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COMPOSITES THEORY AND PRACTICE

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EFFECT OF TiC AND BN NANOPARTICLES ON MECHANICAL AND MICROSTRUCTURAL CHARACTERISTICS OF Al7085 HYBRID NANOCOMPOSITES

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This study regards investigations of the mechanical properties of aluminum 7085/TiC/BN hybrid metal matrix nanocomposites (HMMNCs). The ultrasonic assisted stir casting (UASC) route was used to manufacture the Al7085 HMMNCs by varying the wt.% of titanium carbide (TiC) and boron nitride (BN) (0.0, 0.5, 1.0, 1.5, and 2.0). By means of scanning electron microscopy (SEM) it was observed that the nanoparticles are evenly distributed in the nanocomposites. Additionally, the EDS and XRD results indicate that there were no signs of oxide formations, secondary phases, or impurities in the nanocomposites. The yield tensile strength (YTS), ultimate tensile strength (UTS) and microhardness of the nanocomposites improved with increases in the wt.% of TiC and BN particles up to 1.5, and thereafter decreased. The % elongation of the nanocomposites was reduced and the density of the nanocomposites improved with the addition of TiC and BN nanoparticles.

Keywords: **nanocomposites, ultimate tensile strength, yield tensile strength, scanning electron microscope, TiC, BN**

INTRODUCTION

In recent studies, it has been observed that metal matrix composites (MMC) reinforced with nanoparticles exhibit better mechanical characteristics in comparison to MMCs reinforced with micron-sized particles. Compared to microparticles, the incorporation of a small percentage of nanoparticles into MMCs results in improvement in the strength by maintaining the ductility of the matrix [1]. Among MMCs, aluminum metal matrix composites (AMMCs) possess high hardness, stiffness, strength, low density and admirable thermal conductivity. Due to all these properties, AMMCs are extensively used in aerospace, sporting goods, marine, and automobile industries [2].

Adding microsized reinforcements to aluminum metal matrix composites (AMMCs) can reduce their fracture toughness and ductility. However, if nanosized particles are used instead, the resulting materials, called aluminum metal matrix nanocomposites (AMMNCs), can have improved fracture toughness and ductility. This is because of the toughness, ductility and superior strength of the nanoparticles. AMMNCs are therefore well-suited for use in structural applications, providing good strength, stiffness, load-bearing capacity, dimensional constancy, and erosion resistance.

For the past twenty years, research has focused on identifying ceramic particles that can potentially reinforce various grades of aluminum alloys, evaluating their compatibility with different manufacturing methods, and assessing their microstructural, mechanical, and tribological properties. Some common ceramic materials used in AMMCs include titanium dioxide (TiO_2), titanium boride (TiB_2), titanium carbide (TiC), alumina (Al_2O_3), boron carbide (B_4C), silica (SiO_2), and boron nitride (BN) [3, 4]. Among these materials, TiC and BN are highly appealing materials owing to their characteristics like low density, high melting point, exceptional mechanical properties, and the capacity to absorb neutrons, as well as a strong bonding capability with aluminum and its alloys. When used as reinforcement in AHMMNCs, TiC and BN nanoparticles are effective in improving the strength, toughness, wear resistance, and they also have self-lubricating properties [5-7].

Firestein et al. determined the mechanical behavior of Al/BN nanocomposites with various wt.% (0.5, 1.5, 3, 4.5, 6, and 7.5) of BN nanoparticles manufactured by the spark plasma sintering route. The results revealed that the UTS was superior by 50% with an increment in wt.% of BN nanoparticles in the AMMNCs [8]. Gostariani et al. determined the mechanical properties of Al/BN nanocomposites with different wt.% of BN particles employing ball milling and manufactured by the hot extrusion route. The results revealed that the hardness improved from 55 HV and the tensile strength was enhanced up to 333 MPa with the addition of BN particles to the matrix [9].

