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Characterization of mechanical properties of aluminium/tungsten carbide composites

K. Ravikumar [*], K. Kiran, V.S. Sreebalaji

Department of Mechanical Engineering, Dr. N.G.P Institute of Technology, Coimbatore 641048, India

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This study deals with the investigation on mechanical properties of aluminium alloy (AA 6082) composites reinforced with tungsten carbide particles. Stir casting process was employed to fabricate the aluminium composite specimen by varying tungsten carbide in 2, 4, 6, 8 and 10% by weight. The composites were exposed to density, hardness, tensile and impact studies. Scanning electron microscope was used to investigate the mechanism of the fractured tensile and impact test specimen. The density, impact strength and elongation of the composites decreased with increase in addition of tungsten carbide, while the hardness of composites increased with increase in tungsten carbide. The tensile strength of the composites increased initially and then tends to decrease. Fracture of the composites is characterized by dimples, voids, cracks, ridges, pits and particle fracture. Brittle fracture of composites in the form of cracks and particle fracture are due to the strong interfacial bonding between the tungsten carbide and aluminium matrix at high strain rate. High impact strength of composites are due to ductile failure in the form of dimples, while low impact strength are due to brittle and plastic deformation characterized by micro and macro cracks, particle fracture.

1. Introduction

Metallic Matrix Composites (MMCs) reinforced with ceramic particles very encouraging materials for marine, defense, aerospace and automotive applications that require stronger, light weight and less expensive materials. Aluminium matrix composites owning excellent properties like high stiffness, high strength, high fatigue resistance, low density and superior wear resistance at elevated temperature is a challenging replacement for conventional alloys. Selection of appropriate reinforcement particles and fabrication process with a control over processing conditions improves the mechanical properties of composites. Doel et al. [1] revealed that the tensile and fracture toughness of aluminium/SiC composites fabricated by co-spray deposition process differs with the ageing conditions and inter particle spacing. Composites reinforced with fine particulates showed better yield strength, fracture stress and ductility compared to those of composites reinforced with coarse particulate. Velasco et al. [2] fabricated aluminium/Fe_3Al particles by powder metallurgy technique and reported that the composites exhibited better tensile strength than the conventionally forged components. Peng et al. [3] fabricated aluminium matrix composites by squeeze casting and observed that the composites reinforced with alumina in the form of perform exhibited higher tensile strength compared to that of the alumina fiber reinforced composites. Kok [4] employed vortex method and subsequently applied pressure to fabricate composites and revealed that coarser Al_2O_3 particles dispersed uniformly in aluminium matrix, while agglomeration and porosity were observed in composites with finer Al_2O_3 particles. In situ mechanical properties of Al–Lithium alloy reinforced with SiC particles studied by Rodriguez et al. [5] exposed that hardness of the composites was higher than that of the base alloy and decreases with increase in distance from the reinforcement particle. Hamouda et al. [6] worked on processing aluminium/quartz/silicon dioxide composites by sand mould technique and suggested that decrease in tensile strength and young's modulus of composites are due to increase in silicon dioxide content and the quartz particulate having high compressive strength. Yadav et al. [7] embedded nickel particles into Al matrix by friction stir processing and reported that the composite exhibited significant improvement in tensile strength with an appreciable retention in ductility.

Anilkumar et al. [8] processed aluminium/fly ash composites by stir casting process and reported that increase in reinforcement particle size decreased the strength, hardness and ductility of

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[*] Corresponding author.
E-mail addresses: ravik_krish@yahoo.com (K. Ravikumar), kirankarthik91@gmail.com (K. Kiran), balajivsv71@gmail.com (V.S. Sreebalaji).

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composites. Wichianrat et al. [9] developed aluminium/SiC composites and observed that the impact strength and micro hardness of composites increased due to the modification in microstructure at the residing node and struts of the ceramic particles. Rajmohan et al. [10] reported that the density of aluminium composites reinforced with mica was higher than those of the composites reinforced with SiC fabricated by stir casting process. Aruria et al. [11] fabricated aluminium, SiC and Al_2O_3 particles by friction stir processing and reported that increase in micro hardness of composites is due to the pining effect of SiC and Al_2O_3 particles. Kumar et al. [12] reported that the tensile surface of aluminium was branded by uneven distribution of dimples leading to ductile failure, while aluminium fly ash composites fabricated by stir cast route is characterized by brittle failure due to the plastic flow of the matrix. Sivaprasad et al. [13] worked on stir cast rice husk ash and SiC particles reinforced composites and reported that the density, coefficient of thermal expansion of hybrid composites decreased, while the yield strength, ultimate tensile strength, porosity and hardness increased in composites. Vijaya Ramnath et al. [14] observed that the impact strength and hardness of unreinforced aluminium was less than that of the alumina/boron carbide reinforced composite. Das et al. [15] reported that the impact strength of aluminium matrix composites increased due to ageing and the mechanical failures are due to the initiation and growth of micro cracks, particle pull-out and particle fracture. According to Amirkhanlou et al. [16] the tensile strength of composites increased with increase in number of continual annealing and press-bonding process cycles. Bodunrin et al. [17] reported that boron carbide, alumina, silicon carbide, graphite and carbon nano tubes can be used as reinforcement particles in aluminium composites. Ghasali et al. [18] fabricated Al/boron carbide composites using a microwave furnace for sintering and reported that the hardness and strength of composites increased with increase in addition of boron carbide. Sharma et al. [19] found that addition of 12% of graphite decreased the hardness of the aluminium alloy by 11.1% and revealed a non-uniform distribution of graphite particles. Rana et al. [20] recorded that aluminium composites reinforced with SiC, Al_2O_3, fabricated by ultrasonic assisted stir casting decreased the porosity of composites leading to higher tensile strength, compression strength, hardness and elastic modulus of the composites was Alaneme and Sanusi [21] worked on alumina, rice husk ash and graphite based aluminium matrix hybrid composites and observed that the % elongation of composites decreased in the range of 10–13%. Kursun et al. [22] reinforced glass bubbles with aluminium–alumina matrix composites and reported that the addition of glass bubbles decreased the density, plastic deformation, impact strength and compression strength of the composites.

