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INFLUENCE OF NANO-ZIRCONIA ADDITION ON THE MECHANICAL PROPERTIES OF AL-7075 REINFORCED BY NANO-BORON CARBIDE AND ALUMINUM DIOXIDE

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ABSTRACT
The wide use of aluminum alloy in the aerospace and automotive industry is because of its excellent erosion resistance, formability, quality and light weight which is demanded in many industries. Herein, aluminum (Al-7075) composite is fabricated with the aid of stir casting method, nanofillers like boron carbide (B_4C), aluminum dioxide (Al_2O_3) and Zirconia (ZrO_2) were added to the composite. Nanoparticles of ZrO_2 were added with different weight fraction of 2, 4, 6 and 8 wt.%. The B_4C and Al_2O_3 nanoparticles were added to the aluminum composites with fixed ratio of 5 wt.% and 10 wt.%, respectively. The samples were fabricated according to ASTM E8M standards for tensile test. Hardness test specimens were prepared according to ASTM E10. Tests were carried out on the ceramic nanoparticles reinforced Al-7075 composites. The results cleared that the addition of nanofillers especially ZrO_2 has significant enhancements on the mechanical properties of the metal matrix composites.

KEYWORDS
Zirconia; stir casting; Al-7075; ceramic nanoparticles; mechanical properties.

INTRODUCTION
The metal matrix composites (MMCs) especially aluminum composites have potential applications in various fields such as aerospace, marine and industries of automotive. Al-7075 features a lightweight, wear and erosion resistance compared to other kinds of metal matrix composite materials, [1-6]. Many research groups are used ceramic nanoparticles to study its effect on the tribological and mechanical properties of MMCs [7-8]. MMCs are a category of materials with good erosion and wear resistance properties, with a lower density and higher stiffness and durability compared to the matrix without reinforcement [9-10]. Ceramic nanoparticles reinforcements in Al-7075 matrix improve erosion and enhance resistance to composite wear as well, [11-12]. Throughout the liquid casting process, nanoparticle reinforcement is mechanically finely spread over liquid metal before casting and solidification, [13-16]. MMCs have enhanced mechanical properties quite unreinforced aluminum alloys and are widely used thanks to their higher density ratio and better

mechanical strength. This leads to being used in many applications in industry. H.G. Rana et al., [17] manufactured Al-7075 reinforce by boron carbide (B_4C) particles using a friction stir method. The results showed that wear resistance increased due to the good dispersion of B_4C particles. Qiang Shen et al., [18] synthesized Al-7075/B_4C using a bottom-up process and the results showed that increasing of B_4C fraction leads to enlarge in the compressive yield strength, flexural strength and composite hardness. T. Senthilvelan et al., [19] studied the mechanical properties of Al-7075/reinforced by ceramic nanoparticles. They concluded that the composites tensile strength and hardness was highly improved due to these additives. Ravi kumar et al., [20] manufactured the coconut shell ash (CSA) and Zirconium oxide (ZrO_2) reinforced Al-6082 composite and they investigated Zirconia effect on the mechanical properties. Khare et al., [21] studied the tribological properties of Al-7075 reinforced by B_4C and Al_2O_3 composites. The results presented that addition of ceramic nanoparticles has greatly enhanced wear rate. Raghavendra N. et al., [22] studied the effect of the weight fraction and the particle size of Al-7075/Al_2O_3 composites, they founded that with the reduction of particle size the hardness of the composite was increased. The mechanical properties and tribological behavior of the hybrid composite Al-7075/Al_2O_3 have been studied by A. Baradeswaran, [23] et al., the results displayed that with the addition of nano Al_2O_3 the hardness of the Al-7075/Al_2O_3/GR hybrid composite was improved. Khare et al., [24] studied the mechanical properties of the Al_2O_3 reinforced Al-7075 composite. The results showed that the mechanical properties were significantly improved. Xiaoxuan P. et al., [25] used Al_2O_3 and B_4C to reinforce Al-6061 using powder metallurgy method. Tensile properties and strengthening effects of composite were investigated with the usage of numerical modeling analyses. The addition of nano- Al_2O_3 significantly improves the tensile strength of the composite. Kuldeep P. et al., [26] used powder metallurgy to fabricate MMCs reinforced by the addition of Zirconia. The addition of ZrO_2 significantly enhances the mechanical properties of composites compared to aluminum base metal matrix.