The manufacture of MMNCs can be performed by liquid and solid state routes like stir casting (SC) [10], powder metallurgy [11], ultrasonic assisted stir casting (UASC) [12-14], and squeeze casting [15]. Among all these methods, the SC route is the least expensive and has industrial scalability. It is difficult to distribute the nanoparticles evenly in the metal matrix because of their poor wettability and high surface area-to-volume ratio. As a consequence of these problems, stir casting is not an effective technique for the production of MMNCs. For the production of MMNCs, the UASC technique can be effectively used and produces composites with an even dispersion of the nanoparticles in the matrix, improves the material properties and refines the microstructure of the composite. Jia et al. discovered that ultrasonic treatment effectively fragmented the dendritic structures of the aluminum matrix alloy, resulting in a refined grain structure with improved mechanical properties [16]. Zolfaghari et al. evaluated the impact of nanoparticles on the mechanical and fatigue behaviors of aluminum nanocomposites manufactured by SC. The FESEM micrographs confirm the presence of SiO_2 evenly distributed in the nanocomposites. The results revealed that the nanoparticles had a substantial effect on the fatigue life and improved the hardness [17]. Yong et al. manufactured AA356/SiC nanocomposites using the UASC technique and witnessed even distribution of the SiC particles in the composite. The impact energy and % elongation of all the combinations of hybrid nanocomposites was higher than the base matrix [18]. Aybarc et al. determined the effect of micro- and nanoparticles on the material and mechanical properties of AA356/Al_2O_3 MMCs and nanocomposites that were produced using the ultrasonic assisted stir casting technique. The SEM micrographs showed that the particles were evenly distributed in the AA356 MMCs and nanocomposites. The results revealed improved UTS, % elongation and low porosity with an increase in the wt.% of reinforcement particles to 0.5. The nanocomposites exhibited better mechanical properties than the composites [19]. Rao [20] determined the effect of SiC nanoparticles on the mechanical and tribological properties of Al7075/SiCNP composites manufactured utilizing the UASC method. The SEM micrographs confirm the evenly distributed SiCNP in the Al7075/SiCNP composites. The results disclosed that the UTS and YTS were enhanced with additions of SiCNP up to 2 wt.% in the Al7075 matrix. The wear rate (WR) of the prepared composites declined with a rise in SiCNP in Al7075 up to 2 wt.%. Banerjee et al. [21] examined the effect of graphite and WC nanoparticles on the corrosion and hardness properties of AZ31/Gr/WC HMMNCs manufactured by the UASC route. The results indicated that the incorporation of 1 wt.% Gr nanoparticles on AZ31-WC nanocomposites increased both the elastic modulus and microhardness as well as enhanced the corrosion resistance. Aybarc et al. [22] determined the impact of various casting techniques on the mechanical behavior of Al356/SiC composites. The SEM micrographs revealed that the SiC particles were evenly distributed in the hybrid composites prepared by the UASC technique compared to other techniques. The examinations also revealed that better mechanical properties were received using the UASC technique. Li et al. [23] fabricated composites from the Al356 alloy reinforced with 2 vol.% SiC nanoparticles via the UASC route and observed homogeneous dispersion of the nanoparticles and a 20% enhancement in hardness compared with the base matrix. Harichandran et al. [24] studied the impact of B_4C and BN nanoparticles on the mechanical and wear behavior of Al/B_4C/BN nanocomposites prepared by means of the UASC technique. The conclusions revealed that the UTS was enhanced with an increment in B_4C particles up to 6 wt.%. The composite containing 4 wt.% B_4C and 2 wt.% BN exhibited the highest impact strength and the lowest wear rate. The WR of the HMMNCs was lower compared to the base matrix and the Al/B_4C nanocomposites [25].

From the literature survey, it was ascertained that limited work has been conducted to determine the mechanical and material properties of Al/TiC/BN hybrid nanocomposites manufactured by the UASC route. Hence, in the present work, an in-depth study of the mechanical and material properties of Al7085/TiC/BN HMMNCs prepared via the UASC route is studied.

MATERIALS AND METHODOLOGY

7085 aluminum alloy

The Al7085 alloy was used as the matrix with TiC and BN nanoparticles as the reinforcing materials. The chemical composition of the matrix material is presented in Table 1. The major elements in the base material are Zn, Mg, Cu, Fe and Si. The Al7085 alloy was procured from a commercial source in the form of plates.

TABLE 1. **Chemical composition of AA7085 (based on supplier's certificate)**

Element	Si	Fe	Cu	Mg	Zr	Zn	Ti	Mn	Cr	Ni	Al
wt.%	0.12	0.15	1.7	2.1	0.1	5.8	0.04	0.1	0.05	0.05	Bal

Titanium C carbide (TiC) and boron nitride (BN)

The TiC and BN nanoparticles procured from a commercial source were used as the reinforcement material in the Al7085 matrix. The specifications of the TiC and BN nanoparticles are displayed in Table 2.