Rashad et al. [23] attributed that increase in strength of aluminium/graphene nano platelets composites is due to the change in load transfer mechanism, crystallographic texture and dislocation densities between the aluminium alloy and the platelets. Singh and Chauhan [24] observed that fly ash, SiC aluminium alloy were not uniformly distributed in aluminium composites due to the gravity regulated segregation of particles in the melt. Tamilarasan et al. [25] investigated the mechanical properties of carbon fiber reinforced aluminium sandwich laminates and observed pit formation, fuzziness, debonding and fiber fracture on the surface. Radhika and Raghu [26] recorded that the functionally graded aluminium composites reinforced with SiC, Al_2O_3 and Al/TiB_2 exhibited higher hardness and tensile strength at the particle-rich outer region of the specimen.

Harichandran and Selvakumar [27] added micro and nano B_4C carbide particles to aluminium matrix by stir and ultrasonic cavitation assisted casting processes and reported that the nano composites exhibited better tensile stress, ductility and impact energy compared to that of micro B_4C particle-reinforced composites. Jiang et al. [28] fabricated aluminium/iron bimetallic composites by hot-dip galvanizing and aluminizing method and observed uniform and compact intermetallic layer between the aluminium and the iron.

From the literature review, it is implicit that works were carried to study the mechanical properties of various metal matrix composites fabricated by different liquid and solid state techniques. Aluminium alloy (AA 6082), a medium strength alloy having outstanding corrosion resistance and good machinability replaces other similar kind of alloys in engineering applications. Presence of large amount of manganese in AA6082 alloys control the grain structure making it a very strong competent even at elevated temperatures. Studies revealed that adequate investigations were not carried out using Tungsten Carbide (WC) as a potential reinforcement in aluminium matrix composites. Tungsten carbide owing to its high hardness, low density, high strength, high rigidity, good chemical stability and better resistance at high temperature is one of the most promising ceramic materials. An attempt has been made in this study to explore the mechanical properties like hardness, density, tensile strength, impact strength, elongation and the related mechanisms of aluminium (AA6082)/tungsten carbide composites. Stir casting is one of the low cost processes employed in the present study for manufacturing the composites.

2. Materials preparation

In this work, aluminium alloy (AA6082), shown in Table 1 in the form of rod of 100 mm diameter and 300 mm length is used as base material, while tungsten carbide with particle size in the range of (53–75) μm is used as reinforcement. The properties of AA6082aluminium alloy is shown in Table 2. The density of the tungsten carbide and AA6082 aluminium alloy is 2.05 g/cm^3 and 2.69 g/cm^3 respectively. Composite samples were prepared by varying tungsten carbide in 2, 4, 6, 8 and 10% by weight. Stir casting process is one among the highly productive, low cost manufacturing techniques used to fabricate aluminium matrix composites for a wide range of processing conditions [24]. Aluminium metal matrix is melted in a graphite crucible at 850 °C by stir casting process as shown in Fig. 1. Simultaneously the tungsten carbide parti-

Table 2
Properties of AA6082 aluminium alloy.

Sl. no.	Properties	
1	Density	2.71 g/cm^3 (Max)
2	Young's modulus	71 GPa (Max)
3	Ultimate tensile strength	140–330 MPa
4	Yield strength	90–280 MPa
5	Thermal expansion	23.1 μm/m K (Max)
6	Proof stress	85 MPa (Max)
7	Tensile strength	150 MPa (Max)

Table 1
Composition of aluminium 6082 alloy.

Weight %	Al	Si	Fe	Cu	Mn	Cr	Mg	Zn	Ti	Others
6082	Bal	1.12	0.19	0.02	0.87	0.15	0.92	0.17	0.086	0.075

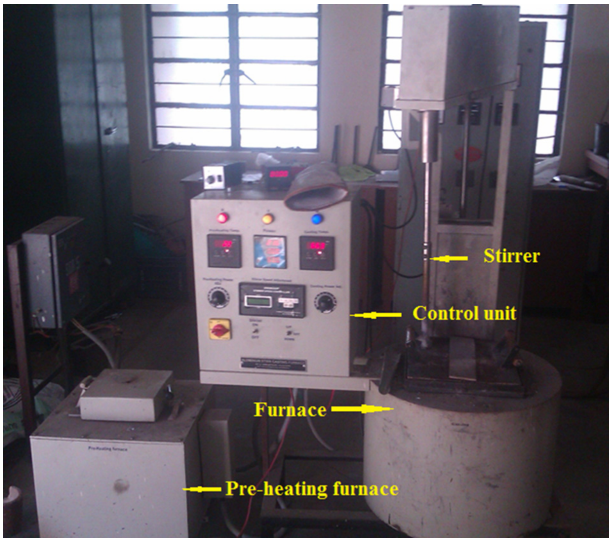


Fig. 1. Stir casting setup.

cles are also preheated at 400 °C to remove the moisture content and then mechanically mixed to the molten melt with the help of an automatic controlled stirrer. Stirring takes place for 5 min at a stirring speed of 500 rpm for uniformly scattering the tungsten carbide particles in the aluminium alloy matrix. The molten composite material is then poured into split type die of size 15 mm in diameter, 120 mm length and then allowed to solidify at room temperature. X-ray diffraction (XRD) and optical microstructure examination of the aluminium composite samples were carried to study the phases present and their disseminations along the composites. A fair uniform distribution of the tungsten carbide particles along the aluminium matrix is observed from Fig. 2. XRD method is used to examine the presence of materials present in the composites. It can be observed from Fig. 3 that aluminium and tungsten carbide are the predominant elements present in the composite which is in line with the optical microstructure of the composite.