In the current research, Al-7075 having nano Al_2O_3 and nano B_4C with fixed fractional weight is reinforced by nano ZrO_2 in order to study Zirconia effect on mechanical properties such as tensile strength, hardness and flexural strength. The composites have been developed using a stir casting technique.

Materials and methods

Materials

The unreinforced aluminum base metal selected for the present study is Al-7075. It has high erosion resistance and high strength because of zinc existence in its chemical composition. Table 1 shows aluminum-7075 chemical composition. Nanofillers used are alumina (Al_2O_3), boron carbide (B_4C) and Zirconia (ZrO_2). Figures 1(a-c) show SEM of nanofillers photos which illustrate that nanoceramic powders morphology is coarse, irregular in shape and non-uniform size. The composition of testing specimens is a fixed weight percentage of 5 wt. % of nano B_4C (50 nm) and 10 wt. % of nano Al_2O_3 (25 nm) used as reinforcements to Al-7075 aluminum alloy for all specimens. Nano ZrO_2 is added with varying weight percentage of 2, 4, 6 and 8 wt. % to composite. A nano ZrO_2 powder used with an average grain size of 35 nm, its surface area is 10±2 m^2/g and it has a purity of 99.9 percent. Nanoparticles were supplied by Sigma-Aldrich. Composition of samples in percentage is given in Table 2. The

tests are conducted using Brinell hardness and universal testing machine.

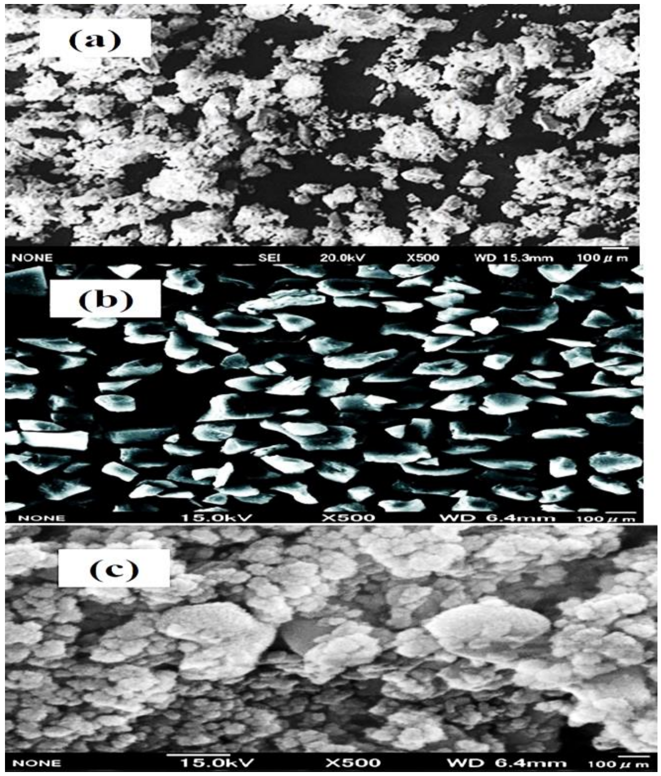

Fig. 1 SEM micrographs (a) Zirconia, (b) boron carbide, and (c) alumina.

Table 1. Chemical composition of Al-7075.

Aluminum-7075	Cu	Si	Mn	Ti	Cr	Fe	Zn	Mg	others
Composition %	1.4	0.052	0.05	0.047	0.19	0.2	5.9	2.1	0.025

Table 2. Percentage of samples composition.

