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ORIGINAL ARTICLE

Mechanical Characterization and Micro-structural Analysis on AA2024 Hybrid Composites Reinforced with WC and Graphene Nanoparticles

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Abstract The development of new engineering materials is in demand for different kinds of manufacturing sectors. In this context, metal matrix composites have been focused by many industrialists and recent researchers because of their various attractive features. In the present attempt, an aluminium-based hybrid metal matrix composites have been fabricated using stir casting process. AA2024 has been chosen as the base metal and tungsten carbide (WC) and graphene nanoparticles have been used as reinforcements. The size and shape of the reinforcement particles have been confirmed by means of SEM micrographs. By reinforcing the WC particles at different wt% such as 0, 1, 2 and 3, and reinforcing the graphene nanoparticles at 0, 0.15 and 0.3 wt%, 9 different composite samples have been prepared. The tensile, compression, hardness and impact tests have been performed on the prepared composite samples by following respective ASTM standards. The maximum tensile strength of 242.77 MPa and the maximum compressive strength of 398.05 MPa have been noted with the test samples. The tensile failure mechanism has been observed from the SEM micrographs and explained. The characterization study results revealed that there was a significant influence of adding WC and graphene nanoparticles on the mechanical properties of the proposed MMC.

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1 Introduction

Metal Matrix composites (MMCs) are used for manufacturing the parts of automotive and aircraft. The components like piston, piston rings, connecting rods, engine blocks, brake rotors and liners are commercially manufactured using Aluminium Metal Matrix Composites (Al-MMCs). The mechanical and tribological characteristics of Al-MMC's are found to be superior to Al alloys. The inclusion of suitable reinforcement particles helps to improve the desirable properties of Aluminium alloy MMCs [1].

Ravikumar et al. investigated the mechanical properties of aluminium-based metal matrix composites reinforced with tungsten carbide (WC) particles at five different weight fractions such as 2 wt%, 4 wt%, 6 wt%, 8 wt% and 10 wt%. The results of the proposed investigation revealed that the tensile strength of the prepared composite specimens increased with increasing the addition of reinforcement particle initially; after that it followed the decreasing trend. The hardness of the composites got increased with the addition of WC particles [2]. Hariharasakthisudhan et al. fabricated and tested the wear behaviour of aluminium alloy 6061 metal matrix composites reinforced with alumina, graphite and silicon nitride nanoparticles. The proposed composite specimens was fabricated using stir casting process, and subjected to wear test on pin on disc apparatus following ASTM G99 standards. The inclusion of the reinforcement particles resulted in better wear resistance properties with the Al 6061-MMC [3]. Kar et al. prepared AA7075/WC and AA7075/Red mud composites by adding the reinforcements at 3, 6, 9 and 12 wt%. The addition of such reinforcement particles resulted in decrement of impact strength and elongation properties in the prepared MMCs. The ultimate strength value was observed to be improved by 48% with the AA7075/WC composites, whereas the AA7075/red mud composites yielded ultimate strength value which was 71% lesser than the base material [4]. Raghav et al. investigated the mechanical and tribological characteristics of Co-25C cermet nanocomposites reinforced with nanotungsten (W) particles. The hardness and compressive strength values of the Co-25C-8 wt% W nanocomposites were noted to be superior than that of Co-25C-2 wt% W nanocomposites [5]. Nykiel et al. characterized the mechanical and wear behaviour of AISI-316L metal matrix composites reinforced with titanium carbide (TiC) particles. The composite specimens for the investigation were fabricated using powder metallurgy technique. The authors reported that the addition of TiC particles improved the hardness and wear resistance of the AISI-316L MMC [6].

Selvam et al. characterized the mechanical properties of AA6061/titanium bromide/alumina hybrid metal matrix composites. The SEM micrographs taken on the prepared composite specimens confirmed the uniform distribution of the reinforcement particles in the aluminium alloy. In the micrographs, the dispersion of alumina particles was identified with spherical shape; and the TiB_2 particles with the hexagonal and cubic shapes. The hardness and tensile strength of the particle reinforced composites seemed to be better [7]. Krishnan et al. tested the influence of adding waste materials and scrap aluminium on the mechanical properties of aluminium alloy metal matrix composites. The scrap aluminium alloy/alumina composites yielded better physical and mechanical properties (among the proposed composites with four different combinations) such as lowest porosity, highest hardness, and highest ultimate compressive strength [8]. Several research studies confirm that the aluminium-based metal matrix composites are mostly fabricated by means of stir casting process. And the relevant literatures reported that the mechanical and wear resistance characteristics got improved while adding suitable reinforcement particles with aluminium alloys such as silicon carbide (SiC), boron carbide (B_4C), alumina (Al_2O_3), titanium carbide (TiC), tungsten carbide (WC), titanium bromide (TiB_2), silicon nitride (Si_3N_4) etc., at correct proportions [9, 10]. Hariharasakthisudhan et al. analysed the influence of metal powder premixing on the mechanical characteristics of AA6061/Al_2O_3, AA6061/Si_3N_4 composites, and AA6061/Al_2O_3/Si_3N_4 hybrid metal matrix composite. The hybrid MMC showed superior tensile properties than the prepared composite specimens with single reinforcement. The authors also reported that the yield strength, ultimate strength and ductility of the AA6061 composites were highly dependent on the premixing of Si_3N_4 nanoparticles [11]. Logesh et al. studied the mechanical behaviour of AA356/AlN/MWCNT/Graphite/Al powder MMCs. The composite specimens were prepared with different volume fractions of the reinforcement particles. Tensile test, compression test and hardness test were performed on the prepared composite specimens by following the respective ASTM standards. The optimum volume fractions of reinforcement for achieving better mechanical properties were identified and reported as MWCNT: 1% and AlN: 0.75% [12].