The particle size is of the order of 30 to 50 nanometers and the densities of TiC and BN are 4.93 g/cm^3 and

2.28 g/cm^3, respectively. SEM micrographs of the TiC and BN nanoparticles are shown in Figure 1.

TABLE 2. **Properties of boron nitride and titanium carbide**

Properties	BN	TiC
Particle size [nm]	30-50	30-50
Color	white	black
Density [g/cm^3]	2.28	4.93
Elastic modulus [GPa]	675	449
Melting point [°C]	2973	3160
Thermal conductivity [W/m K]	30	21

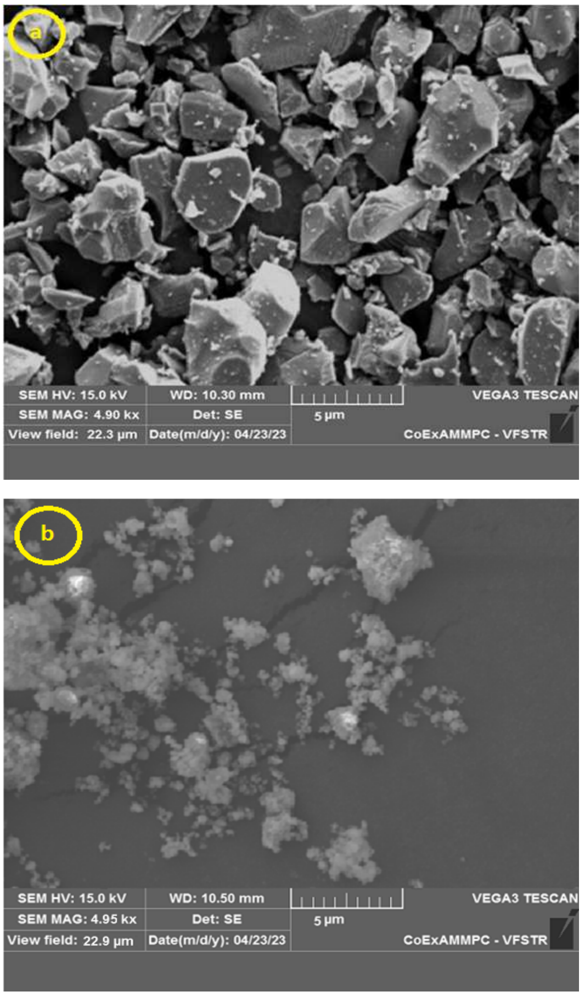

Fig. 1. Morphology of: a) TiC, b) BN nanoparticles

Preparation of nanocomposites

The process of producing aluminum hybrid metal matrix nanocomposites (AHMMNCs) involves several steps which are designed to ensure that the resulting composites have the desired properties. The first step is to melt the Al7085 alloy in a 1.5 kg graphite crucible using the ultrasonic method. This is done under argon gas protection at the temperature of 750°C for each casting. The use of ultrasonic waves helps to break down the oxide layers on the metal surface, which can improve the wetting of the nanoparticles and facilitate their dispersion. To enhance the wettability of the nanoparticles, the TiC and BN nanoparticles were heated to 400 °C in a muffle furnace. This process helps to remove any surface contaminants that may hinder interaction between the nanoparticles and the molten metal. The molten metal was then stirred for 30 minutes at 500 RPM using a mechanical stirrer. This helps to ensure that the nanoparticles are evenly dispersed throughout the molten metal. An ultrasonic probe was then submerged into the melt, 30 mm from the bottom of the crucible, and vibrated for 25 min to break any clustered nano TiC and BN particles. The ultrasonic waves generated by the probe cause cavitation bubbles to form, which helps to disperse the nanoparticles more uniformly. The molten metal was then poured into a preheated mild steel mold and allowed to cool before solidifying. This helps to ensure that the resulting solidified composites have the desired microstructure and properties. The properties of the produced solidified composites were then tested by cutting standard specimens utilizing a wire-cut EDM machine to evaluate the mechanical, thermal, and electrical properties of the AHMMNCs, which are important for their various applications.