Sample code	Al-7075 wt.%	Nano Al_2O_3 wt.%	Nano B_4C wt.%	Nano ZrO_2 wt.%
S_1	100	0	0	0
S_2	95	0	5	0
S_3	85	10	5	0
S_4	83	10	5	2
S_5	81	10	5	4

S_6	79	10	5	6
S_7	77	10	5	8

2.2. Specimen preparation

In the present study nano ZrO_2 particles are introduced to Al-7075/B_4C/Al_2O_3 composite by means of stir casting process as illustrated in Fig. 2. In the presence of argon gas, the casting was done to avoid formation of oxides, [27]. Nano B_4C and nano Al_2O_3 are applied in Al-7075 matrix with a fixed weight percentage of 5 and 10, respectively. After that, nano ZrO_2 with different weight fractions of 2, 4, 6 and 8 wt. % was added to the composite. In order to enhance wettability, Potassium Titanium Fluoride (K_2TiF_6) was used as filler. In a separate furnace the nanoparticles were preheated to 575°C. The Al-7075 composite was gradually heated at 350 °C and melted in a blower furnace at approximately 850 °C to ensure Al-7075 melted completely. Then the preheated nanofillers powder was added slowly, a motor with 1200 rpm stirred the molten for 7 minutes. In order to avoid moisture, the temperature is saved persevering at 850 °C. Then the mixture is poured into steel molds that were heated previously. The process data and parameters during composites casting are listed in Table 3. The different types of fabricated composites are listed below: -

S_1. Al-7075 alloy + 0% B_4C + 0% Al_2O_3 + 0% ZrO_2
S_2. Al-7075 alloy + 5% B_4C + 0% Al_2O_3 + 0% ZrO_2
S_3. Al-7075 alloy + 5% B_4C +10% Al_2O_3 + 0% ZrO_2
S_4. Al-7075 alloy + 5% B_4C+10% Al_2O_3 + 2% ZrO_2
S_5. Al-7075 alloy + 5% B_4C +10% Al_2O_3 + 4% ZrO_2
S_6. Al-7075 alloy + 5% B_4C +10% Al_2O_3 + 6% ZrO_2
S_7. Al-7075 alloy + 5% B_4C +10% Al_2O_3 + 8% ZrO_2

Table 3 Composites casting data.

Furnace capacity	3-4 Kg
Furnace Operating Voltage	440 Volts, 3 Phase
Furnace Operating Temperature	100-1600 °C
ZrO_2 Preheat temperature	350 °C
Speed of Stirring	1200 rpm
Temperature of stirring	850 °C
Time of stirring	7 mins

2.3. Mechanical properties

Mechanical properties including hardness, bending strength and tensile strength were studied for all samples. A 60 mm x 60 mm x 10 mm specimen is used for hardness test and the average value is estimated at four different locations. Tensile specimens were fabricated according to ASTM E8M; and tested using a computerized universal testing machine WAW-

300B (300 kN, Zhejiang Jingyuan Mechanical Equipment Co., Ltd., Jinhua, China). Tensile testing machine WAW-300B with a constant strain rate of 6 mm/min was also used to measure the flexural strength.