3. Experimental procedure

Three set of tests were conducted and the average value was taken to calculate the mechanical properties of the composites to minimize the possibilities of error. Aluminium (AA6082)/tungsten carbide composite specimens machined as per ASTM - B-557M standards (Fig. 4) were exposed to tensile test in a universal testing machine (TUE-C model) to study the influence of WC particles in aluminium composite.

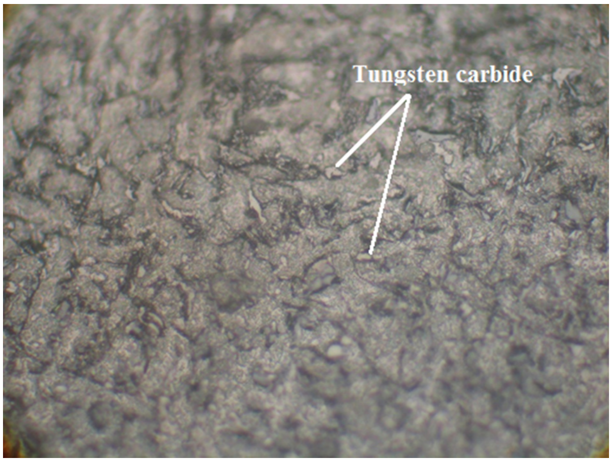


Fig. 2. Optical microstructure of composite sample (8% of Tungsten carbide).

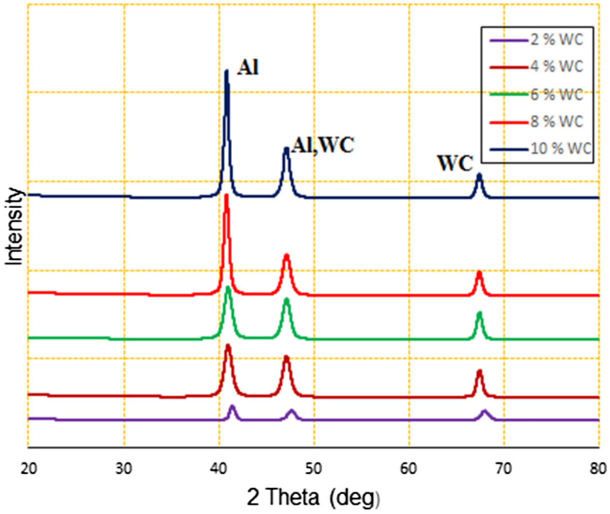


Fig. 3. XRD pattern of composite samples.

A standard ASI make impact pendulum-type testing machine (AMT-8 model) having a capacity of 184 J is used to measure the impact strength of composites samples machined as per ASTM standard shown in Figs. 5 and 6.

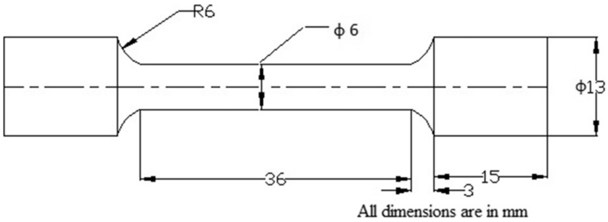


Fig. 4. Schematic representation of the tensile test specimen.

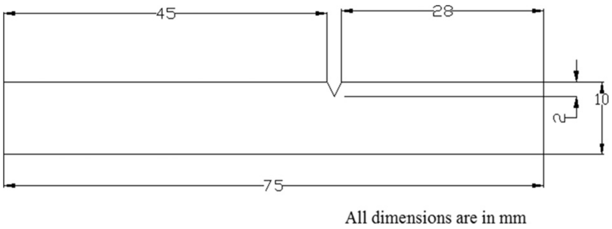


Fig. 5. Schematic representation of the Izod test specimen.

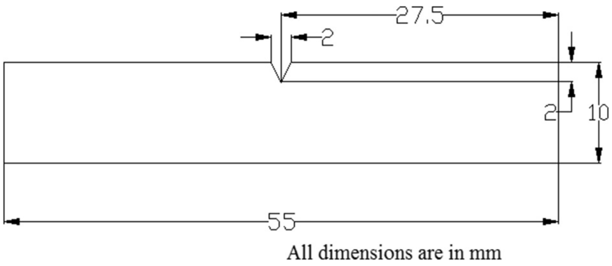


Fig. 6. Schematic representation of the Charpy test specimen.

Brinell hardness tester with a 5 mm ball diameter and a load carrying capacity of 200 kg is employed to find the hardness of composites. Hardness test was carried in a specimen of 15 mm diameter and 10 mm thick.

Density is defined as the ratio between mass and volume of the object. Density is measured using a specimen of 10 mm diameter and 100 mm height. Mass of the specimen is assessed with the help of an electronic weighing machine having accuracy of 0.001 mg. Volume of the specimen was estimated by multiplying the area and length measured by means of a vernier. Density of the specimen is calculated by dividing volume from mass.