Characterization and testing

To analyze the microstructure of the base alloy and nanocomposites, an SEM model JEOL JSM-660LV with EDS was used for microstructural analysis, while XRD analysis was carried out by means of an X'pert PRO PAN analytical diffractometer with CuKα radiation. Tensile tests were conducted using an INSTRON Universal Testing Machine, and the microhardness of the nanocomposites was measured with a Daksha Vickers microhardness tester. The specimens used for the tensile test were designed to conform to ASTM E8-08 standards [3] and are shown in Figure 2. The experimental density was determined by means of the Archimedes' principle, while the theoretical density was calculated employing the rule of mixtures [9].

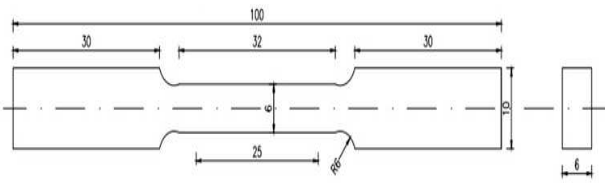

Fig. 2. Tensile test specimen measurements

RESULTS AND DISCUSSION

Microstructure and XRD analysis

Figure 3 presents the SEM micrographs with EDS spectra of the AMMNCs with various wt.% of TiC and BN nanoparticles. The micrographs of the prepared AHMMNCs reveal that the TiC and BN nanoparticles are evenly distributed in the base metal. Uniform dispersion of the TiC and BN nanoparticles is an important prerequisite to enhance the mechanical of the AHMMNCs. The EDS analysis confirms the occurrence of various elements in the Al7805 alloy and Al7085/TiC/BN nanocomposites. Peaks of aluminum, zinc, magnesium, boron, nitride, zirconium, silicon, copper and iron were found in the AHMMNCs. Thanks to UASC, there was a lack of casting faults like porosity and oxide inclusion as identified in the SEM micrographs of the AHMMNCs [6, 26].

Figure 4 displays the elemental maps obtained from the Al7085/TiC/BN nanocomposite shown in Figure 3b. These maps visually depict the presence and dispersion of aluminum (Fig. 4a), titanium (Fig. 4b), carbon (Fig. 4c), boron (Fig. 4d), and nitrogen (Fig. 4e) within the material.

The phase purity of the Al7085/TiC/BN nanocomposites was determined using XRD. The XRD analysis graphs are presented in Figure 5a-c. The results reveal strong and long peaks of the base matrix were identified in addition to small peaks of Tic and BN. The XRD pattern of the AHMMNCs only contains phases of Al, TiC, and BN, which indicates the absence of any secondary or intermetallic phases. The XRD pattern of the AHMMNCs shows that there was no oxygen reaction during UASC.

Mechanical properties

Effect of TiC and BN nanoparticles on tensile strength and percentage of elongation

Figures 6 and 7 show the influence of the wt.% of TiC and BN nanoparticles on the UTS and YTS of the AHMMNCs, respectively. It can be observed that both the UTS and YTS grow with the addition of BN nanoparticles up to 1.5 weight per cent and then decrease. This trend can be attributed to the strong interfacial bonding between the base alloy and TiC and BN nanoparticles up to 1.5 wt.%, which enhances the overall strength of the AHMMNCs. Nevertheless, beyond 1.5 wt.%, the decline in properties may be because of the agglomeration of the TiC and BN particles, which can result in the formation of voids or other defects in the composite [14].