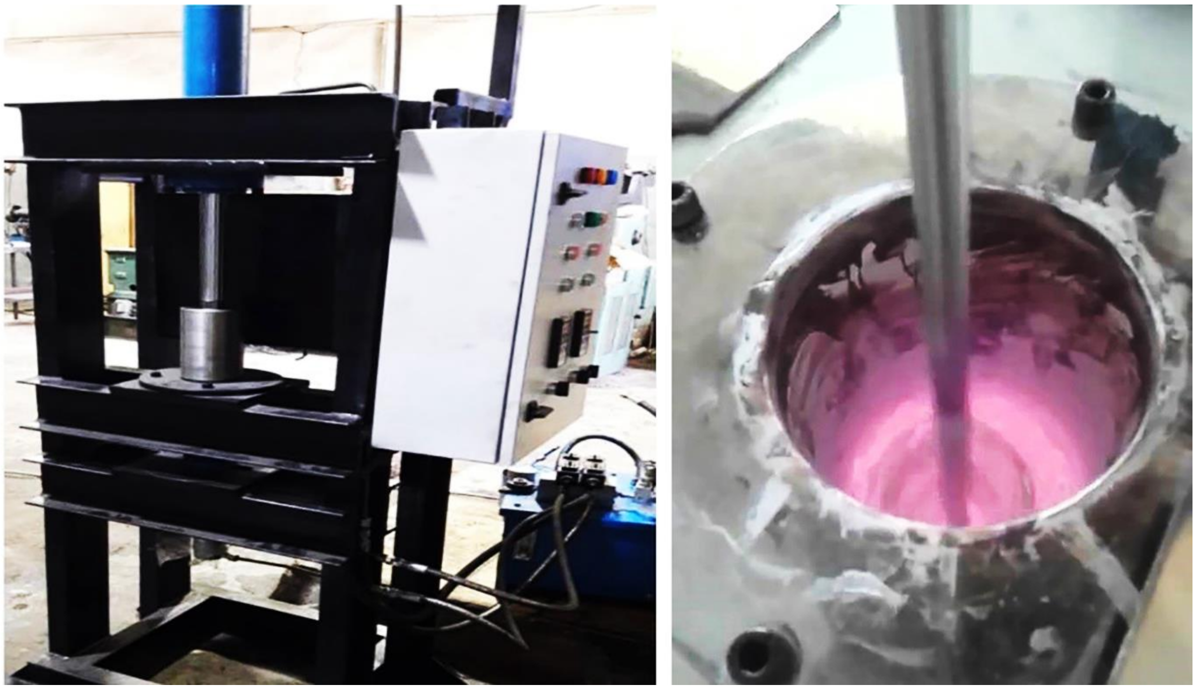

Fig. 2 Stir casting furnace setup.

RESULTS AND DISCUSSION

Hardness

During a period of 15 seconds the standard test method of ASTM E10 was carried out in Brinell for hardness tests with 50 grams of load. Figure 3 shows the different hardness plots of various composites. The results showed that the hardness increases with the addition of Al_2O_3 and B_4C to Al-7075 composite. The alloy hardness was above the base alloy hardness this refers to the particulate nature of B_4C and Al_2O_3. The presence of alumina nanoparticles protects the softer matrix. Therefore, it restricts the deformation as well as preventing penetration and cutting of slides on the composite surface, [28]. Hamid Abdulhaqq et al., [29] observed that ceramic nanoparticles addition greatly enhances the bulk hardness of Al alloys and concluded that the dispersion of Al_2O_3 by 8 wt.% into aluminum achieved the highest hardness value. This is in a good agreement with Mahdavi and Akhlaghi 's results, [30]. It was observed that with increasing the nano Zirconia reinforcement in Al-7075 nanocomposites the hardness was increased. The composite with 8 wt% of ZrO_2 has higher hardness value compared to the other composites (the enhancement was about 13.77%). The increased hardness of ZrO_2 particles could be attributed to the increased presence of hard Zirconia particles and their restriction on localized plastic deformation, coupled with good matrix enhancement interfacial integrity and this shows significant improvement of the resistance of Al-7075/ZrO_2 nano composites against indentation. Different researcher groups

have noted the similar trends, [31-34].

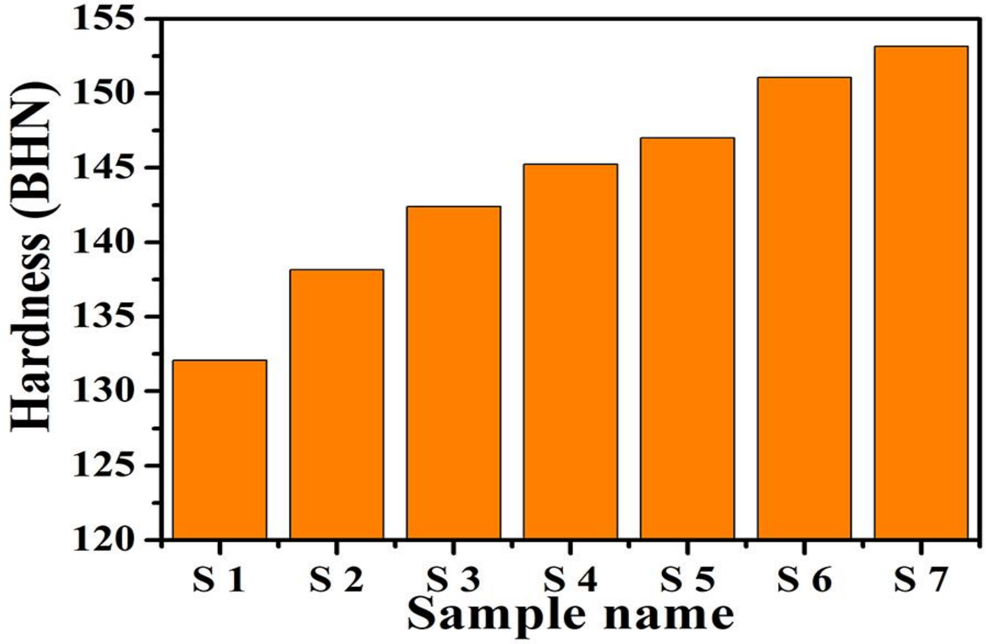

Fig. 3 Hardness comparison of all metal matrix composites.