Ravikumar et al. performed an analysis on the mechanical properties of AA6063/TiC MMCs. SEM micrographs and the XRD patterns were used for analysing the fracture mechanism. Mechanical properties like hardness, tensile strength and physical property (density) were noted to be significantly increased with the addition of titanium nitride particles to the AA6063 [13]. Srivastava et al. investigated the effect of adding graphite nanoparticles on the mechanical characteristics of AA1100 metal matrix composites. The maximum yield strength and ultimate strength could be achieved with the AA1100/graphite nanoparticles MMCs reported as 155.67 MPa and 170.28 MPa, respectively [14]. Venkatesan et al. analysed the positive changes in the tensile behaviour of AA7050 metal matrix composites when reinforced with graphene particles. The investigation results clearly revealed that the minor addition of graphene particles to the AA7050 MMC helped to improve the tensile characteristics; however, the inclusion of graphene particles beyond 0.3 wt% led to cluster formation [15]. Hariharasakthisudhan et al. performed multi-objective optimization to predict the optimal combination of input variables and percentage of reinforcement to achieve better wear characteristics to AA6061/Al_2O_3/Si_3N_4/graphite nanoparticles hybrid nanocomposites. The research findings stated that the inclusion of Si_3N_4 particles to the AA6061 MMC helped to reduce the wear rate significantly [16]. Logesh et al. had fabricated aluminium-based metal matrix composites to analyse the influence of stir casting process parameters on the physical, tensile and wear properties [17].

The extensive literature survey reveals that the researchers in the field of Metal Matrix Composites have so far carried out several attempts on improving the mechanical properties of various metal matrix composites by adding different reinforcement particles. Also it is evident from the literature study that the addition of more than one reinforcement results in comparable improvement in the mechanical properties over that of the inclusion of single reinforcement. Aluminium alloy 2024 (AA2024) has been found to have good fatigue resistance and better strength to weight ratio. It shows that no work has been still attempted on preparing and characterizing the AA2024 metal matrix composites by adding tungsten carbide (WC) nanoparticles and nanographene powder as reinforcements. Hence, in the present work, it has been planned to prepare AA2024/WC/Graphene MMCs at different proportions and to analyse the improvement in the mechanical properties such as tensile strength, compressive strength, hardness and impact strength with reference to the base material.

2 Materials and Methods

AA-2024 alloys were commercially purchased in the form of rods and cut into small pieces in order to stack in the furnace. The chemical composition of AA-2024 used in the present work is detailed in Table 1. The melting point and mass density of the base metal were noted to be 500 °C and 2.78 g/cc, respectively.

The reinforcement particles such as tungsten carbide (WC) nanoparticles and graphene nanopowder were purchased from Sigma-Aldrich with 98.5% purity. The SEM images taken on the reinforcement particles are shown in Fig. 1a, b. The spherical shaped WC particles were noted from Fig. 1a with average size of 43.62 nm. The microimages revealed that the shape and size of the graphene nanopowder were platelet shape and 30.44 nm, respectively.

The energy-dispersive spectroscopy images (EDX) taken on the reinforcement particles are presented as Fig. 2a, b. The presence of tungsten (W), carbon and oxygen can be noted from Fig. 2a. The higher amount of carbon content present in the graphene nanopowder was noticed from the EDX plot as shown in Fig. 2b. The other significant elements noted in the EDX graph of graphene particles were sodium (Na), sulphur (S) and oxygen (O). Thus the generated EDX plots confirmed that the tested particles were tungsten carbide and graphene.

Aluminium-based metal matrix composite specimens were prepared with nine different compositions of base metal and proposed reinforcements. Tungsten carbide particles were added in different wt% viz. 0, 1, 2 and 3; and the graphene particles were added in different wt% such as 0.1 wt% and 0.3 wt% to the base metal. The proposed compositions of composite specimens are detailed in Table 2.