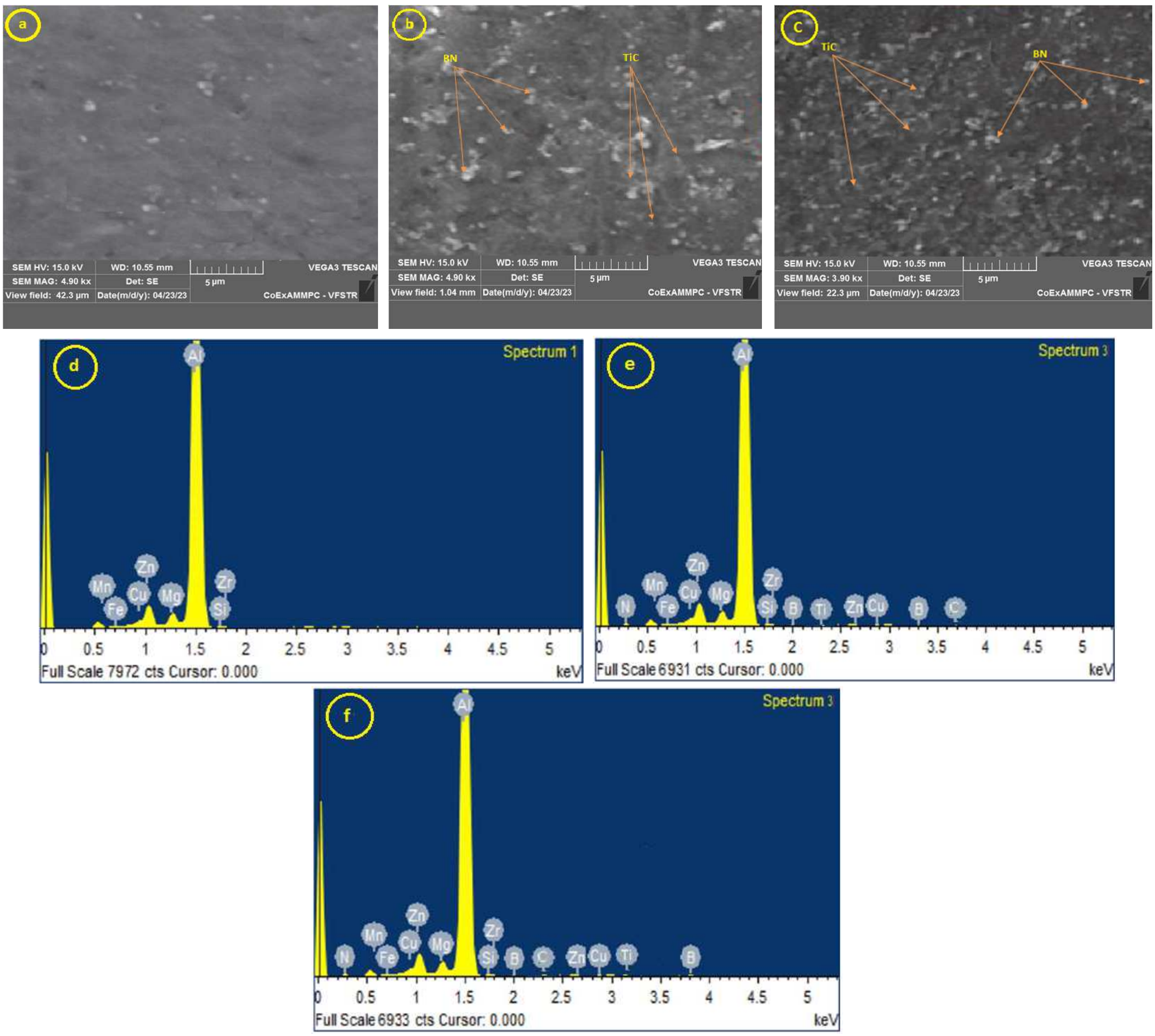

Fig. 3 SEM micrographs and EDS spectra of Al7085/TiC/BN HMMNCs with various wt.% of TiC and BN (0, 1, 2)

