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Effect of TiC_{np} on microstructure and mechanical behaviour of high-performance Al7150-TiC nanocomposites

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ABSTRACT

This research deals with Al7150-TiC nanocomposites and its mechanical, microstructure and fracture surface studies. Two-step stir casting and vortex methods were employed to fabricate Al7150-TiC nanocomposites. TiC was selected as a ceramic reinforcement and added 0.5, 1.0, and 1.5 wt% to find the effect of reinforcement on hardness and strength of nanocomposites. Optical Microscope was used to analyse the grain boundaries, the average grain size of nanocomposites through “*Linear Intercept Method*” and compared with monolithic. SEM was used to study particle distribution and failure surface analysis. *ImageJ-software*” was used to analyse particle size distribution in the SEM images. EDS was performed to find the chemical compounds of the composite materials. Addition of 1.0 wt% of reinforcement showed better mechanical properties. Uniform dispersion and grain refinement were obtained and mechanical properties were enhanced by 33.3% in tensile strength and 14.7% in micro hardness at 1.0 wt% as compared to monolithic.

1. Introduction

Aluminium alloy nanocomposites have achieved high popularity in various technical sectors and are playing a major role in aerospace and automobile structural applications due to their superior properties such as mechanical strength, corrosion resistance and strength to weight ratio [1]. In such attempts, the 7xxx series alloys (Al-Cu-Mg-Zn) met the above properties and are widely using for critical structures in aerospace applications due to low weight, high toughness, ultimate tensile strength (UTS), and fatigue resistance [2]. The hard phase particulate reinforced composites have paved a novel path to develop high wear-resistant and strength [3]. The investigation of TiC nanoparticle reinforced to Al-MMCs has not been adequately researched and it has come into popularity only recently due to its low CTE, high melting point, superior hardness and wear resistance [4]. The size of the particles ranging from micro to nano level scale increases the mechanical properties but it tends to increase the clusters and agglomerations [5]. It is also an important task to produce a homogeneous distribution of nanoscale reinforced particles in dense liquid metals to attain the required properties [6]. The preparation cost of the nanocomposites using different methods is quite expensive as compared to liquid metallurgy route and two-step stir casting is chosen for manufacturing particle reinforced composites due to maximum yield with minimum investment, low wastage and damage [7]. Some research has been proved that the different alloys have enhanced fatigue resistance and temperature creep resistance [8] but the preparation of Aluminium MMCs with the ultra-fine (nm) particles in liquid metal is quite challenging task to disperse homogeneously due to formation of agglomerations and poor wettability. In such research struggles, two-step stir casting process provided a good solution for the distribution of ultrafine particles in Al-based alloy melts [9]. The liquid casting route is an extremely advisable method to fabricate the Aluminium-based MMCs, low cost and flexibility of process [10].

Nagaral et al. [11], studied the effect of two-step stir casting technique to analyse the mechanical as well as wear behaviour of Al2014-ZrO_2 nanocomposites at the as-cast condition and compared with monolithic material. Results were confirmed that the wear loss enhances with the load and % elongation degraded with the particle reinforcements. Aravindan et al. [12], fabricated AZ91D-SiC composites

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through a two-step casting process and analyzed the effect of volume fraction as well as particle size on material properties of fabricated composites at T6 and as-cast conditions. The material properties of AZ91D-SiC composites were enhanced with increasing SiC particulates and decrease with increasing of particulates size. Qiang Li et al. [13], analyzed nanoparticles distribution and solidification behaviours of nanocomposites which are prepared through an ultrasonic-assisted based casting process. Wei-Si-Tian et al. [14], manufactured microparticles and nanoparticles based composites using in-situ technique and examined various material properties at atmospheric and high temperatures. Mahathanabodee S et al. [15], used P/M method to manufacture SS316L-hBN composites and analyzed hBN influence on materials properties and tribological properties as well. In this procedure, nanoparticles were added to the molten matrix using the vortex technique [16] to avoid the floating of nanoparticles and two-step stir casting process is performed to improve the wettability. Therefore, it reduces the porosity of the composites and the cost of the final product [17].

This work deals with Al7150 with various weight percentages of TiC nanoparticles as reinforcement to produce the nanocomposites by using two-step stir casting process. The mechanical and microstructural characteristics are studied for nanocomposites. The Optical Microscope (OM), Scanning Electron Microscope (SEM) and Energy Dispersive X-Ray Spectroscopy (EDS) are used to analyze the grain boundaries, particle distribution, fracture surface, and chemical composition of the nanocomposites under optimal conditions for determining mechanical properties.