4. Results and discussion

4.1. Effect of WC particles on density

Variation in density with increase in tungsten carbide was depicted in Fig. 7. It can be noted that the density of composites decreased with increase in WC. The average reduction in density of composite is 1.15% while adding WC in multiples of 2%. Density of the composites (10% of WC) decreased to a maximum of 5.88% as against the base aluminium alloy. The reason for decrease in density is due to the less weight of the tungsten carbide (2.05 g/cm^3) compared to that of the base AA6082 aluminium alloy (2.69 g/cm^3). Decrease in density is in line with other researchers while investigating aluminium/rice husk ash/SiC composites and aluminium/graphene nano platelets composites [13,23].

4.2. Effect of WC particles on tensile strength and % elongation

Influence of tungsten carbide particles on yield strength and Ultimate Tensile Strength (UTS) of aluminium composite is shown in Fig. 8. It can be observed that the strength of composite increased with increase in tungsten carbide upto 8% by weight and then decreases with further increase in tungsten carbide. The UTS increased upto16% and the yield strength increased upto 22% when compared to that of the base aluminium alloy. Increase in UTS and yield strength may be due to the interfacial bonding between the soft aluminium matrix and the hard tungsten carbide. Researchers also reported similar trend while studying the tensile strength of aluminium composites reinforced with mica, fly ash and SiC respectively [10,12,20]. The fractured tensile test specimen showing different profile is presented in Fig. 9. It can be observed from Fig. 10 that elongation of the composites decreases with increase in tungsten carbide content. This finding is well supported by other researchers that the elongation of aluminium composites decreases with increase in SiC, Al_2O_3 and nickel particles [1,4,7]. In this study percentage elongation of composites reduced to a maximum of 46% against their base aluminium. This may be attributed to the fact that the % elongation decreases with increase in UTS and yield strength. Addition of tungsten carbide particles influences the interfacial bonding between the aluminium alloy and WC particles. Addition of reinforcement particles reduces the elastic deformation and gradually promotes the plastic deformation of composites. The presence of hard and sharp WC particles tends to the formation of cracks and subsequent debonding leads to elastic deformation with increase in load.

To analyze the failure mechanism during tensile test fractured surfaces of the samples were subjected to SEM examination shown in Fig. 11. The unreinforced aluminium alloys are related to the ductile type of fracture due to shearing in the form of dimples, void growth coalescence and ductile failure as shown in Fig. 11a. Presence of voids is observed in unreinforced alloy and composites with 2% of tungsten carbide as shown in Fig. 11a and b. However addition of WC reduces the quantum of voids and dimples

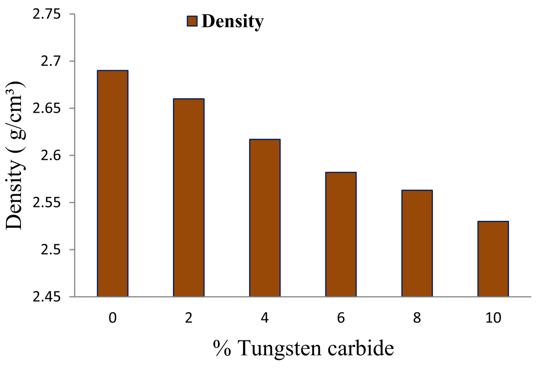


Fig. 7. Influence on density.

Fig. 9. Fractured tensile test specimen.

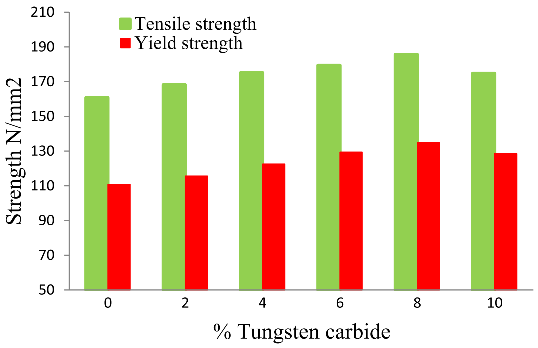


Fig. 8. Influence on tensile strength.