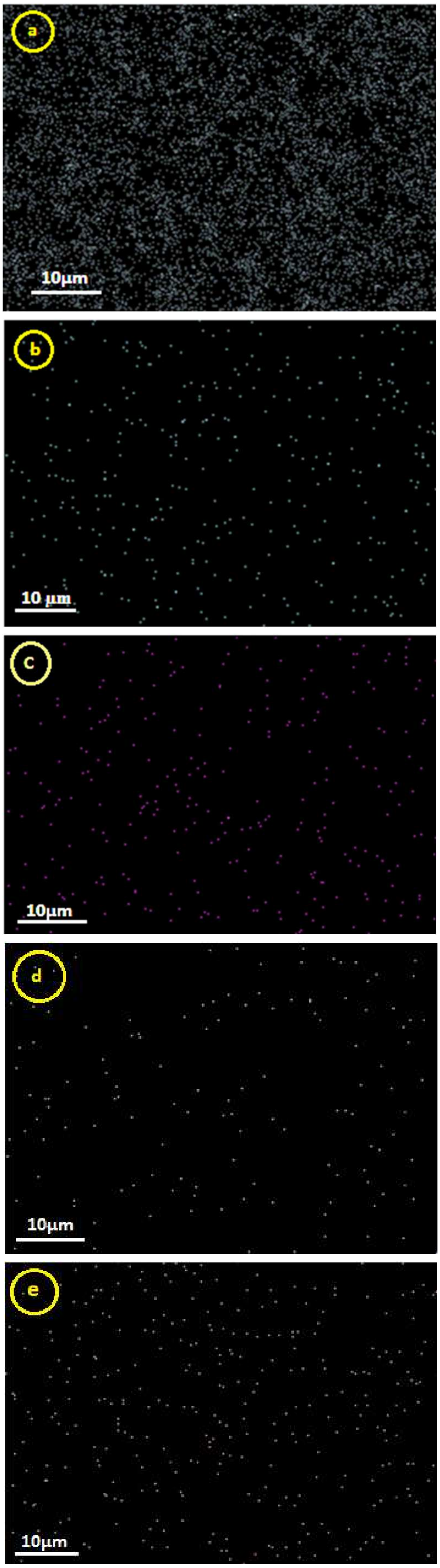

Fig. 4. EDX elemental map analysis of Al7085/TiC/BN HMMNC: a) Al, b) Ti, c) C, d) B, e) N

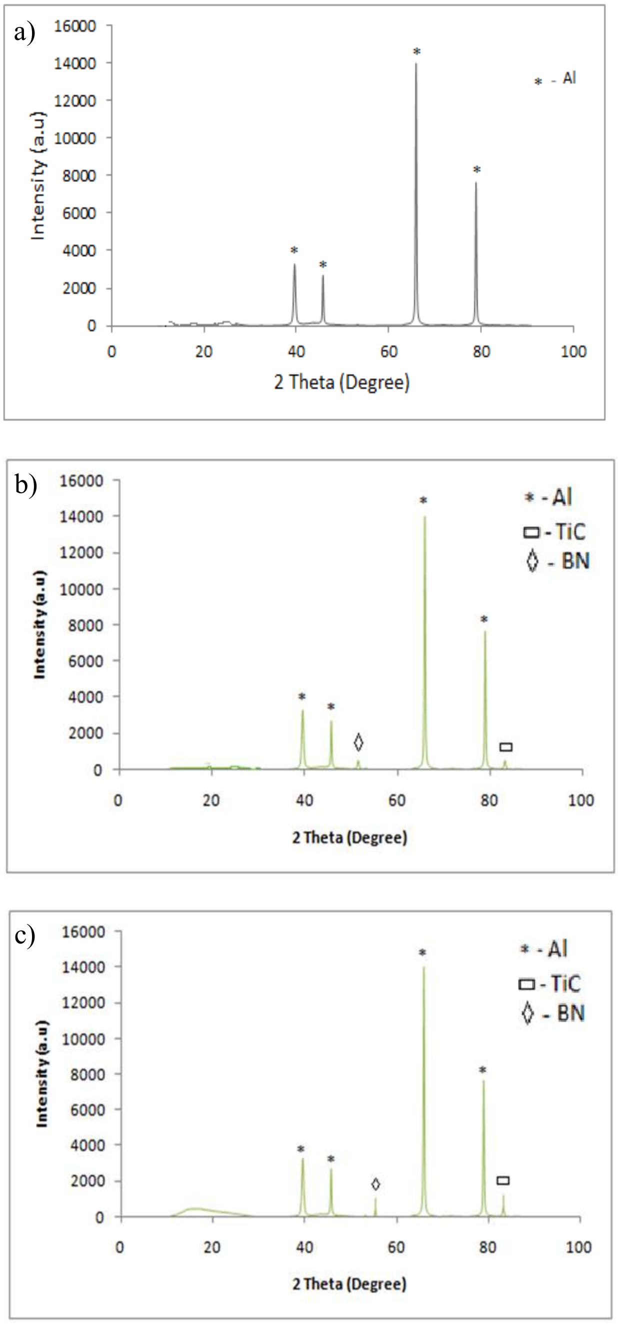

Fig. 5. XRD patterns of Al7085/TiC/BN HMMNCs with various wt.% of TiC and BN: a) 0, b) 1, c) 2