For preparing the proposed composite specimens, stir casting process was used. In each case, the required amount of aluminium alloy 2024 metallic bar pieces was taken in an EN8 steel crucible of size 55 × 150 mm, and kept inside an electric resistance heating furnace. The temperature of the furnace was maintained at 750 °C. By keeping the AA2022 at molten state, the pre-heated reinforcement particles were added in the correct proportion. Mechanical stirrer was used for about 10–20 min at an average speed of

Table 1 Chemical composition of AA2024 in Wt%

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Max	0.5	0.5	4.9	0.9	1.8	0.1	0.25	0.15	Remaining
Min	0	0	3.8	0.3	1.2	0	0	0	Remaining
Actual	0.163	0.18	4.04	0.825	1.38	0.0134	0.0346	0.0233	Remaining

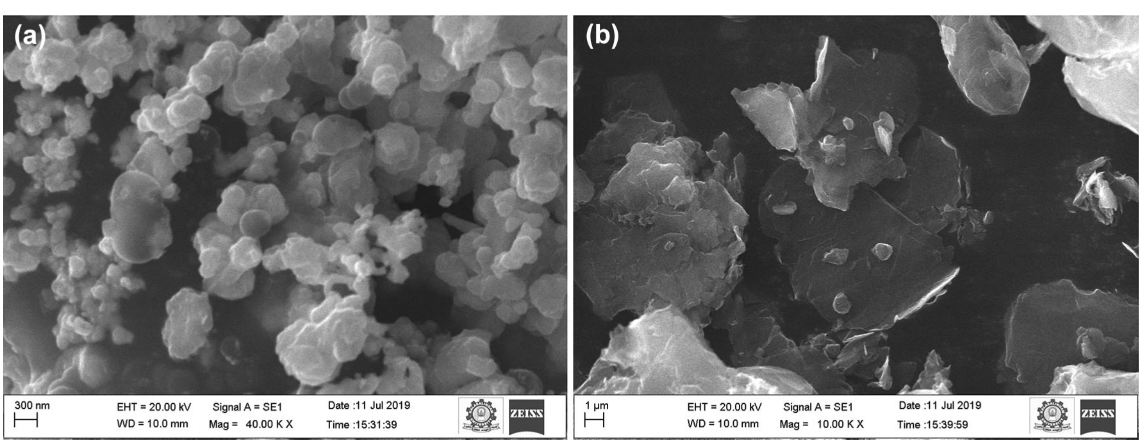

Fig. 1 SEM micrographs of **a** WC, and **b** Graphene nanopowder

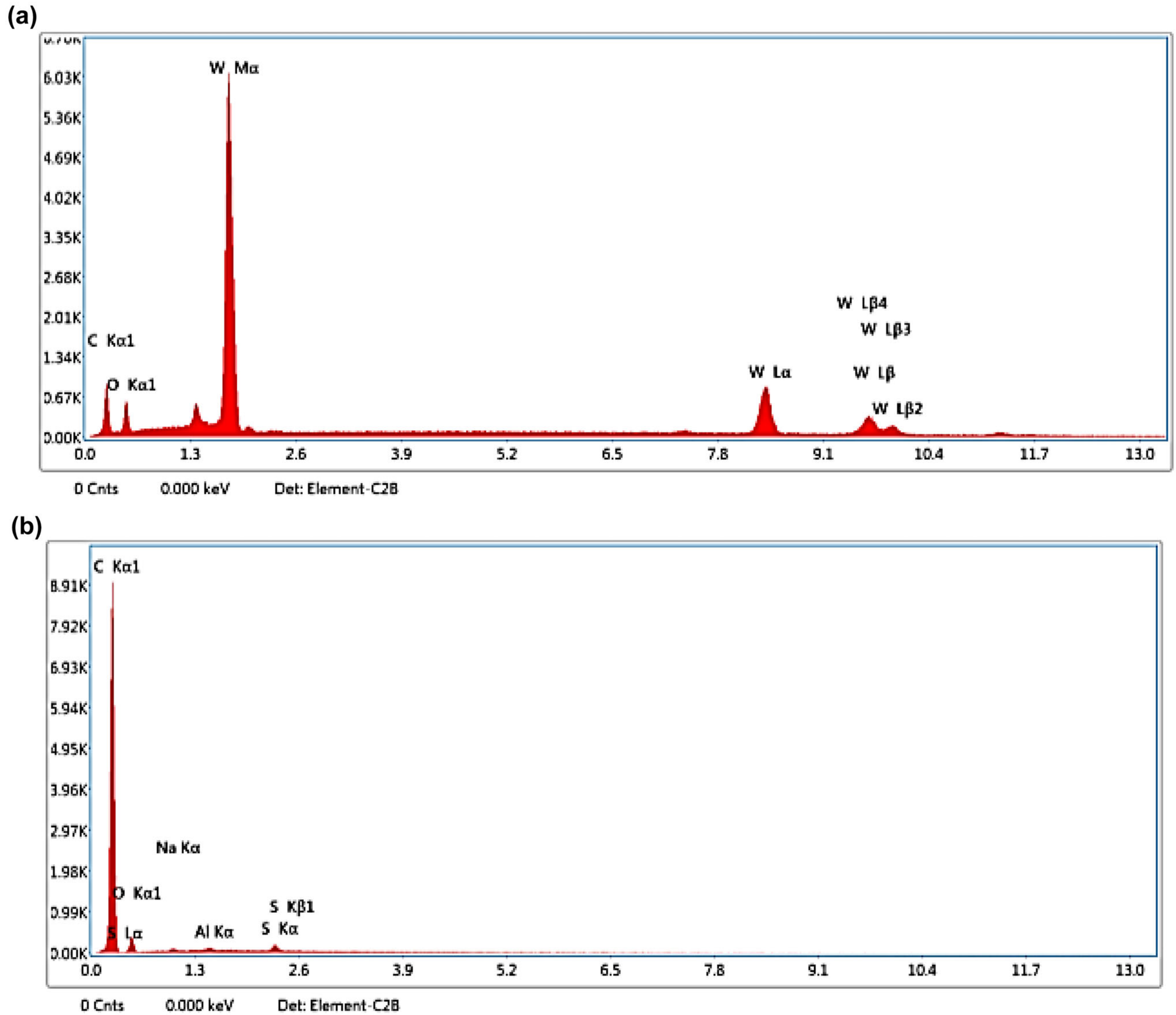

Fig. 2 EDX images of **a** WC, and **b** Graphene

750 rpm for agitating the molten metal by creating the turbulence. The depth of the mechanical stirrer was kept around 2/3rd of the height of molten metal from the bottom of the crucible. The molten metal was allowed to keep in the crucible for about 30 min. The molten metal was then poured into a mild steel die of size 20 mm × 280 mm and allowed to solidify. Then the specimens were taken from the mold and the casted composites were polished and the SEM images of the microstructure were observed and presented in Fig. 3.

The SEM images taken on all the prepared composite specimens clearly indicated that the reinforcement particles were uniformly distributed in the aluminium metal matrix. The EDX plot taken on a composite specimen (C9) is presented in Fig. 4, in which the distribution of tungsten carbide and graphene nanopowder particles was witnessed.

Table 2 Proposed composition of AA2024 composites

Sample	AA2024 (wt%)	WC (wt%)	Graphene (wt%)
C1	100.00	–	–
C2	099.85	–	0.15
C3	099.70	–	0.30
C4	098.85	1	0.15
C5	098.70	1	0.30
C6	097.85	2	0.15
C7	097.70	2	0.30
C8	096.85	3	0.15
C9	096.70	3	0.30