2. Materials and methods

Al7150 was selected as a matrix material and purchased from “Venuka Engineering Private Limited, Hyderabad, India”. TiC_{np} used as reinforcement particulate and purchased from “Sisco Research laboratories private limited, India” with a purity >99.9%, density 4.90 g/cc and APS 30–50 nm. The chemical composition of Al7150 is shown in Table 1. To fabricate the TiC reinforced nanocomposite, two-step stir casting technique was adopted and it involves 20 min. Each step of the mechanical stirring process took 10 min to achieve the proper dispersion of reinforcements in liquid metal and first stage performed at 650 °C and the second one at 750 °C. The preheated (500 °C) TiC_{np} were added with various reinforcement weight percentages (0.5, 1.0, and 1.5 wt%) into the Aluminium metal pool by using vortex method and mechanical stirring action was then performed.

The degassing tablet (C_2Cl_6) was used to degas from the molten liquid and 1% Mg added for wettability improvement of nanoparticles into a melt pool. The fabricated liquid was poured into preheated (500 °C) die steel mould and allowed to cool for 24 hrs at atmospheric temperature. The solidified Al7150-TiC samples were machined as per ASTM standards such as ASTM E8M small for the tensile test (gauge length is 45 mm and gauge diameter is 9 mm).

Test samples were polished on the various grades of silicon carbide emery papers (“I/0, II/0, III/0, and IV/0”), cloth polishing (Disc) with diamond paste and etching. The polishing direction (⊥) from grade to grade has been changed to void the hatching lines on the polished surface. After that test samples were cloth polished for 10–12 min with the help of Al_2O_3 fine powder particles to provide better surface polish and etched (25–27 min) in a Kellar solution to elevates better grain boundaries and than Kellar solution was cleaned with acetone.

Table 1
Elemental composition of Al7150 (in weight %).

Element	In weight %)
Mg	2.56
Zn	6.37
Cu	2.25
Fe	0.12
Zr	0.11
Si	0.08
Mn	0.009
Al	Balance

Mechanical properties such as tensile strength were tested using UTM (Model: WDW 100S Blue Star, India) and with a cross over the speed of 0.5 mm/min. Sample sizes for the microstructure and microhardness examinations were maintained as 1.5 aspect ratio (12 mm diameter and 8 mm length) conducted tests at National Institute of Technology, Warangal, India. Microhardness test was conducted on Vickers hardness tester (Make: Economet VH 1MD, 2 Kgf, India) with 15 sec dwell time and a load of 200 g. The microstructure of the composites has been studied by employing three techniques such as OM (Olympus MX63, Japan) at 50 μm (400× magnification), SEM (Tescon, Vega 3LMU, U.K) at 1 μm (22,000× magnification), EDS (Oxford Instruments, U.K) at optimal properties. “*ImageJ-software*” was used to find the particle size distribution in the SEM images.

3. Results and discussion

The microstructure results of Al7150-TiC nanocomposite are carried out at optimal and lower mechanical properties (1 wt% & 1.5 wt%) and compared with the monolithic alloy. The grain refinement was observed through an OM and the average grain size (AGS) of nanocomposites calculated by linear intercept method at monolithic, 1.0 wt% and 1.5 wt % using *ImageJ-software* at perpendicular directions (Fig. 1). The AGS values (100.82 μm, 46.81 μm, and 55.57 μm) were measured using “AGS = length of line/no. of grains” and it plays a major role in mechanical properties. The respective graph of grain refinement and error bars as shown in Fig. 1d.

It was also noticed that the increasing of ceramic TiC_{np} in the molten liquid increases the microstructural properties and grain refinement upto 1 wt%. The AGS of Al7150-1 wt% TiC nanocomposite was reduced from 100.82 to 46.81 μm and the fraction of grain refinement was enhanced to 53.57%. It is mainly due to TiC_{np} addition which exhibits small dislocation mismatch between TiC_{np} & Al7150. Further improvement in wt%TiC_{np} leads to an increase in grain size, which results in deterioration of the mechanical properties of the composite materials. The visual observation of the images also confirms finer grain sizes at 1.0 wt% as compared to its counterparts.