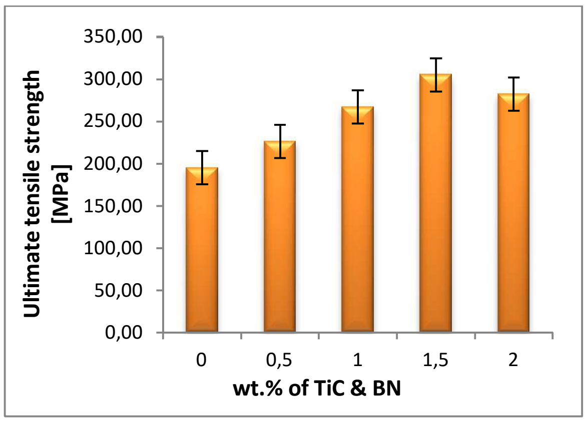

Fig. 6. Influence of nanoparticles on UTS of nanocomposites

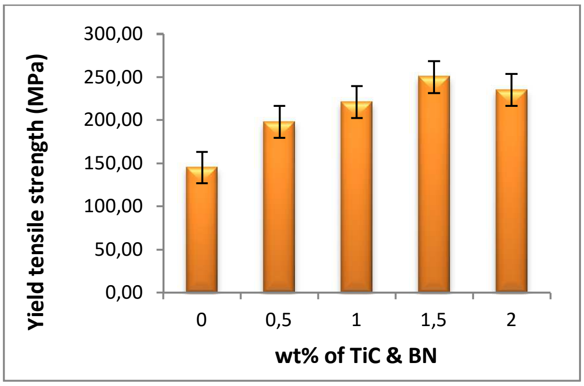

Fig. 7. Influence of nanoparticles on YTS of nanocomposites

Figure 8 displays the graph of % elongation with the addition of TiC and BN particles to the HMMNCs. The results indicate that the % elongation decreased with a rise in the wt.% of TiC and BN particles up to 1.5 and then grew. This behavior can be explained as follows: the decrease in % elongation up to 1.5 wt.% TiC and BN particles may be a consequence of the rise in the strength of the HMMNCs. The added reinforcement particles restrict the movement of dislocations, making it harder for the material to deform and thus reduce the % elongation. Nonetheless, beyond 1.5 wt.% TiC and BN particles, the % elongation starts to increase, which may be due to the reduced strength of the HMMNCs. This can be explained by the soft nature of the TiC and BN particles, which act as stress concentration points, leading to a lowered overall strength of the composites. Therefore, the % elongation rises resulting from the easy deformation of the composites at higher concentrations of TiC and BN particles [6, 14]. Figure 9 displays the tensile test specimens before and after testing.

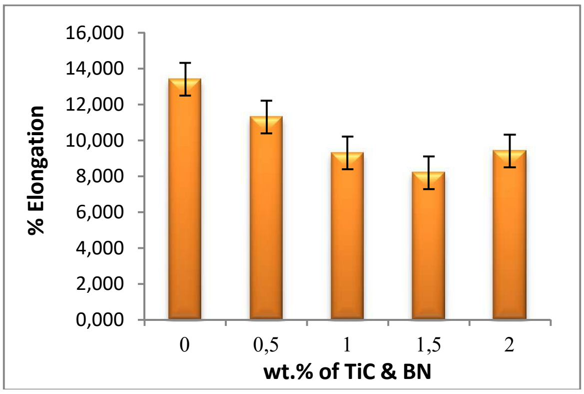

Fig. 8. Effect of nanoparticles on % elongation of composites

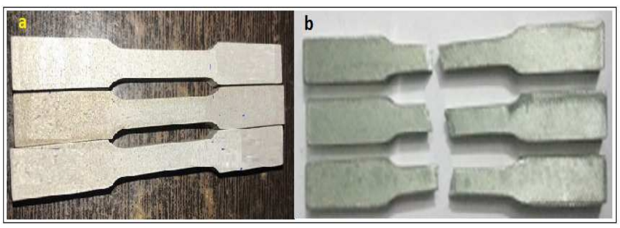

Fig. 9. Tensile test specimens before and after testing

Influence of TiC and BN nanoparticles on microhardness

Figure 10 shows the impact of the wt.% of TiC and BN nanoparticles on the microhardness of the AHMMNCs. The results suggest that an increment in the wt.% of TiC and BN nanoparticles leads to a rise in microhardness up to 1.5 wt.%, followed by a drop in microhardness. This can be attributed to the fact that the strength of the AHMMNCs rose with the addition of TiC and BN nanoparticles, which in turn led to growth in microhardness. Nevertheless, beyond 1.5 wt.% TiC and BN nanoparticles, the microhardness dwindles. This could be because of the soft nature of the TiC and BN particles, which may lead to a decrease in microhardness. Overall, the results indicate that there is an optimum wt.% of TiC and BN nanoparticles that can maximize the microhardness of the AHMMNCs [6, 14].