Tensile strength

Figure 4 shows the tensile strength variation during the addition of nano ZrO_2 to metal matrix nanocomposites. Tensile tests were evaluated according to ASTM E8M standard test method. The results showed that by adding B_4C and Al_2O_3, the mechanical properties were enhanced. The presence of B_4C is found to prevent dislocation, which results in higher hardness compared to Al-7075 alloy, [35]. By adding Al_2O_3, the hardness is more improved as the stress transfer from the aluminum matrix to the strengthened B_4C and Al_2O_3 particles. This is due to orowan mechanism where dislocation circumvents impenetrable barriers where the dislocation is strong enough to leave a dislocation loop around a particle [36]. The interaction of the dislocations with B_4C, Al_2O_3 and ZrO_2 improves strength. More addition of ZrO_2 particles leads to increase in tensile strength. It is clear that the composite with 8 wt. % of nano ZrO_2 has higher strength compared to other composites. It reaches 31.5% of the base metal alloy. This increase could be mainly attributed to the homogeneously dispersed nanoparticles due to the growth of the Zirconia particles on the aluminum particles. This resulted in an efficient transmission during tensile deformation and thus improved composite strength. This takes place because of the enhanced particle in the nucleation that inhibits movement on the grain boundaries. As a result, the grain size in the matrix has become smaller than the alloy Al-7075 unreinforced. The dislocation of the suspension throughout the matrix has reduced grain size. This inhibits the dislocation of synthesized hybrid composites to accumulate a strengthening effect. ZrO_2 is important for the determination of tensile tests, thanks to its superior characteristic, also in the aluminum matrix alloy. The aluminum hybrid composite elongation percentage was decreased within the ceramic enhancement percentage in the matrix alloy. In order to reduce the ductility, the

breakdown of reinforced ceramic particles plays a crucial role. The weight increases of ceramic nanoparticles in composites may contrast with the aluminum matrix's flowability in decreasing the contents of the ductile matrix. This has reduced synthesized hybrid composites' percentage elongation. Similar trends were noted by other researchers, [37-47].