The morphology of Al7150-TiC nanocomposites was carried out by using SEM for particle analysis at 10,000× (2 μm) magnification and respective images as shown in Fig. 2a–c. The colour threshold image was representing the particle location and corresponding histogram for the particle size distribution throughout the composite. Histogram of each wt% was confirming that the TiC_{np} was well distributed in Al7150, although some of the noticeable agglomerations remain in the microstructure because of two-step stirring phenomenon. The first stage of the stirring process at 650 °C breaks the larger size agglomerations into micron level clusters due to the shearing effect (high viscosity of liquid metal at low temperature). The second stage of the stirring process at 750 °C promotes the broken micro size clusters and nanoparticles into considerable dispersion throughout the composite material (low viscosity of liquid metal at high temperature) which leads to grain refinement, and superior mechanical properties. It was also noticed that the mechanical properties of nanocomposites increasing with increasing of TiC upto 1 wt% and further reinforcement of nanoparticles leads to clusters & porosity due to higher surface area to volume ratio (Fig. 2c). Better distribution of nanoparticles at 1 wt% TiC_{np} reinforced nanocomposite observed in Fig. 2b is compared to counterparts. A histogram is also confirmed that the more number of particles (in-between 50 and 150 nm range) with 1 wt% reinforcement and uniformly spread over the composite which leads to *Orowan* strengthening mechanism. EDS spectroscopy results are shown in Fig. 2d and it confirmed that major elements such as Al, Zn, Cu, Mg and minor elements such as Si, Zr, Mn, Fe, T & C.

The microhardness test was conducted on Al7150-TiC

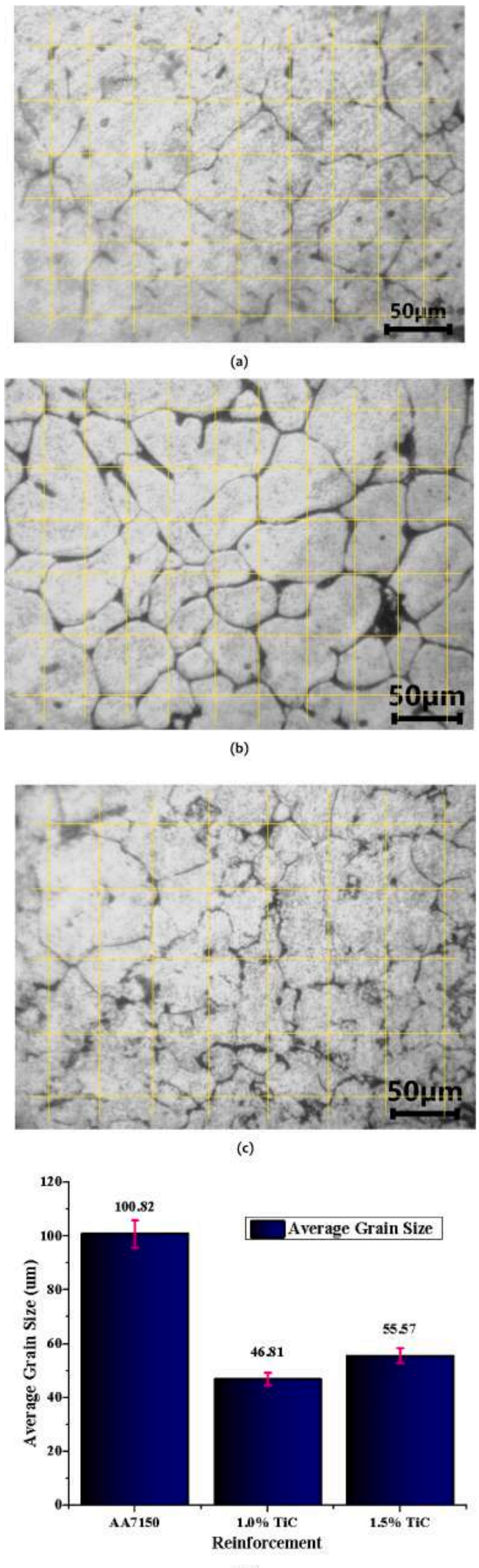

Fig. 1. Microstructures of (a) Al7150 (b) 1.0 %TiC (c) 1.5%TiC and (d) AGS.

