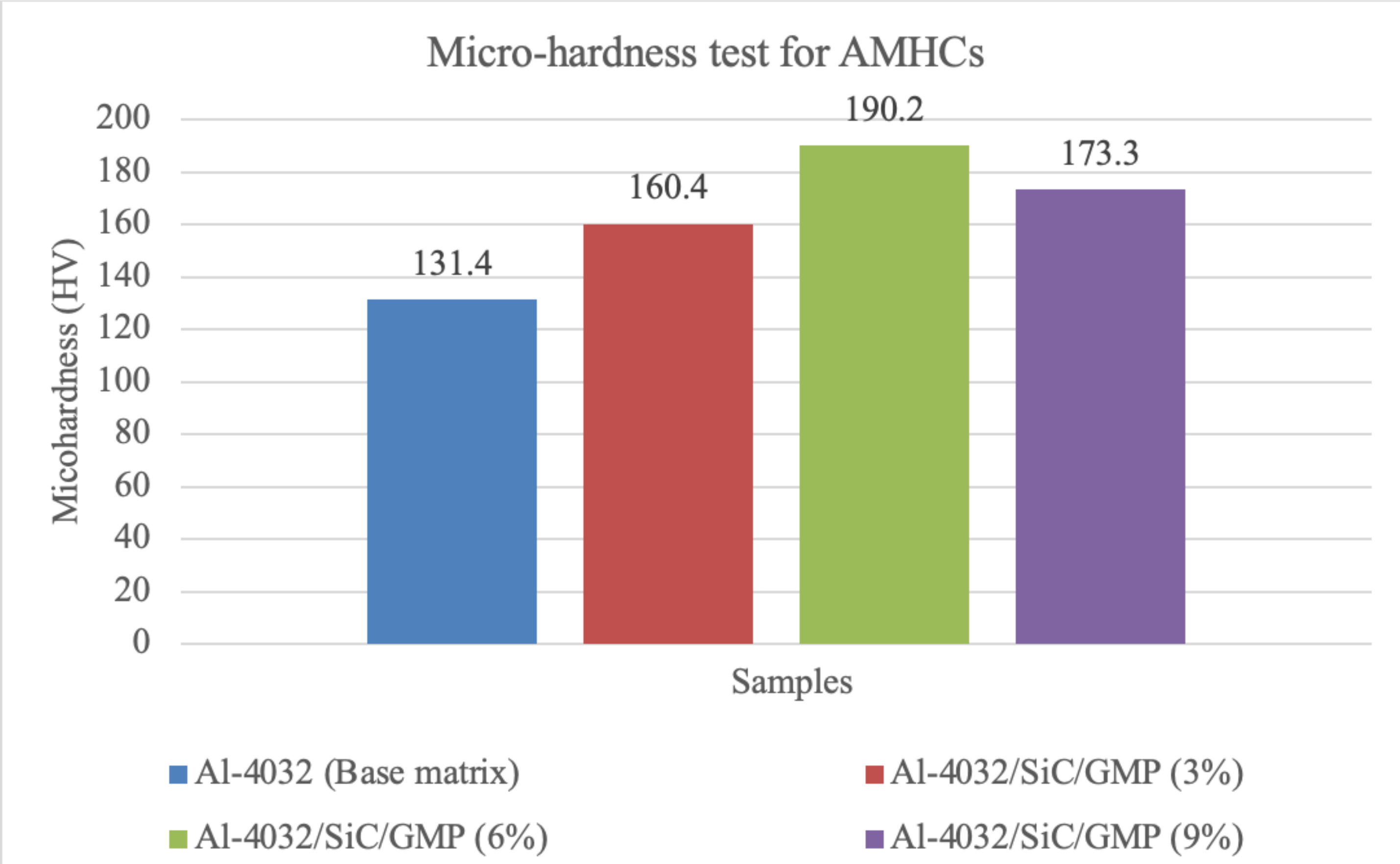


Figure 9

Graphical representation of micro-hardness test results for AMHCs