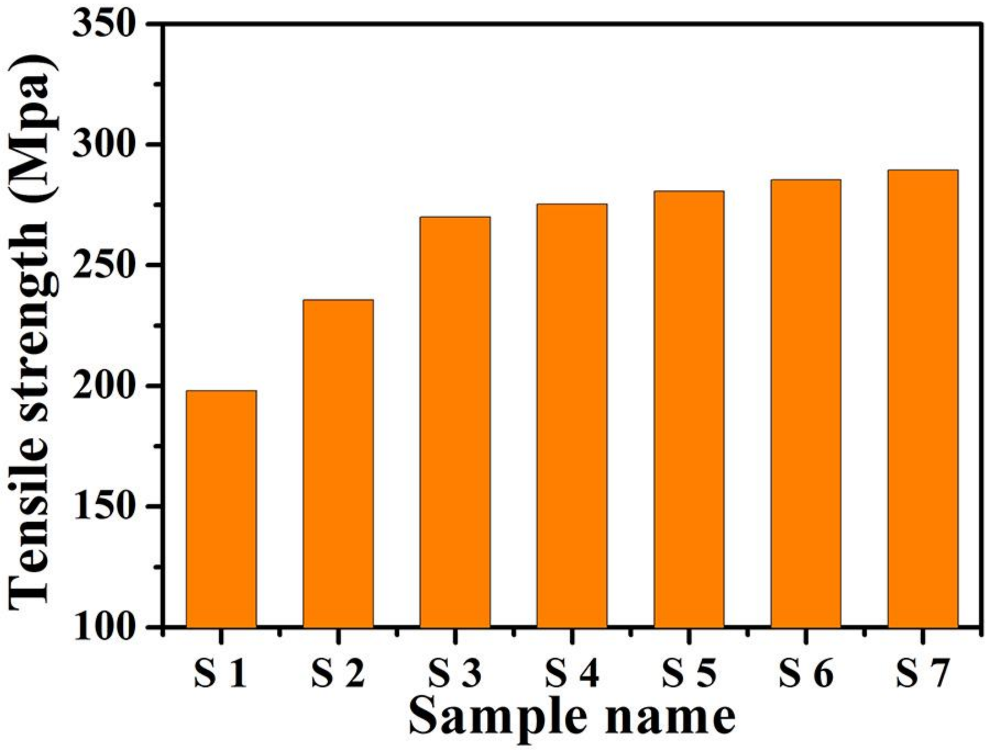

Fig. 4 Tensile strength of Al-7075 nanocomposites as a function of Zirconia weight fraction.

Flexural strength
The flexural strength of Al-7075 nanocomposites can be calculated using the flexural strength formula, which is given by:

$$\sigma = 3FL / 2bd^2$$

where σ is the flexural strength in Pascals (Pa), F is the maximum force applied to the material in Newtons (N), L is the span length of the material in meters (m), b is the width of the material in meters (m), and d is the depth or thickness of the material in meters (m).

Al-7075 nanocomposites flexural strength variation during the reinforcement of Zirconia weight percentage is shown in Fig. 5. It was shown that with the addition of B_4C, Al_2O_3 and ZrO_2 the flexural strength was increased. Structure and characteristics of the fillers control the mechanical characteristics of the composite that are due to the interface which transfers and distributes the load from the matrix to the reinforcements. This leads to an increase in strength and elastic module [48]. It is also observed that the flexural strength increases with the increase of nano Zirconia weight percent up to 8%. The brittle nature of nanofillers and the interface between the fiber and the matrix increases the composite flexural strength and

it was higher than the aluminum base alloy. The flexural strength was increased by ~ 46% than that of Al-7075 alloy.

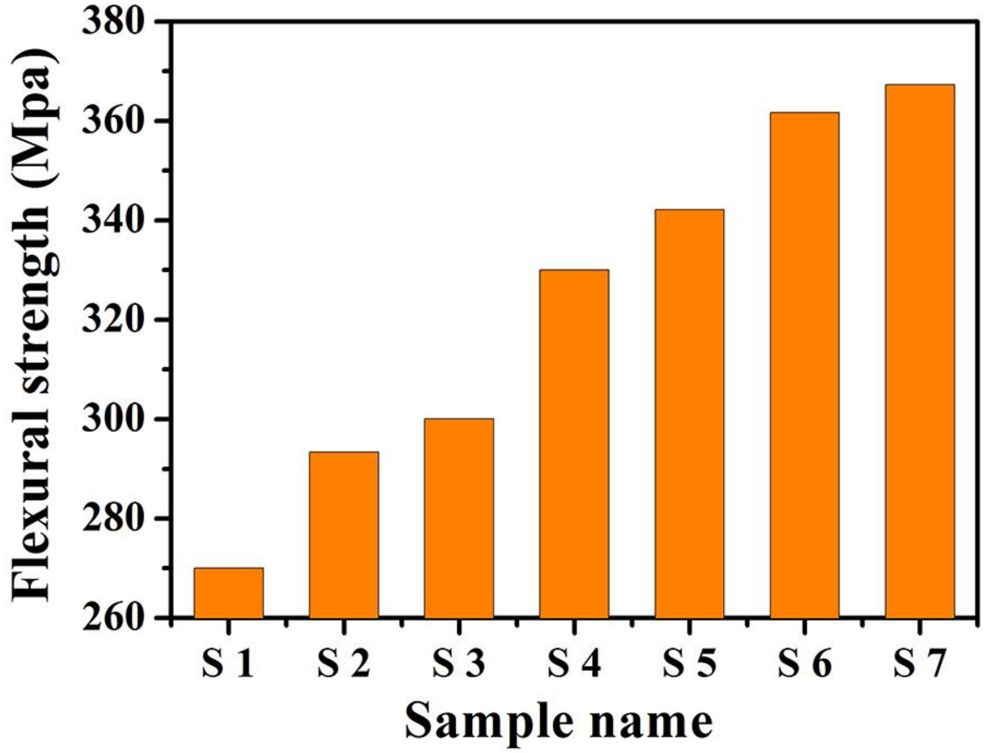

Fig. 5 Variation of flexural strength of all Al-7075 nanocomposites with Zirconia weight fraction.