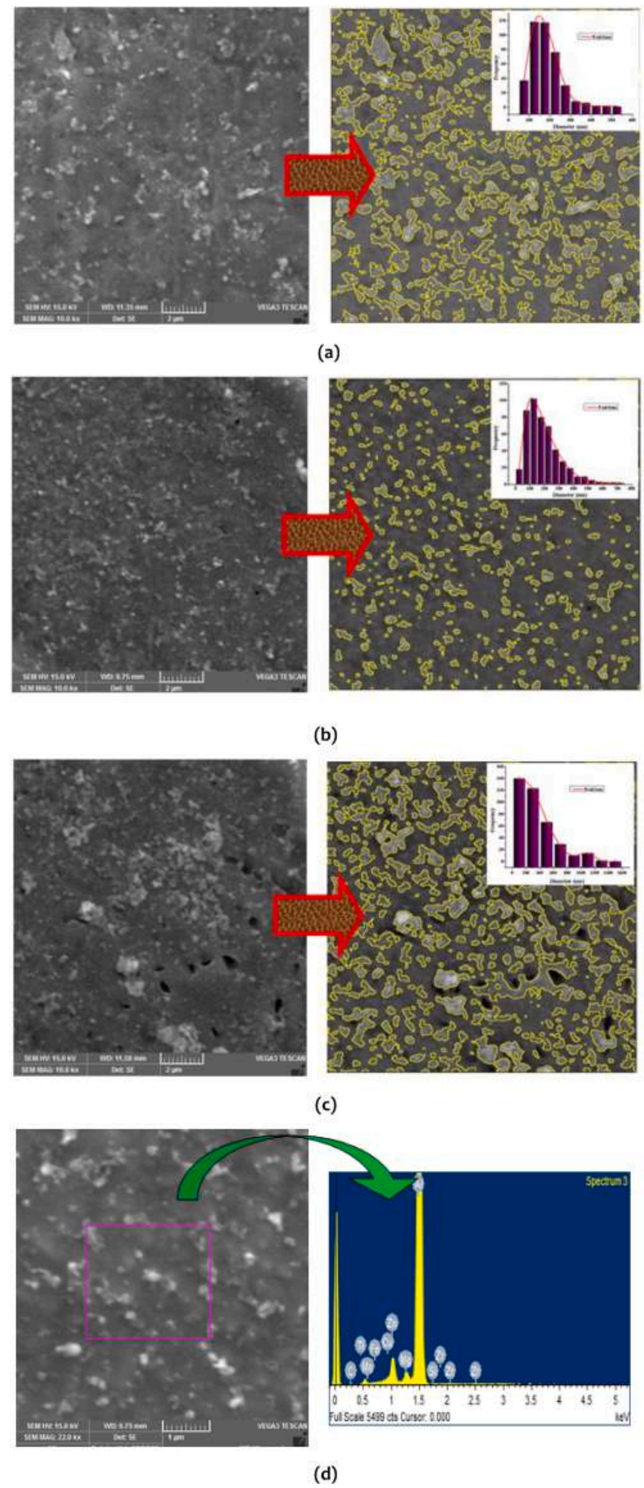

Fig. 2. SEM images for particles distribution (a) Al7150-0.5 %TiC (b) Al7150-1.0% TiC (c) Al7150-1.5% TiC (d) EDS for elements at 1.0% TiC.

nanocomposites by using Vickers hardness tester. The experimental results are graphically represented in Fig. 3a. It was found that the hardness of nanocomposite increases (14.7%) with an increase in TiC_{np} content of upto 1 wt% and superior at 1 wt% (150.76 HV) than that of monolithic due to the hard nature of TiC. TiC_{np} in Al7150 offers a protective layer to soft Al-alloy, which results in lower deformation and protest the cutting of slides and penetration on the nanocomposite surface; further increment of wt% leads to decrease in hardness due to agglomerations/clusters/voids.