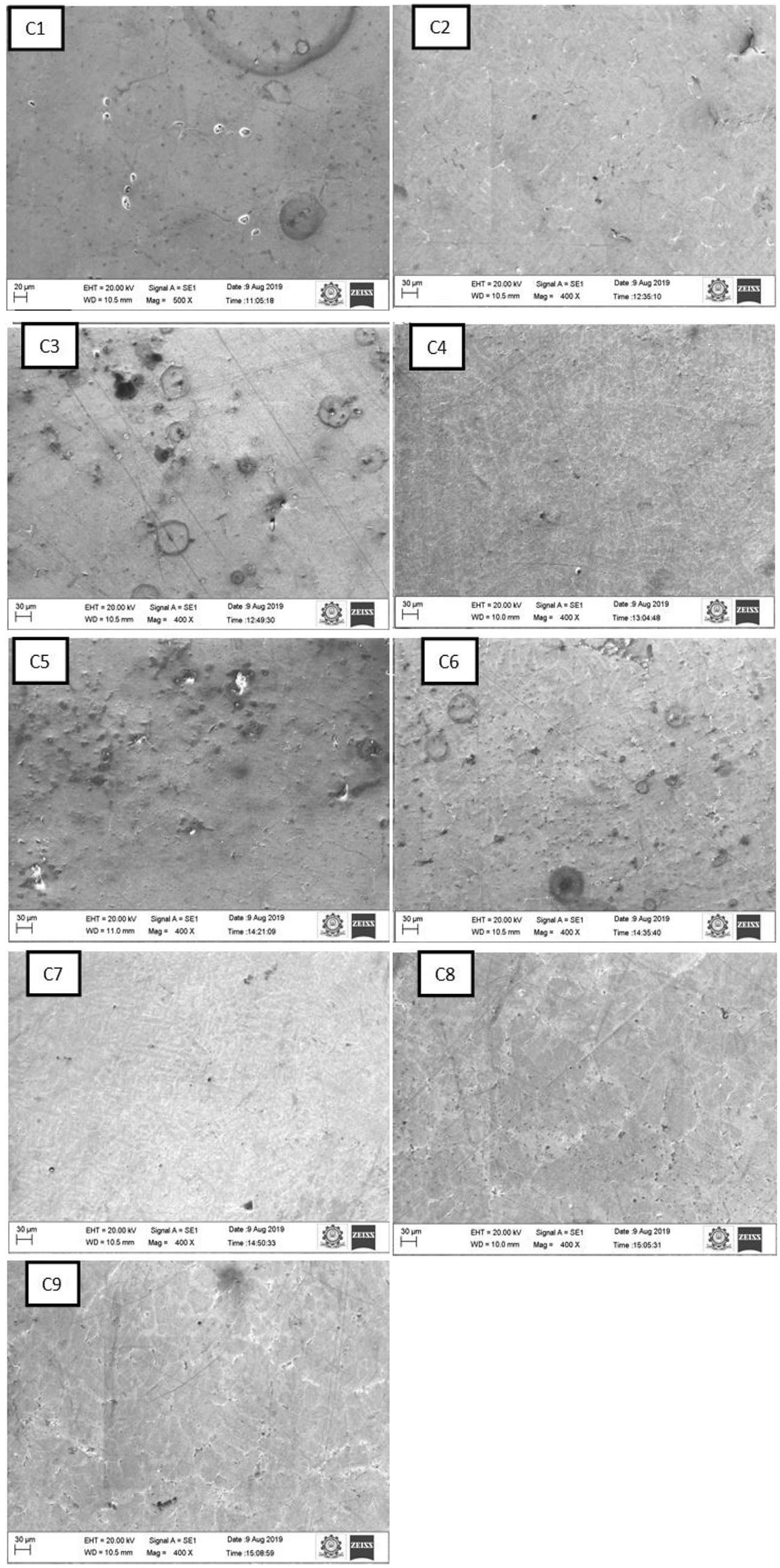

Fig. 3 SEM images of prepared composite samples

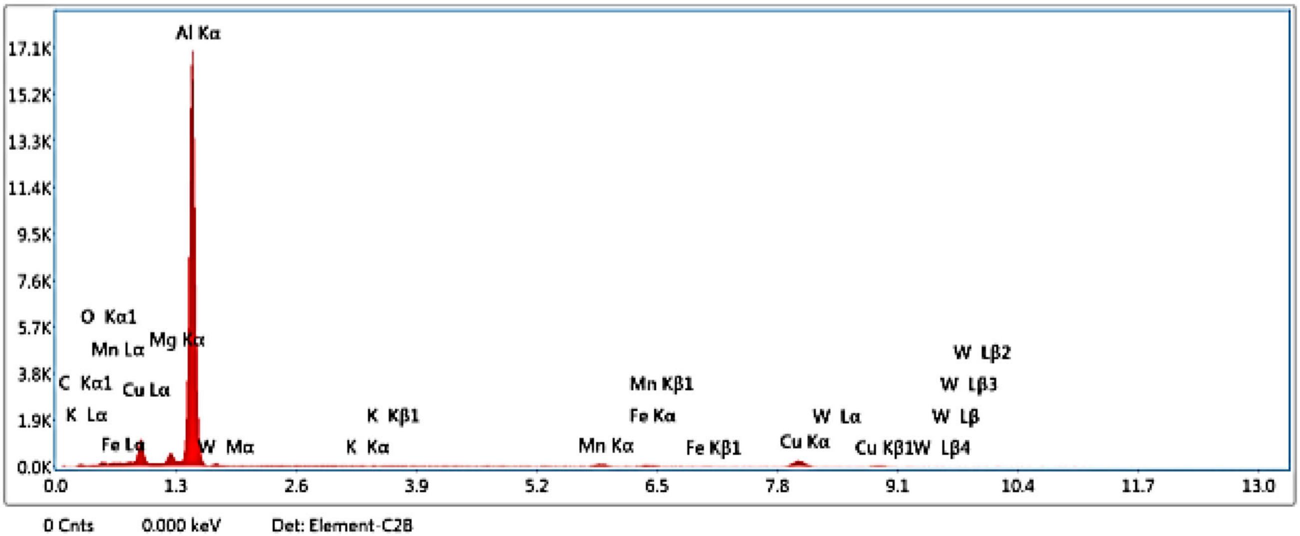

Fig. 4. EDX plot taken on C9 composite specimen

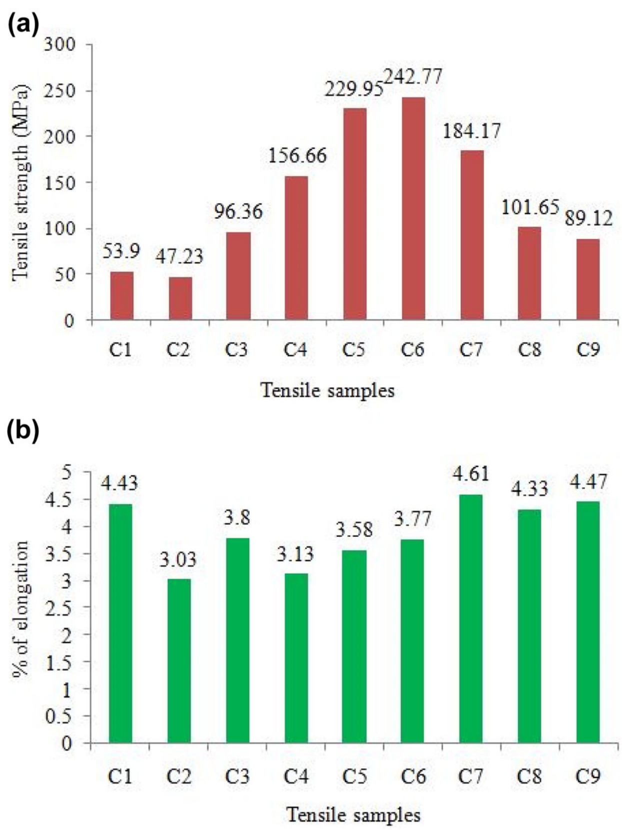

Fig. 5 **a** Tensile strength results for the proposed composite samples. **b** % of elongation results for the proposed composite samples

In Fig. 4, the presence of aluminium, oxygen, tungsten and carbon was witnessed as the major elements, which confirmed that the tested sample was an aluminium-based metal matrix composite sample hybridized with WC and graphene particles.

The test specimens were prepared with respective ASTM standards for mechanical characterization. Tensile specimens were prepared by following ASTM-E8 standard. Compression test and Vicker's hardness test specimens were prepared based on the ASTM standards E9 and E18-07 standards, respectively. Impact test specimens were prepared with standard dimensions.

3 Results and Discussion

3.1 Effect of the Inclusion of Reinforcement Particles on Tensile Properties

The tensile test results for the proposed composite samples are presented in a bar chart as shown in Fig. 5a, b.

From Fig. 5a, it was clear that the addition of the selected nanoreinforcement particles had improved the bonding in the interface between the matrix medium and the added reinforcement medium, in turn the tensile properties of AA2024 MMC for sure. From Fig. 5b, it is palpable that the addition of WC and graphene nanoparticles improved the tensile behaviour of the prepared composite samples to some extent. This phenomenon is due to the obstacles created by the added reinforcement particles towards the crack propagation [2]. However, the tensile strength showed decreasing trend with the further addition of nanoparticles beyond 2 wt% of WC particles. The reason behind the decrement in the results is attributed to the agglomeration of the reinforcement particles in the grain boundaries [3]. Similarly, with the 0 and 1 wt% of WC addition, the higher inclusion of graphene nanoparticles (0.3 wt%) resulted in better tensile properties. But, the

