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Microstructural and mechanical properties of Al_2O_3 reinforced Al7010 matrix composites, fabricated by stir casting

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Abstract

The microstructural and mechanical properties of alumina reinforced Al7010 matrix composites, fabricated by stir casting, were investigated by varying size and volume fractions of alumina particles. The optical microscopy, micro Vickers hardness test, tensile test, and impact test were performed to evaluate the microstructure and mechanical properties of produced alumina reinforced Al7010 matrix composites. Results show that the alumina reinforced Al7010 matrix composites, incorporating lower volume fractions of alumina particles, exhibited much better morphological and mechanical properties than composites with higher volume fractions. The composite with 14% alumina particles of size 15 µm exhibited uniform dispersion of alumina particles in the Al7010 matrix with superior interfacial bonding and negligible agglomeration of alumina particles and excellent morphological properties. On the other hand, the composite, having 21% alumina particles of size 1 µm demonstrated very poor morphological properties and intensive agglomeration of alumina particles. Similarly, the maximum values of R_m (349 MPa) and $?_T$ (3.41%) were also offered by composite, incorporating 14% Al_2O_3 particles of size 15 µm attributed to the uniform dispersion and negligible agglomeration of alumina particles throughout the matrix. The composite with 21% alumina particles of size 1 µm offered the minimum values of R_m (172 MPa) and $?_T$ (1.69%) due to the presence of intensive agglomeration of alumina particles. The superior impact toughness (11.4 J) and the overall optimum combination of morphological and mechanical properties were offered by the composite with 14% alumina particles of size 15 µm.

Keywords: Aluminum Matrix Composite, Alumina Particles, Stir Casting, Microstructure, Mechanical Properties.

1. Introduction:

The demand of aluminum matrix composites (AMCs) is rapidly increasing in structural, aerospace, automotive, arctic chemical processing equipment, pressure vessels, subsea pipelines, and drill industries due to their attractive properties, such as higher strength to weight ratio, excellent wear, and corrosion resistance, and lower thermal conductivity [12]. In the last few years, extensive work has been done to improve the mechanical properties of AMCs by the incorporation of reinforcing particles, such as alumina (Al_2O_3) [34], Al_4TiC, Al_4Fe_3C, Al_4Mo_2C, and Al_4WC [2], titanium carbide [5], TiB_2 + Al_2O_3 [1], multi-walled carbon nanotubes [2,6], aloe vera powder [5], Al-20Cu10Mg [7], sillimanite [8], silicon carbide [910], graphene nanosheets coated copper [11], titanium particles [12], bamboo leaf ash [13], iron oxide [6], titanium

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dioxide [14], and boron carbide (B_4C) [15]. Various techniques, i.e., powder metallurgy, infiltration, diffusion bonding, stir casting, squeeze casting, mechanical alloying, co-spray deposition, and vacuum hot pressing have been employed for fabricating AMCs [1,7,16].

Stir casting is the simplest, inexpensive, mass productive, and frequently used method of manufacturing AMCs [1,78,11]. Stir casting provides an excellent combination of dispersion and distribution of micro-sized particles inspite of their high viscosity, large surface-to-volume ratio, and poor wettability in the molten metal [17]. Stir casting develops a good interfacial bond between the aluminum matrix and reinforcing particles by their inter-diffusion [18]. Parameters of stir casting, such as stirring time and speed, particle size, particle volume fractions, have a significant impact on the quality of casted AMCs. Considerably higher stirring speed and prolonged stirring time cause homogeneous dispersion of reinforcing particles [19]. Along with several benefits, stir casting also has some drawbacks, such as undesirable chemical responses between aluminum matrix and reinforcing particles, non-uniform distribution of particles, which can be controlled by optimizing stir casting process parameters [20].