SEM fractography

The morphological fractures SEM images of all samples are shown in Fig. 6. Figure 6(a) shows the SEM photo of pure Al-7075 alloy. It was clarified that the Al-7075 alloy is distributed uniformly with voids. With the addition of nanofillers to the pure Al-7075 alloy the voids ratio was significantly decreased as illustrated in Fig. 6(b-g). There were three morphologies are shown in Fig. 6(a-c) to demonstrate the evidence of the ductile fracture, it was more apparent in pure Al-7075 alloy and medium ductile fracture in Al-7075 reinforced by B_4C and Al_2O_3 composite. It is clear that the ductility and the percentage of elongation are reduced, due to the hardness of B_4C and Al_2O_3 particles, [49]. The morphological fractures SEM photos of Al-7075 after the tensile test of Al-7075+B_4C+Al_2O_3+ZrO_2 nano hybrid composites are shown in Fig. 6(d-g). The ductile fracture mode with reinforcing decohesion particles has been revealed. In most cases B_4C fracture can be easily observed, which leads to pull-out of particles and cause microvoids. However, Al-7075 nanocomposites reinforced by ZrO_2 particles are well-preserved. This revealed that the matrix and the nanofiller particles are better linked as described, [50]. From the morphology of fracture images, it could be noticed that there is a presence of ductile fracture, however it appears clearly in Al-7075 alloy and it is not much clear in case of nanocomposites, [51]. The ZrO_2, B_4C and Al_2O_3 nanoparticles remained intact in various locations, which provide reliability

for improved bonding between the aluminum matrix and nano filler particles.

3.5. SEM test

Figure 7 shows the distribution of reinforcements within the Al-7075-matrix alloy reinforced by 5wt.% B_4C+ 10 wt.% Al_2O_3 +8wt.% of ZrO_2. Figure shows clearly that nanoparticles of B_4C, Al_2O_3 and ZrO_2 are uniformly dispersed in metal matrix. There is a great improvement in the bond between the materials and as there is no porosity. Optimal use of stirring during casting could be the reason for homogenous mixing. That explains the better enhancement of mechanical properties of aluminum nanocomposites.