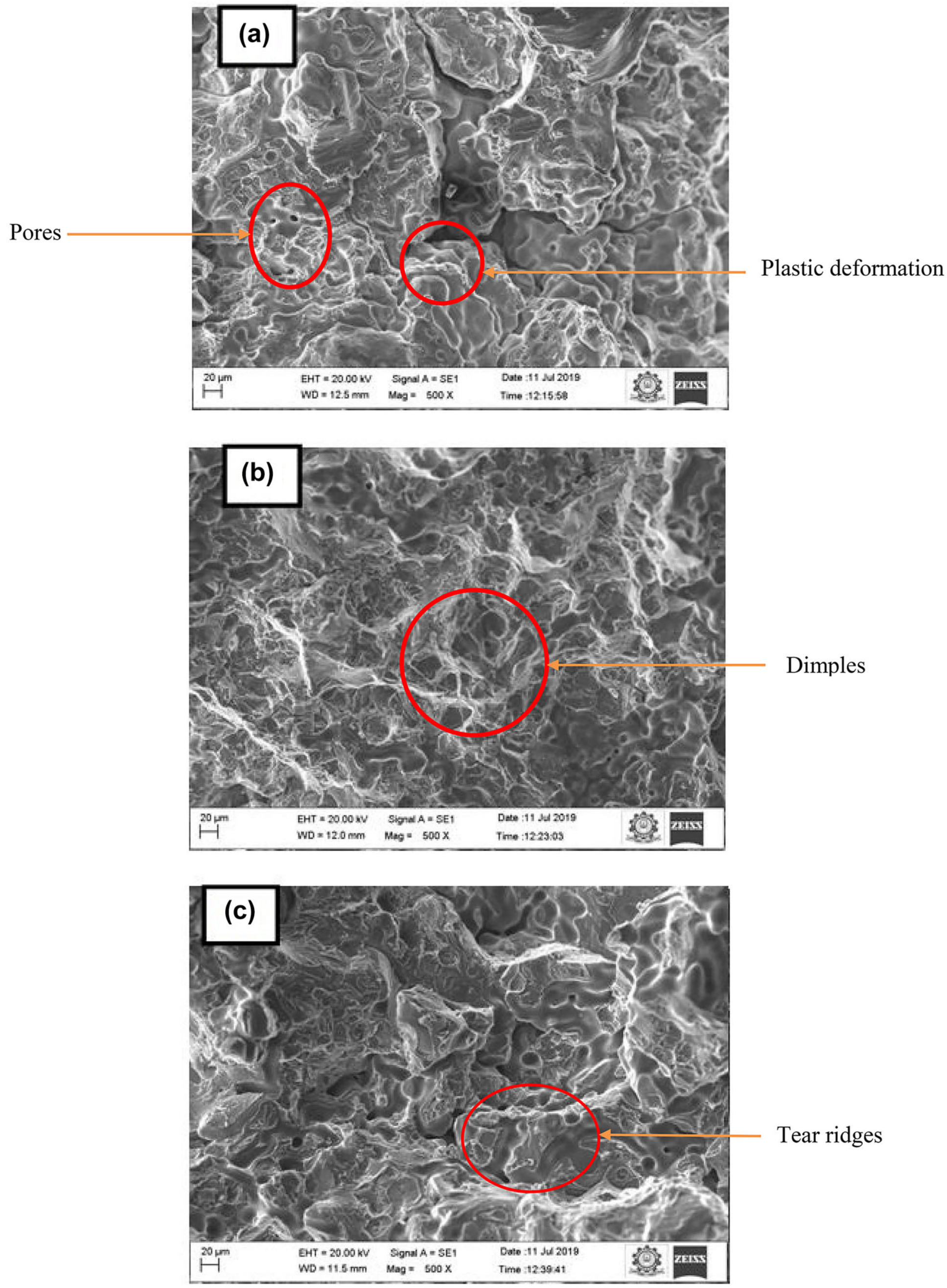

Fig. 6 Tensile fractured specimens of **a** sample C1, **b** sample C8, and **c** sample C6

strength got reduced with the graphene particles while increasing the addition of WC particles.

The tensile fractured specimens of samples C1, C8 and C6 are shown in Fig. 6a–c. Porous media and plastic deformation were observed in sample C1 from Fig. 6a, which resulted in poor results in tensile strength value in comparison with that of the other proposed samples. The absence of pores and the presence of dimples were noted on the surface of the fractured tensile sample C8 which is shown in Fig. 6b. These can be attributed to the addition of WC particles and graphene particles with the base metal. Tear ridges were observed in the SEM images taken on the fractured tensile sample C6 as shown in Fig. 6c. The occurrence of tear edges is due to the resistance offered by the WC and graphene particles against fracture, and which are uniformly distributed along the grain boundaries. From the test results, it is palpable that the sample 6 exhibited better tensile strength compared to others.

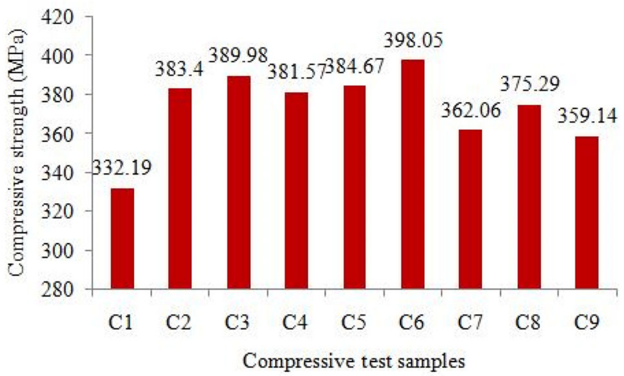

Fig. 7 Compression test results for the proposed composite samples

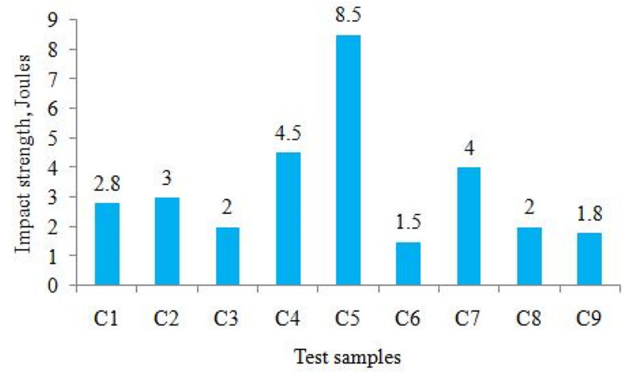

Fig. 8 Impact strength results of the composite samples

3.2 Effect of the Inclusion of Reinforcement Particles on Compression Strength

The results of the compression test taken on the proposed composite specimens are plotted and presented in Fig. 7. The result trend seems to be very much similar to that of the tensile results.

It is already known that the graphene particles will get buckled for the compressive loading condition. Therefore, the contribution of graphene nanoparticles on the compressive strength of the AA2024 MMC will almost be negligible [18]. This fact can be observed from the results shown in Fig. 7. There is no significant difference between the compressive strength of the prepared test samples with the inclusion of graphene nanoparticles.