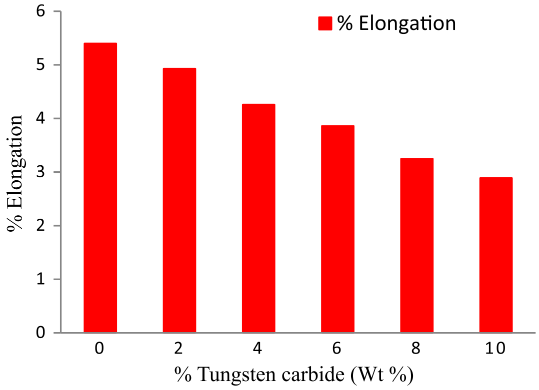
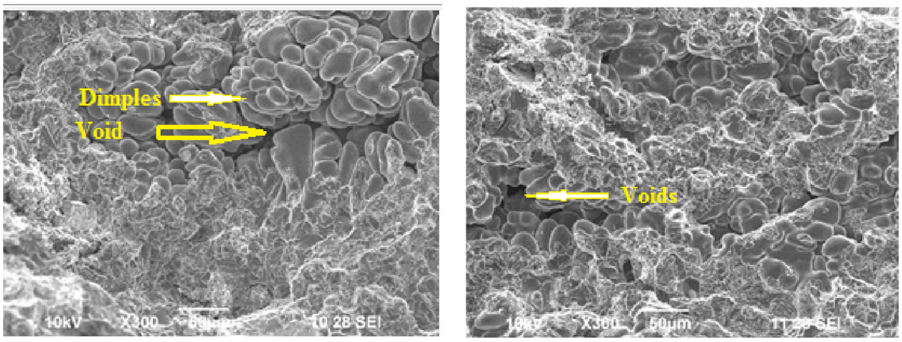
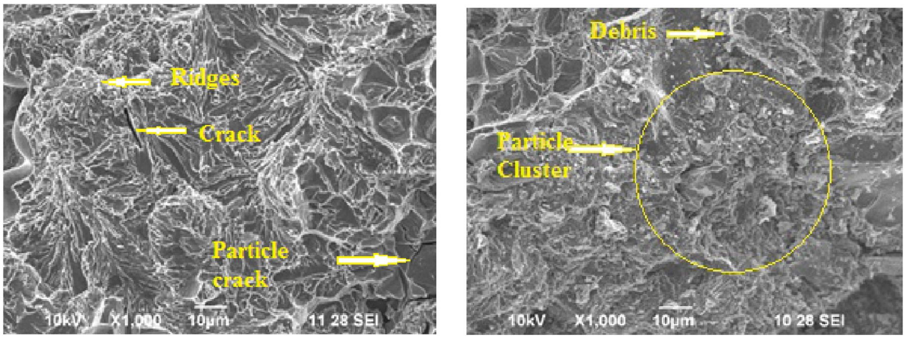


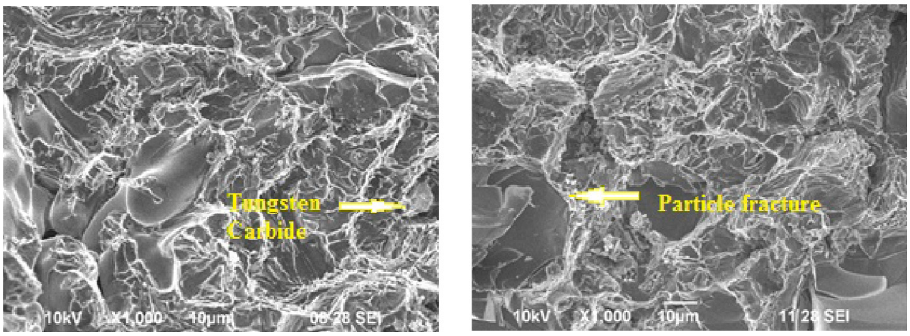
Fig. 10. Influence on % elongation.



(a) Alu minium alloy (AA6082) (b) Aluminium + 2% Tungsten carbide



(c) Aluminium + 4 % Tungsten carbide (d) Aluminium + 6 % Tungsten carbide



(e) Aluminium + 8 % Tungsten carbide (f) Aluminium + 10 % WC

Fig. 11. SEM microstructure of Tensile test.

(Fig. 11b) indicating the reduction in elongation and thereby increasing the tensile strength (Fig. 8). At this stage the failure of composite is primarily of ductile in nature. The presence of another feature in the form of ridges is obtained in composites (Fig. 11c) with 4% tungsten carbide indicating a ductile mode of fracture. These ridges are due to the disintegration and decohesion of tungsten carbide particles from the aluminium alloy. Minor cracks due to shear are also witnessed along the shear plane due to the possible brittle fracture. At this stage, the failure is a combination of ductile and brittle fracture. From Fig. 11d presence of tungsten carbide particles in the form of clusters and also protrusion of particles along the surface is revealed. This may be due the non-uniform distribution of particles and weak bonding created due to improper casting. Fig. 11e shows the combination of ductile and brittle failure; however the brittle failure is more dominant than the ductile failure. In Fig. 11e the failure is almost fully of brittle in nature which is characterized by the particle fracture due to the strong interfacial bonding between the matrix and WC particles. This principal brittle failure may be the reason for the decrease in tensile strength as shown in Fig. 8. In summary the unreinforced alloy are subjected to ductile mode of fracture. With increase in % tungsten carbide the mode of failure gradually transforms to brittle fracture. The tensile strength of composite increases with increase in WC particles (8%) and then tends to decrease with further increase in WC particles.

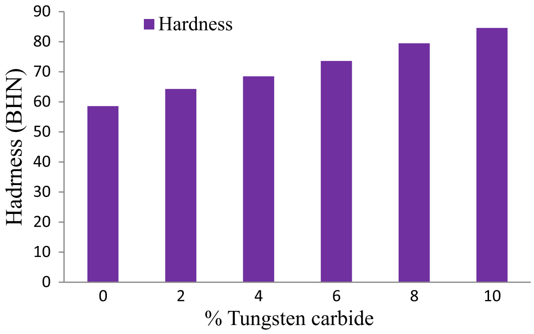


Fig.12. Influence on hardness.

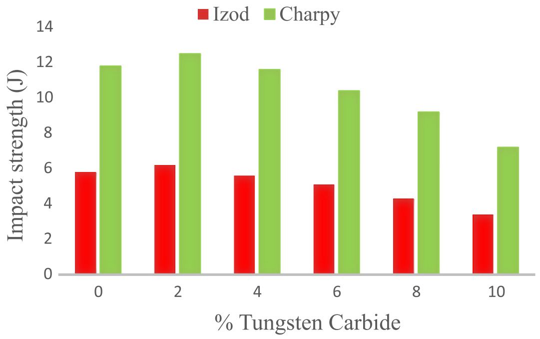


Fig. 13. Influence on impact strength.