Several investigations have been reported in this field. Afkham et al. [3] worked on alumina nanoparticles reinforced AMCs and reported that pyrex powder of ZnO and TiO_2 in 4 to 6 wt% better enhanced the hardness, tensile strength, and yield strength, whereas reduced the elongation, compared to pure ZnO and TiO_2 powder [3]. Similarly, Gireesh et al. [5] reported that the addition of powder form of aloe vera significantly improved the hardness and tensile strength of AMCs, compared to ash form aloe vera. Ravikumar et al. [21] found that increasing the percentage of titanium carbide increased the density, hardness, and tensile strength and decreased the impact toughness and elongation of AMCs. The microstructure of these AMCs contained dimples, cracks, voids, and ridges. Liu et al. [11] worked on nano sheet graphene-coated copper reinforced AMCs and found that strongly bonded copper improved the tensile strength of AMCs upto 200%, compared to pure aluminum. This strengthening is attributed to the load transfer by the copper network in the aluminum matrix and formation of Al_2Cu compounds after annealing and dislocation strengthening. Al7010 is one of the widely used aluminum alloy, particularly designed for the aerospace industry [22]. As it replaced the classical 7075 aluminum alloy used in various die forging applications, therefore it is considered to be a milestone in the aluminum alloy development [23]. Al7010 alloy possesses an excellent combination of tensile strength, impact toughness, and resistance to stress corrosion cracking but also encountered various cracking failures. Extensive work has been done to improve the properties of conventional Al7010 alloy by the addition of suitable alloying elements but it still needs improvement [22].

Therefore, in the present work, an attempt has been made to improve the mechanical properties of Al7010 alloy by the incorporation of alumina particles. The effect of particle size and volume fractions of alumina particles on microstructural and mechanical properties of stir cast alumina reinforced Al7010 matrix composite was investigated. Al7010 aluminum alloy was produced and stir cast in the laboratory. The alumina particles of size 1 μm and 15 μm were reinforced in the Al7010 alloy in the volume fractions of 14% and 21%. A light optical microscope was used to evaluate the microstructural properties. Tensile test, Charpy V notch impact test, and micro Vickers hardness test were also performed to evaluate the mechanical properties of stir casted alumina reinforced Al7010 matrix composite. The theoretical density values of all casted composites were determined by the rule of mixture, whereas experimental density values were measured by the Archimedes principle. The values of the porosity of produced composites were also calculated.

2 Experimental Work

2.1 Materials

Pure aluminum was purchased in the form of wires as illustrated in Figure 1(a). Other alloying elements, i.e., Zn, Cu, Cr, and Al-Mg master alloy were also purchased and used as received. For the removal of slag and dissolved gases, fluorine salt tablets and CaF_2 were purchased. All the materials were weighed in the separate beakers for subsequent production of Al7010 alloy and stir casting of Al_2O_3 reinforced Al7010 matrix composites.

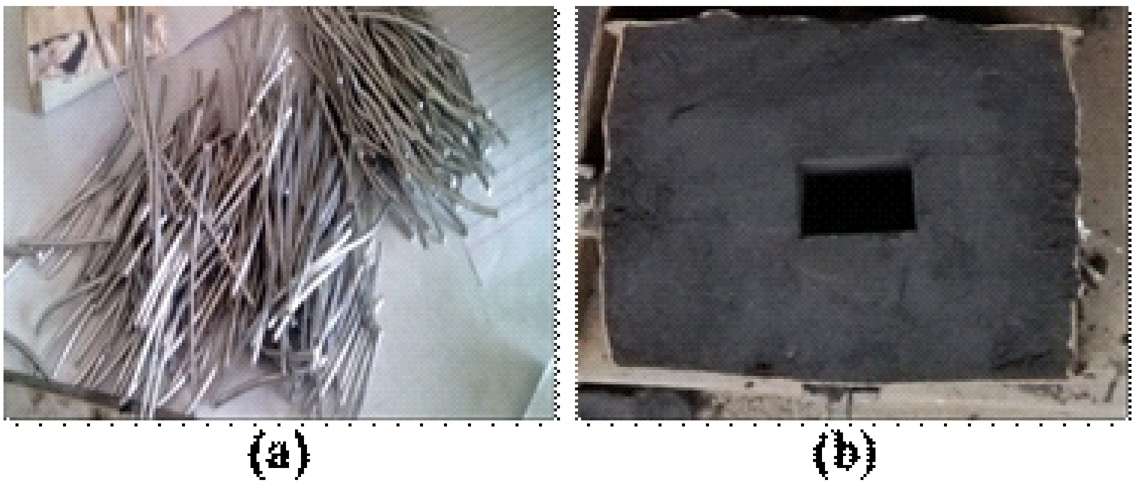

Figure 1: (a) Pure aluminum wires and (b) sand mould, used to produce Al7010 alloy.