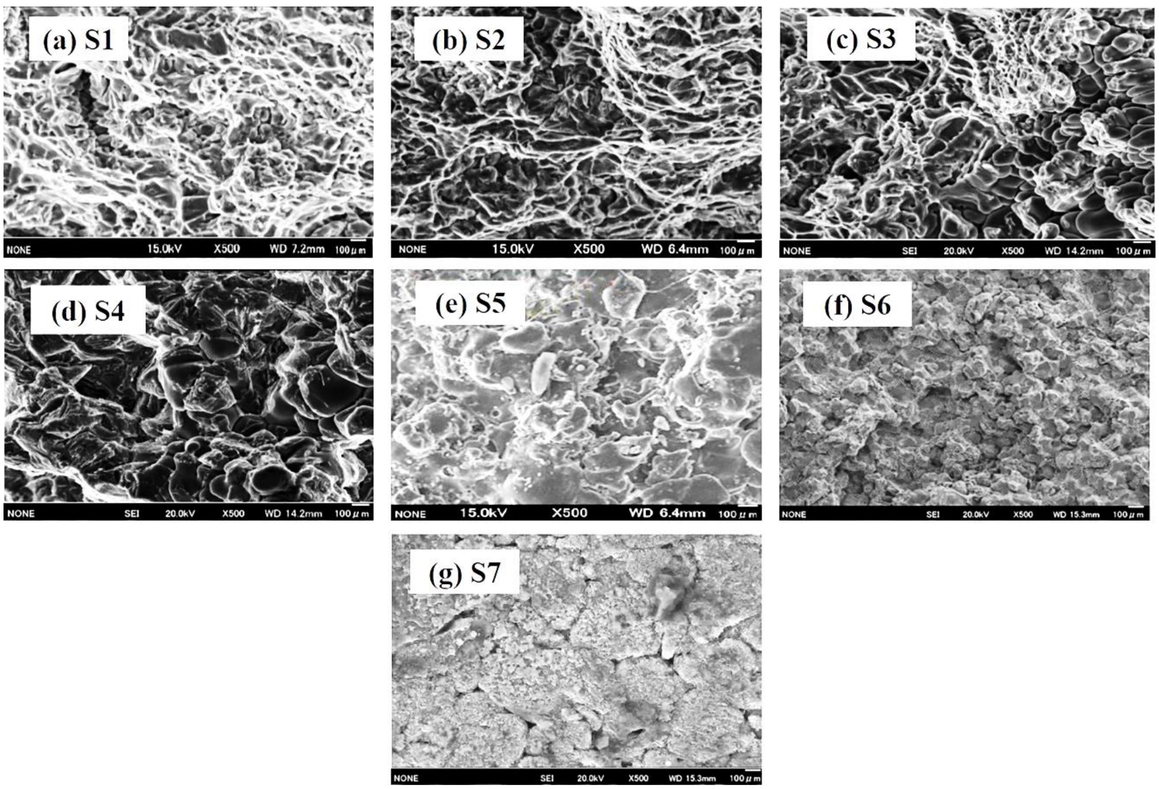

Fig. 6. (a-g) SEM photographs of tensile fracture surface of all samples (S_1-S_7).

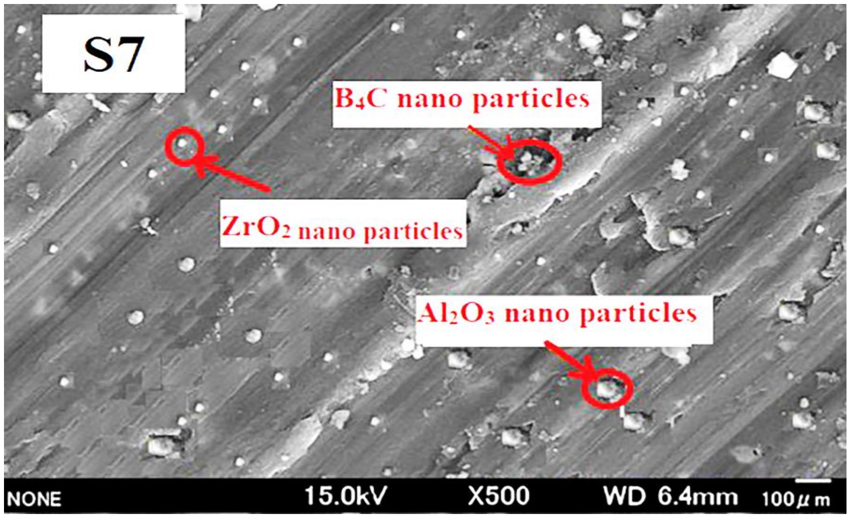

Fig. 7 SEM photograph of sample S_7 showing distribution of nanofillers.

CONCLUSIONS

Aluminum (Al-7075) composite is successfully fabricated with the aid of stir casting method. Nanofillers like boron carbide (B_4C), aluminum dioxide (Al_2O_3), and zirconia (ZrO_2) were found to enhance the properties of (Al-7075) alloy. SEM inspection shows that the nanofillers are uniformly dispersed in metal matrix. Nano-zirconia (ZrO_2) addition increased the hardness of all aluminum composites reinforced by (5% B_4C + 10% Al_2O_3). Hardness reaches a maximum value of 153.15 BHN with 8 wt. % nano ZrO_2. The addition of nano ceramic particles increases the tensile strength of all Al-7075 composites, the enhancement reaches 31.5% more than aluminum-based metal alloy. Also, flexural strength was enhanced by 26.46%. The mechanical characteristics of Aluminum (Al-7075) nanocomposites were greatly improved by the dispersion of nanofiller particles of (B_4C, Al_2O_3 and ZrO_2) into aluminum matrix especially zirconia nano particles. This may due to a standardized placement of nano ceramic particles into the aluminum matrix.

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