4.3. Effect of WC particles on hardness

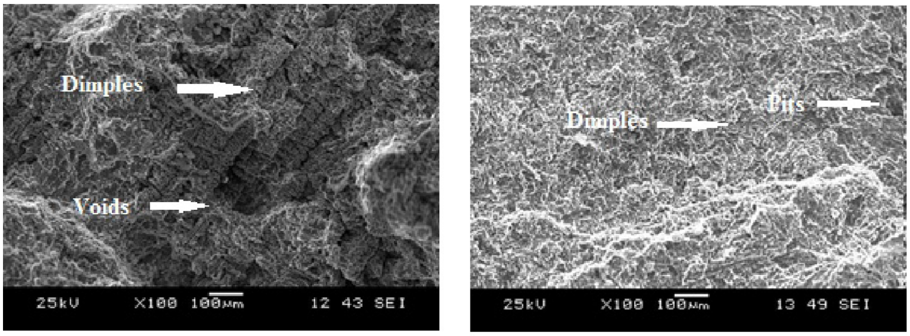
The effect of tungsten carbide particles in aluminium composites is employed in Fig. 12. Increase in presence of tungsten carbide particles in aluminium matrix increases the hardness of composites. Researchers reported similar trend that addition of fly ash, SiC, Al_2O_3, aluminide and SiC improves the hardness of aluminium composites [8,24]. Sharma et al. [19] reported a reverse trend that increase in addition of graphite reduces the hardness of composites due to the lubrication nature of graphite. Rajmohan et al. [10] revealed that addition of mica reduced the hardness of composites; thereby improving the machinability of composites. Increase in hardness is fairly due to the resistance offered to indentation by the hard reinforced particles. Increase in hardness of the composites is also due to the fact that the tungsten carbides withstand the major load transferred by aluminium. Also the presence of porosity inversely influences the hardness of composites.

4.4. Effect of WC particles on impact strength

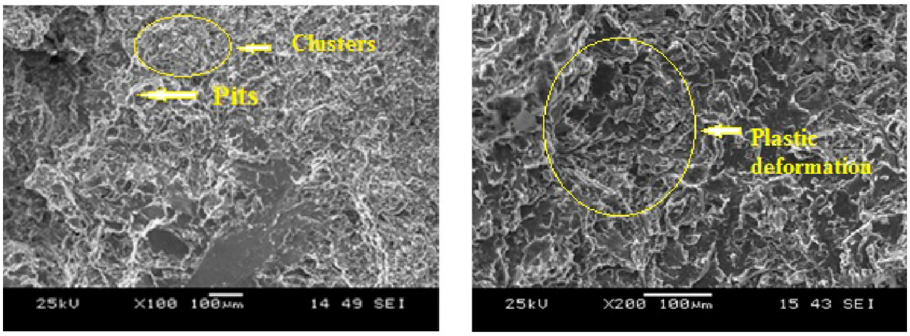
Effect on impact strength by adding tungsten carbide particles are shown in Fig. 13. It can be observed from Fig. 13 that impact strength obtained by both Izod and Charpy test increases initially with 2% WC and then decreases with further increase in tungsten carbide particles. The maximum decrease in impact strength compared to the base aluminium alloy was more than 40% as shown in Fig. 13. Dimensions of the specimen used for impact test in this study are shown in Fig. 14. Similar kind of decrease in impact strength is reported by other researchers in their study using other reinforcements [12,14,22]. Hamouda et al. [6] revealed that the residual stress generated due to the thermal mismatch between the matrix and reinforcement leads to the formation of brittle nature of composites along the crack tips thereby decreasing the fracture toughness of composites. The impact strength observed by Charpy test was nearly double times higher than that of the Izod test value. Increase in hardness of composites increases the brittleness of composites thereby decreasing the impact strength of composites. The impact strength of a material depends on the energy consumed by the material when a high speed load is applied. The impact strength of the aluminium alloy is higher because of the plastic deformation energy stored in the material before cracking. However in the case of composites, plastic deformation energy decreases due to the increase in concentration of energy for debonding thereby reducing the impact strength.

SEM of aluminium (AA6082) composites and its base alloy is shown in Fig. 15. It can be observed from Fig. 15a that the microstructure of aluminium alloy is characterized by dimples indicating a ductile type fracture mechanism. Ductile fracture is the major reason for high impact strength in aluminium alloy (Fig. 15). Fractured surface of the composites with 2% WC (Fig. 15b) shows reduction in dimples compared to that of the base alloy. Presence of plastic deformation is evidenced along the surface. Failure at this stage is a combination of ductile and brittle failure reducing the impact strength of aluminium alloy (Fig. 15). Presence of pits and voids are also evidenced along the surface of the specimen (Fig. 15b and c). These pits and voids are probably due to the weak interfacial bonding between the WC particles and aluminium matrix and also due to non-uniform distribution of WC particles. Presence particle clusters near the pit (Fig. 15c) is an evidence for the improper mixing of WC particles during fabrication. With a further increase in tungsten particles absence of dimples are evidenced along the surface (Fig. 15c–f). The low impact in composite with 6% and 8% of WC composites (Fig. 15d and e) are primarily due to the plastic deformation combined with the brittle mode of fracture. Also from Fig. 15e, in addition to the plastic deformation, formation of micro cracks in the form of cleavages is also evidenced along the surface. These types of cracks are due to the dominant interface strength influencing the cracks within the particles or along the short inter particle line. With further increase in tungsten particle upto 10% (Fig. 15f) major deep and widened cracks are seen along the surface indicating brittle fracture (Fig. 14). These dominant cracks and particle fracture are due to the strong interfacial bonding between the WC and aluminium matrix at high strain rate, increasing the brittle nature of the composite. The microstructure of composite with 6% tungsten carbide is shown in Fig. 16. It can be noted that the failure mode by both Izod (Fig. 15d) and Charpy (Fig. 16) are similar where in the failure is primarily due to plastic deformation. In summary the high impact strength are due to the ductile failure in the form of dimples. Low impact strength is due to the brittle and plastic deformation characterized by micro and macro cracks, particle fracture.