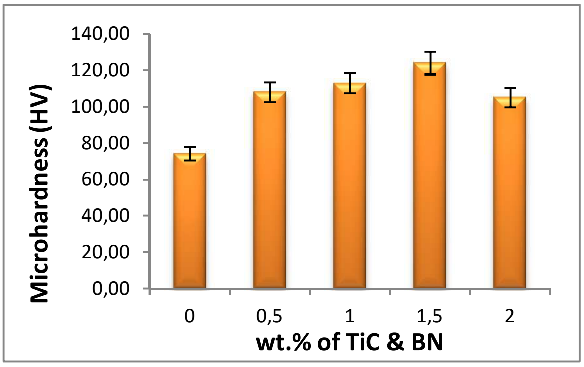

Fig. 10. Effect of nanoparticles on microhardness of composites

Effect of TiC and BN nanoparticles on density

Figure 11 presents the theoretical densities and experimental densities of the HMMNCs, along with standard deviation bars. However, small variations in the densities between the actual and measured values may occur owing to the shifting of some reinforcement into the slag during the casting process. The density of the reinforcements used in the AHMMNCs is greater than the base aluminum alloy (Al7085); the density of TiC and BN is 4.93 g/cm^3 and 2.1 g/cm^3, respectively, while the density of the base alloy is 2.79 g/cm^3. The higher density of the reinforcements contributes to an overall increase in the density of the HMMNCs. Pradeep Sharma et al [26]. conducted a study in which they investigated Si_3N_4 reinforced aluminum composites. They observed that density was enhanced as the amount of added Si_3N_4 was increased, but there was also a peak porosity of 1.43% that resulted from impurities in the aluminum material. Despite the increment in porosity, the overall density of the composites continued to rise with the Si_3N_4 addition. This illustrates the intricate interplay between the reinforcement particle type and quantity, as well as the base material quality in determining the density of metal matrix nanocomposites.

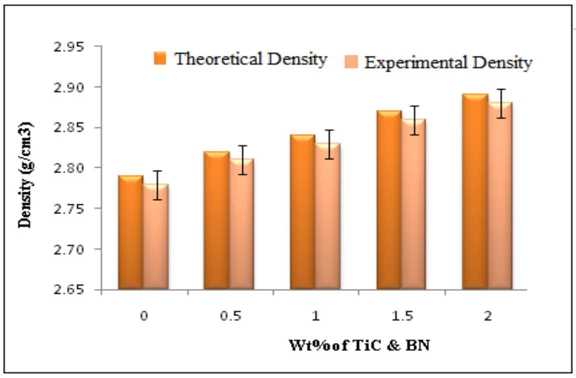

Fig. 11. Influence of nanoparticles on density of nanocomposites

CONCLUSIONS

Titanium carbide and boron nitride-reinforced Al7085 alloy nanocomposites were fabricated by the UASC technique. The microstructure, tensile strength, microhardness, density and porosity were investigated. Based on the results following conclusions were drawn:

– The TiC and BN particles were evenly distributed in the AHMMNCs.
– The XRD analysis of the cast samples revealed the presence of only Al, BN, and TiC particles, and thus the absence of secondary or intermetallic phases, in the AHMMNCs.
– The UTS of the AHMMNCs grew with a rise in the wt.% of TiC and BN nanoparticles up to 1.5 and then after it fell.
– The microhardness of the AHMMNCs increased with an increment in the wt.% of TiC and BN particles up to 1.5 and then after it decreased.
– The % of elongation is declined with the increase in TiC and BN particles up to 1.5 wt.% and then after it grew.
– The experimental densities of AHMMNCs are higher than the theoretical density, which continuously dwindles with the increment in TiC and BN nanoparticles in AHMMNCs due to the high density of the reinforcement particles.

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