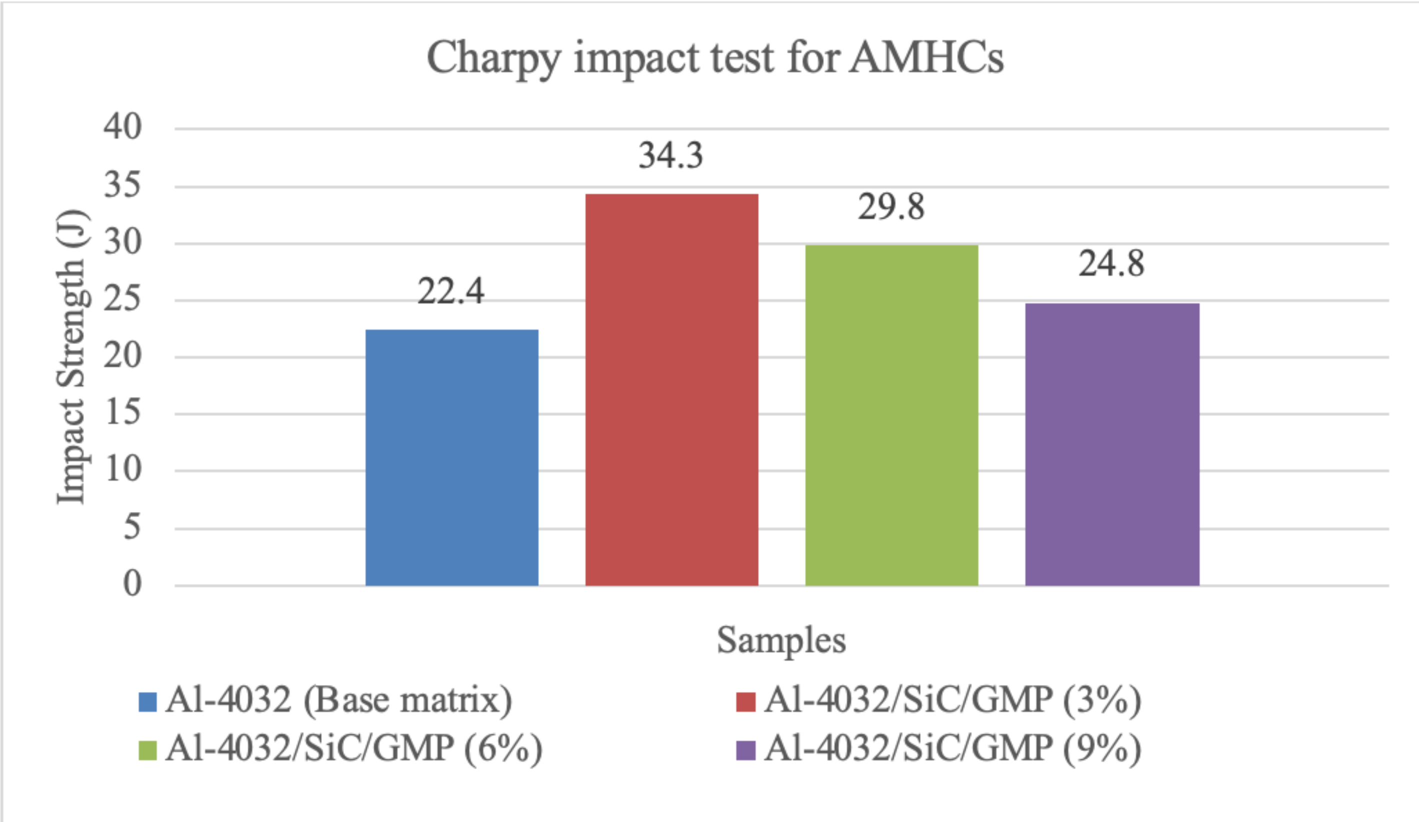


Figure 10

Graphical representation of impact strength test results for AMHCs