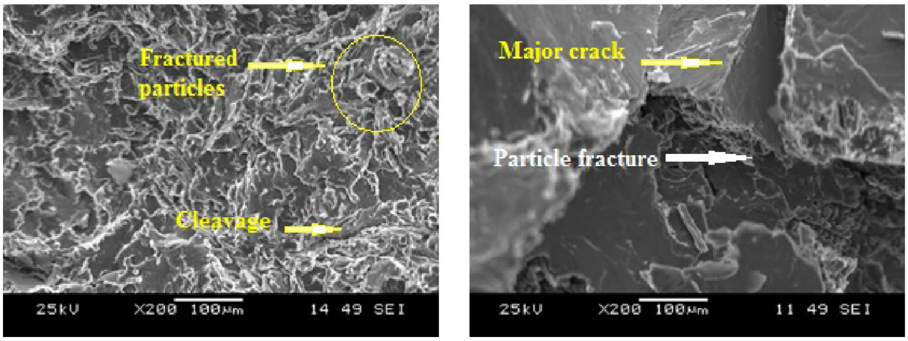
Fig. 14. Fractured Izod impact test specimen.



(a) Aluminium alloy **(b) Aluminium + 2% WC**



(c) Aluminium alloy + 4% WC **(d) Aluminium + 6% WC**



(e) Aluminium alloy + 8% WC **(f) Aluminium + 10% WC**

Fig. 15. SEM microstructure of Izod Impact test.

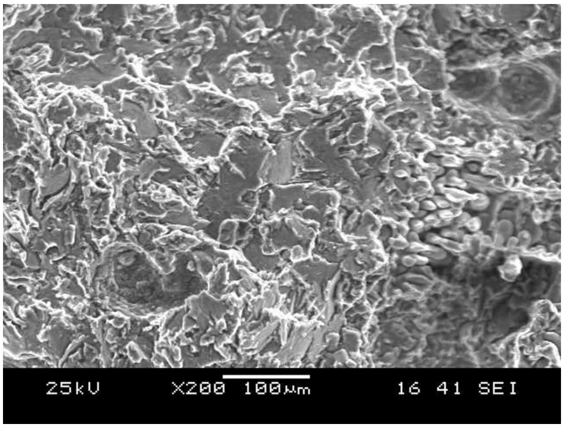


Fig. 16. SEM microstructure of Charpy Impact test (6% WC).

5. Conclusions

In the present study tests were conducted to evaluate the mechanical properties of aluminium/tungsten composites and the following conclusions can be drawn:

- A fair uniform distribution of tungsten carbide particles along the aluminium matrix can be observed by optical microstructure.
- XRD study revealed that aluminium and tungsten carbide are the predominant elements present in the composite.
- Density, impact strength and elongation of the composites decreased with increase in tungsten carbide, while the hardness of composites increased with increase in tungsten carbide. The tensile strength of composites increased and then tends to decrease after 8% of WC.

- The unreinforced alloys are subjected to ductile mode of fracture. With increase in tungsten carbide the mode of failure gradually transforms to brittle fracture.
- The tensile and impact fracture of the composites are characterized by dimples, voids, cracks, ridges, pits and particle fracture.
- The mechanical properties of Aluminium/Tungsten carbide composites along with characterization will serve as a technical database for aerospace, automotive, military and commercial applications.

References

[1] T.J.A. Doel, M.H. Loretto, P. Bowen, Mechanical properties of aluminium-based particulate metal-matrix composites, Composites 24 (3) (1993) 270–275.

[2] F. Velasco, C.E. Da Costa, J.M. Torralba, Mechanical properties and wear behaviour of PM aluminium composite reinforced with (Fe_3Al) particles, Powder Metall. 45 (3) (2002) 247–250.

[3] H.X. Peng, Z. Fan, D.S. Mudher, J.R.G. Evans, Microstructures and mechanical properties of engineered short fibre reinforced aluminium matrix composites, Mater. Sci. Eng., A 335 (2002) 207–216.

[4] M. Kok, Production and mechanical properties of Al_2O_3 particle-reinforced 2024 aluminium alloy composites, J. Mater. Process. Technol. 161 (2005) 381–387.

[5] J. Rodrıguez, M.A. Garrido Maneiro, P. Poza, M.T. Gomezdel Rio, Determination of mechanical properties of aluminium matrix composites constituents, Mater. Sci. Eng., A 437 (2006) 406–412.

[6] A.M.S. Hamouda, S. Sulaiman, T.R. Vijayaram, M. Sayuti, M.H.M. Ahmad, Processing and characterization of particulate reinforced aluminium silicon matrix composite, J. Ach. Mater. Manuf. Eng. 25 (2) (2007) 11–16.

[7] Devinder Yadav, Ranjit Bauri, Processing, microstructure and mechanical properties of nickel particles embedded aluminium matrix composite, Mater. Sci. Eng., A 528 (2011) 1326–1333.

[8] H.C. Anilkumar, H.S. Hebbar, K.S. Ravishankar, Mechanical properties of fly ash reinforced aluminium alloy (Al6061) composites, Int. J. Mech. Mater. Eng. 6 (1) (2011) 41–45.