2.2 Production of Al7010 Alloy:

Al7010 alloy was produced in the laboratory by putting pure aluminum wires into the graphite crucible and placing the crucible inside the pit furnace, maintained at 750°C. After the melting of pure aluminum wires, the molten metal was stirred with a vertical electric stirrer to homogenize the temperature. The alloying elements, such as Zn (50 gm), Al-Mg master alloy (50 gm), Cu (15 gm), and Cr (0.001 gm) were then added and the molten metal was again stirred. After preparation of melt of desire composition, CaF_2 and fluorine salt tablets were added to remove slag and dissolved gasses, respectively. Thereby, Al7010 alloy of chemical composition given in Table 1 was produced. After degassing, the molten metal was poured into the preheated sand mold to obtain Al7010 alloy in the form of blocks, after solidification.

Table 1: Chemical composition of Aluminum 7010 composition (wt%)

Zn	Mg	Cu	Cr	Al
5	2.5	1.5	0.1	Bal

2.3 Stir Casting Process:

The blocks of Al7010 alloy were charged into a crucible furnace and heated to 750°C above the liquidus temperature. After melting, the molten alloy was allowed to cool in the furnace to a semi-solid state at about 600°C. After that 140 gm and 210 gm of pre-heated Al_2O_3 particles of size 1 μm and 15 μm were added separately to produce Al_2O_3 reinforced Al7010 matrix composites with 14% and 21% volume fractions of Al_2O_3. Stirring was performed by a vertical electric stirrer for 5 min. The composite molten metal was then superheated to 780°C and a second stirring was performed. The second stirring operation was performed for 5 min to improve the distribution of the Al_2O_3 particles in the molten Al7010 alloy. The composites in molten form were then cast in prepared sand molds, as illustrated in Figure 1(b).

2.4 Homogenization Treatment:

After fabrication, Al_2O_3 reinforced Al7010 matrix composites were subjected to homogenization treatment for uniform dispersion of Al_2O_3 particles in the Al7010 alloy matrix. For this purpose, the produced composites were heated to 550°C temperature in a muffle furnace and soaked for 8 h. After soaking, composites were allowed to slowly cool inside the furnace. The complete fabrication method of Al_2O_3 reinforced Al7010 matrix composites is schematically presented in Figure 2.

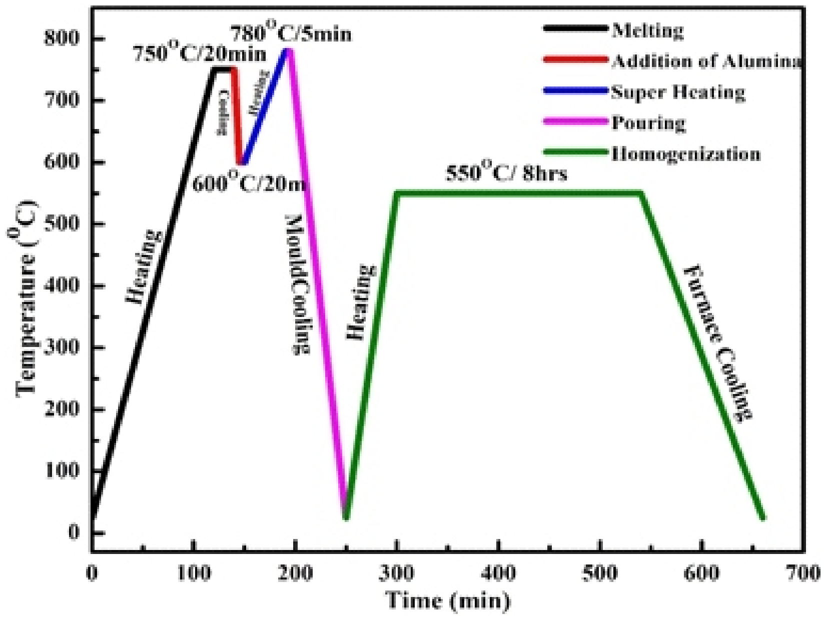

Figure 2: Schematic of fabrication method of Al_2O_3 reinforced Al7010 matrix composites.