The compression test results shown in the bar diagram clearly indicated that the compression strength of the AA2024/WC/Graphene hybrid composite specimens is superior to that of the base metal. As the compression strength of the tungsten carbide particles is very much higher than that of the base metal, obviously the compression strength of the composite specimens has got improved [19]. The enhancement of compressive strength was noted with the increase in the WC particles up to 2 wt%. The maximum value of compressive strength (398.05 MPa) was noted for the C6 composite sample which contains 2 wt% of tungsten carbide and 1.5 wt% of graphene nanoparticles.

3.3 Effect of the Inclusion of Reinforcement Particles on Hardness

The hardness test results of the proposed composite samples are provided in Table 3. It is evidenced from Table 3 that the uniform distribution of the included reinforcement particles improves the hardness of the composites. However, the composite samples C7, C8 and C9 showed decrement in hardness values which may be due to the clustering effect of the reinforcement particles [12].

Generally, the hardness value of the metal matrix composites gets increased by means of including hard reinforcement particles which offers more resistance towards indentation. Increasing the wt% of tungsten carbide resulted in improved hardness in the AA2024 MMCs.

Table 3 Hardness test results

Specimen	Hardness Values HV @ 0.5 kg Load, Dwell: 10 Sec			
	Location-1	Location-2	Location-3	Avg. Hardness, HV
C1	117.2	113.3	120.4	117.0
C2	122.1	117.8	126.5	122.1
C3	104.0	118.5	118.3	113.6
C4	122.3	122.0	125.6	123.3
C5	120.0	100.8	119.5	113.4
C6	123.2	122.3	121.4	122.3
C7	112.3	107.4	116.2	112.0
C8	108.9	97.6	110.3	105.6
C9	117.5	108.9	112.6	113.0

Separately WC is much harder than the base metal in nature [19]. In addition to that, under loading condition, WC shares major amount of load transferred from the matrix medium. A reverse trend was noted with the addition of graphene nanoparticles. The addition of graphene particles reduced the hardness of the composite samples [2]. When 0.15 wt% of graphene particles was added to the base metal, the hardness value got improved over the base metal [18] by 4.36%. The maximum hardness value was obtained with the composite sample C4 (123.3 HV), followed by C6 (122.2 HV).

3.4 Effect of the Inclusion of Reinforcement Particles on Impact Strength

The effect of adding tungsten carbide and graphene nanoparticles on impact strength of the prepared composite samples is presented in Fig. 8.

The effect of adding the proposed nanoparticles presented in Fig. 8 showed a monotonic response on the impact strength results. The impact strength of the pure AA2024 alloy material was noted as 2.8 J. While adding 0.15 wt% of graphene particles, the impact strength of the composite specimen got improved by 7.14%. But, the inclusion of graphene particles by 0.3 wt%, the impact strength got reduced by 28.57% in comparison with that of the base metal. The uniform dispersion of graphene particles (up to 0.15 wt%) increased the resistance towards the suddenly applying loading condition for the MMCs, which resulted in enhanced impact strength [14]. In the AA2024/WC/Graphene nanoparticles reinforced hybrid composites, the impact strength got improved with the addition of 1 wt% of WC along with graphene nanoparticles. The maximum decrement in the impact strength compared to the base metal was recorded with C6 composite sample as 46.43%. The maximum value of impact strength was achieved with the C5 composite sample (8.5 J). The much inclusion of WC improved the hardness in turn brittleness in the MMCs which reduced the impact strength beyond 1 wt% [2].

4 Conclusions

The AA2024-based hybrid composite specimens reinforced with tungsten carbide and graphene nanoparticles were prepared and tested for the mechanical properties. The important conclusions arrived from the proposed study results are as follows.

- Significant influence in the morphology of the prepared composite specimens due to the inclusion of the reinforcements such as WC and graphene nanoparticles was observed and reported.
- The addition of WC and graphene nanoparticles improved the tensile behaviour of the prepared composite samples up to 2 wt% due to the obstacles created by the added reinforcement particles towards the crack propagation.
- Tear ridges were observed in the SEM images taken on the fractured tensile sample which showed maximum tensile strength due to the inclusion of optimal WC particles.
- No significant difference was noted between the compressive strength of the prepared test samples with the inclusion of graphene nanoparticles.
- Increasing the wt% of tungsten carbide particles resulted in improved hardness in the AA2024/WC/Graphene hybrid composite.
- The inclusion of WC beyond 1 wt% resulted in improved hardness in turn brittleness in the hybrid composite which reduced the impact strength of the composite.
- In overall, better mechanical properties can be achieved with AA2024/WC/Graphene hybrid composites by adding 2 wt% of WC nanoparticles and 0.15 wt% of graphene nanoparticles.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest.

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