[9] Ekkapak Wichianrat, Yuttanant Boonyongmaneerat, Seksak Asavavisithchai, Micro structural examination and mechanical properties of replicated aluminium composite foams, Trans. Nonferrous. Met. Soc. China 22 (2012) 1674–1679.

[10] T. Rajmohan, K. Palanikumar, S. Ranganathan, Evaluation of mechanical and wear properties of hybrid aluminium matrix composites, Trans. Nonferrous Met. Soc. China 23 (2013) 2509–2517.

[11] Devaraju Aruria, Kumar Adepu, Kumaraswamy Adepu, Kotiveerachari Bazavada, Wear and mechanical properties of 6061–T6 aluminum alloy surface hybrid composites [(SiC + Gr) and (SiC + Al_2O_3)] fabricated by friction stir processing, J. Mater. Res. Technol. 2 (4) (2013) 362–369.

[12] Krishnan Ravi Kumar, Kothavady Mylsamy Mohanasundaram, Ramanathan Subramanian, Balasubramaniam Anandavel, Influence of fly ash particles on tensile and impact behaviour of aluminium (Al/3Cu/8.5Si) metal matrix composites, Sci. Eng. Compos. Mater. 21 (2) (2014) 181–189.

[13] Dora Sivaprasad, Chintada Shobab, Nallu Ramanaiah, Investigations on mechanical properties of aluminum hybrid composites, J. Mater. Res. Technol. 3 (1) (2014) 79–85.

[14] B. Vijaya Ramnath, C. Elanchezhian, M. Jaivignesh, S. Rajesh, C. Parswajinan, A. Siddique Ahmed Ghias, Evaluation of mechanical properties of aluminium alloy–alumina–boron carbide metal matrix composites, Mater. Des. 58 (2014) 332–338.

[15] Dipti Kanta Das, Purna Chandra Mishra, Saranjit Singh, Ratish Kumar Thakur, Properties of ceramic-reinforced aluminium matrix composites – a review, Int. J. Mech. Mater. Eng. 1 (12) (2014) 1–16.

[16] Sajjad Amirkhanlou, Mostafa Ketabchi, Nader Parvin, Shohreh Khorsand, Fernando Carreno, Effect of processing cycles on aluminum/tungsten carbide composites prepared by continual annealing and press bonding process, IOP Conf. Series: Mater. Sci. Eng. 63 (2014) 1–4.

[17] Michael Oluwatosin Bodunrin, Kenneth Keneth Alanemec, Lesley Heath Chown, Aluminium matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics, J. Mater. Res. Technol. 4 (4) (2015) 434–445.

[18] Ehsan Ghasali, Masoud Alizadeh, Touradj Ebadzadeh, Amirhossein Pakseresht, Ali Rahbari, Investigation on micro structural and mechanical properties of B4C–aluminum matrix composites prepared by microwave sintering, J. Mater. Res. Technol. 4 (4) (2015) 411–415.

[19] Pardeep Sharma, Satpal Sharma, Dinesh Khandujaaa, A study on microstructure of aluminium matrix composites, J. Asian Ceram. Soc. 3 (3) (2015) 240–244.

[20] R.S. Rana, Rajesh Purohit, V.K. Soni, S. Das, Characterization of mechanical properties and microstructure of aluminium Alloy – SiC Composites, Mater. Today: Proc. 2 (2015) 1149–1156.

[21] Kenneth Kanayo Alaneme, Kazeem Oladiti Sanusi, Micro structural characteristics, mechanical and wear behavior of aluminium matrix hybrid composites reinforced with alumina, rice husk ash and graphite, Eng. Sci. Technol. 18 (2015) 416–422.

[22] A. Kursun, E. Bayraktar, M.H. Robert, Low cost manufacturing of aluminium-alumina composites, Adv. Mater. Process. Technol. 1 (3–4) (2015) 515–528.

[23] Muhammad Rashad, Fusheng Pan, Zhengwen Yu, Muhammad Asif, Han Lin, Rongjian Pan, Investigation on microstructural, mechanical and electrochemical properties of aluminum composites reinforced with graphene nano platelets, Prog. Nat. Sci. Mater. Int. 25 (5) (2015) 460–470.

[24] Jaswinder Singh, Amit Chauhan, Characterization of hybrid aluminum matrix composites for advanced applications – a review, J. Mater. Res. Technol. 5 (2) (2016) 159–169.

[25] Uthirapathy Tamilarasan, Loganathan Karunamoorthy, Kayaroganam Palanikumar, Mechanical properties evaluation of the carbon fibre reinforced aluminium sandwich composites, Mater. Res. 18 (5) (2015) 1029–1037.

[26] N. Radhika, R. Raghu, Development of functionally graded aluminium composites using centrifugal casting and influence of reinforcements on mechanical and wear properties, Trans. Nonferrous Met. Soc. China 26 (2016) 905–916.

[27] R. Harichandran, N. Selvakumar, Effect of nano/micro B_4C particles on the mechanical properties of aluminium metal matrix composites fabricated by ultrasonic cavitation assisted solidification process, Arch. Civ. Mech. Eng. 16 (2016) 147–158.

[28] Wenming Jiang, Zitian Fan, Guangyu Li, Xinwang Liu, Fuchu. Liu, Effects of hot dip galvanizing and aluminizing on interfacial microstructures and mechanical properties of aluminium/iron bimetallic composites, J. Alloys Compd. 688 (2016) 742–751.