2.5 Microstructure Analysis:

For microstructure analysis, samples of 10 mm × 10 mm × 10 mm were sectioned by linear sectioning machine (LECO MSX 305, USA). All the samples were metallographically prepared by manual grinding on grinding papers of grades P60, P120, P180, P240, P320, P600, P800, and P1200 grades and polishing on diamond dust polishing cloths, using automatic grinder/polisher (Ecomet 250 Grinder Polisher, USA). After that samples were etched in Keller's reagent for 3 min and analyzed on a light optical microscope (Leica Model DM 15000M, Germany) at 100× and 500× magnifications.

2.6 Micro Vickers Harness Testing:

Micro Vickers hardness of fabricated Al_2O_3 reinforced Al7010 matrix composites was measured, using micro Vickers hardness tester (Shimadzu Model HMV, Japan) under the diamond indenter and a load of 1000 gm for 10 s. Five readings were noted and averaged to get the final value for each sample.

2.7 Tensile Testing:

To evaluate the tensile properties of Al_2O_3 reinforced Al7010 matrix composites, testing procedure and sample dimensions were selected according to the ASM-E8 standard. Tensile testing was carried out on a universal testing machine (Shimadzu-AGS-X), equipped with 400 KN load cell and an extensometer on samples of gauge length 50 mm, width 12.5 mm, radius of fillet 12.5 mm, overall length 200 mm, and reduced section length 57 mm.

2.8 Impact Testing:

Impact testing was performed on Al_2O_3 reinforced Al7010 matrix composite samples of dimensions 10 mm × 10 mm × 55 mm with a V notch of depth 2 mm, using Charpy impact tester (Laizhou Lyric JB-300B, China) according to ASM E-23.

3. Results and Discussion:

3.1 Microstructure Evolution:

The homogenous distribution of reinforcing particles in the matrix offers heterogeneous nucleation sites and consequently refined microstructure [24]. Optical micrographs of Al_2O_3 reinforced Al7010 matrix composites are illustrated in Figures 3 and 4. The Al_2O_3 reinforced Al7010 matrix composite sample, incorporating 14% Al_2O_3 particles of size 1 µm, demonstrated uniform dispersion and excellent interfacial bonding of Al_2O_3 particles with Al7010 matrix with a little agglomeration (Figure 3(a) and (b)). This might be attributed to the significant surface properties of Al_2O_3 particles and intensive mechanical stirring,

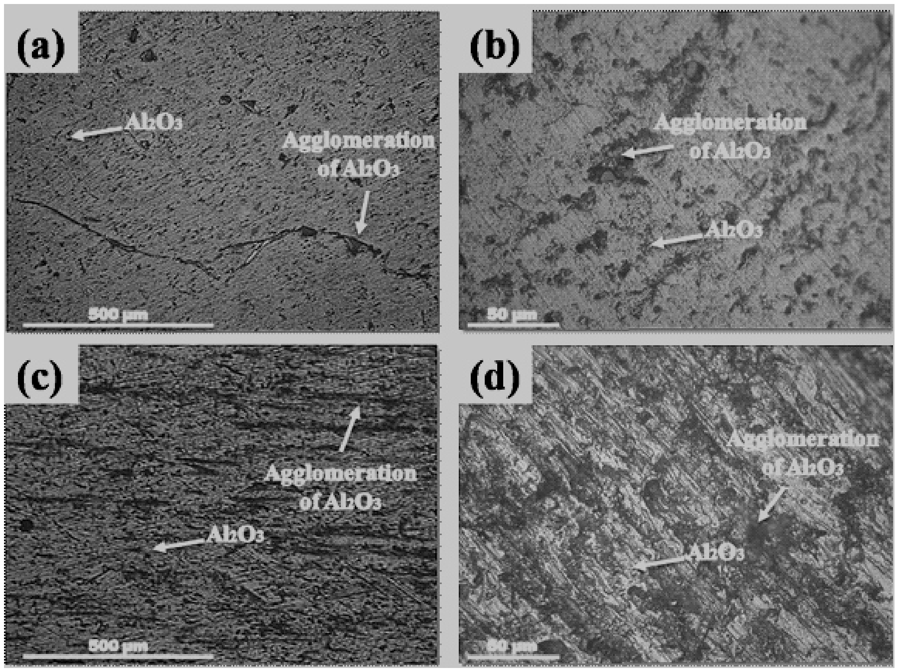

Figure 3: Optical micrographs of Al_2O_3 reinforced Al7010 matrix composite samples; (a) 1 µm14% at 100×, (b) 1 µm14% at 500×, (c) 1 µm21% at 100×, *and* (d) 1 µm21% at 500× magnification.