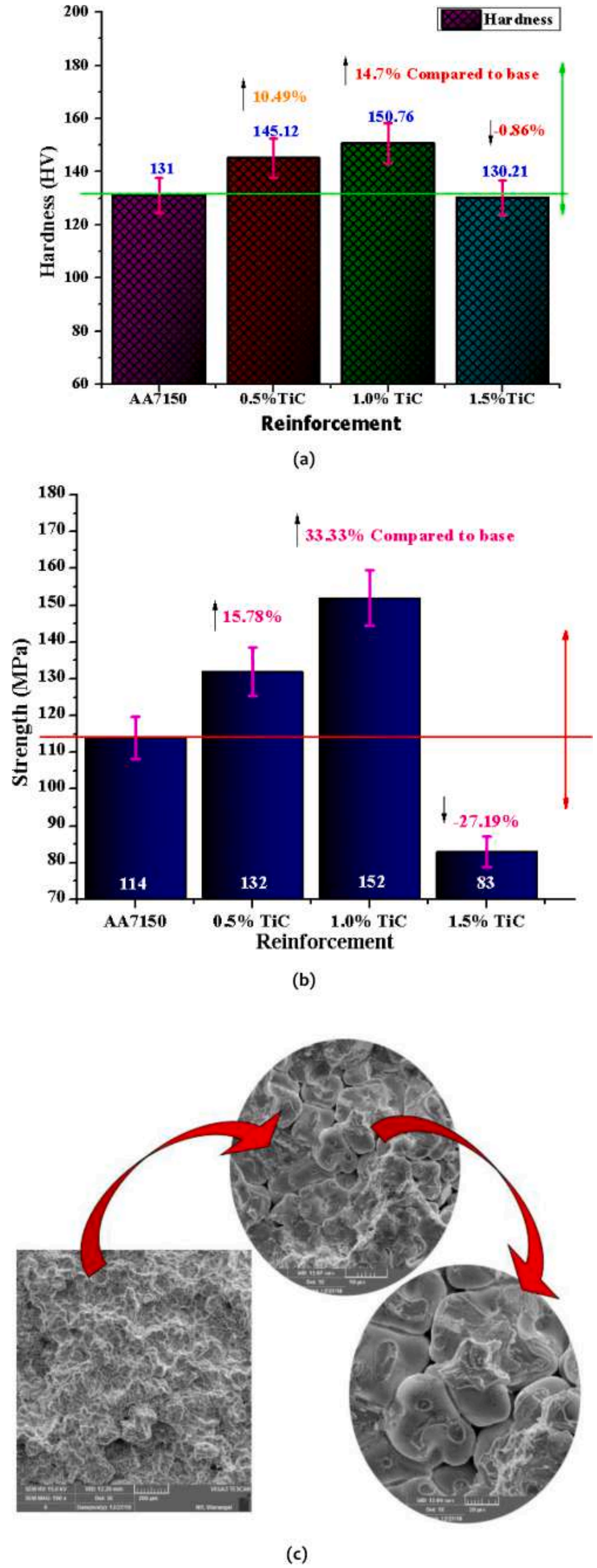

Fig. 3. (a) Hardness Vs wt% TiC (b) Strength Vs wt% TiC (c) Fracture surface of 1.0 wt% Al7150-TiC at 100×, 500×, 1000× magnifications.

UTS for various wt% of nanocomposites are represented graphically (Fig. 3b). From the graph, it was found that the UTS of the nanocomposites increases (33.3%) with TiC_{np} content and this enhancement mainly due to stress transformation from Al7150 to TiC_{np}. This transformation is because of *Orowan* mechanism by which a dislocation bypasses the dense obstacles, where a dislocation plays substantially to leave a dislocation loop around hard phase particle, leading to enhance the UTS up to 1 wt%.

Further improvement of nano TiC particle content leads to a reduction in the strength of nanocomposites due to agglomerations/clusters. These are mainly due to a larger interfacial area, and the presence of many surface atoms which leads to large surface energy potential for agglomerations. The fracture surface of monolithic, and 1 wt% nanocomposite was analyzed at various magnifications and the enlarged microstructure confirms the nature of the failure. The respective microimages are shown in Fig. 3c and minimized micro cracks, as well as voids at 1.0 wt%, reinforced TiC as compared to monolithic. Hence, they resulted in better mechanical property enhancement while the failure is semi brittle in nature due to stepwise dendrites and noticed at higher magnification.

4. Conclusions

In this research article, mechanical and microstructural properties of Al7150-TiC nanocomposites were studied. OM confirms the finer grain size at 1.0 wt% (46.81 µm) and SEM confirm the better distribution of nanoparticles at 1.0 wt% as compared to counterparts. Mechanical properties such as UTS (33.3%) and microhardness (14.7%) were enhanced as compared to monolithic alloy at 1.0 wt%. The fracture surface studies reveal the nature of the failure is semi-brittle and further improvement of TiC_{np} leads to agglomerations/voids.

Declaration of Competing 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.

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