Similarly, the sample, containing 21% Al_2O_3 particles of size 1 µm, also exhibited uniform dispersion and significant bonding of reinforcing particles with the Al7010 matrix. But the maximum agglomeration of particles was observed in this sample among all samples as illustrated in Figure 3(c) and (d). This agglomeration of particles might be associated with the increased volume fractions of Al_2O_3 particles. On the other hand, *the sample, containing* 14% Al_2O_3 particles of size 15 µm, showed excellent results among all samples. Inspite of having large size Al_2O_3 particles, this sample exhibited a very homogeneous distribution of particles with negligible agglomeration (Figure 4(a) and (b)).

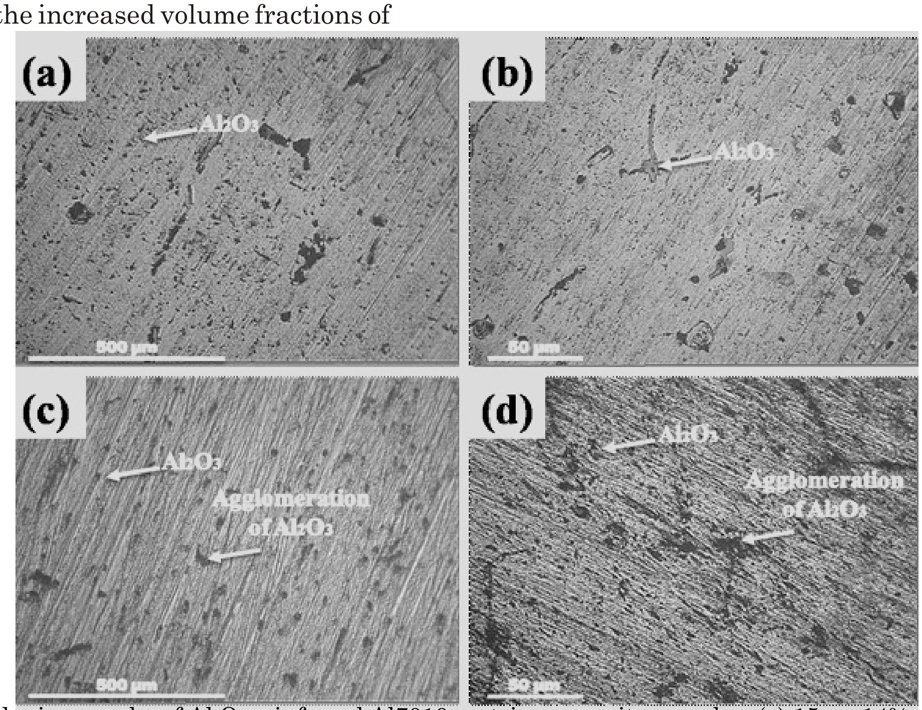

Figure 4: Optical micrographs of Al_2O_3 reinforced Al7010 matrix composite samples; (a) 15 µm14% at 100×, (b) 15 µm14% at 500×, (c) 15 µm21% at 100×, *and* (d) 15 µm21% at 500× magnification.

Similarly, the sample, having 21% Al_2O_3 particles of size 15 µm, also offered good morphological properties with a slightly greater agglomeration of particles than the sample with 14% Al_2O_3 particles of size 15 µm but still less than other samples as illustrated in Figure 4(c) and (d). The Al_2O_3 reinforced Al7010 matrix composites with 14% Al_2O_3 particles were observed to have better morphological properties compared to composites with 21% Al_2O_3 particles.

3.2 Tensile Properties:

Size and volume fractions of the reinforcing particles were found to have a significant effect on the tensile properties of Al_2O_3 reinforced Al7010 matrix composites. Variations in tensile properties, including tensile strength (R_m), yield strength ($R_{P0.2}$), elongation ($_T$), reduction in area (R_A), and yield ratio (YR), under different particle sizes and different volume fractions of Al_2O_3 particles are tabulated in Table 2. The composites, having 14% Al_2O_3 particles demonstrated much better tensile properties than composites incorporating 21% Al_2O_3 particles. This is because of the addition of Al_2O_3 particles in low volume fractions (14%) resulted in their uniform distribution in the matrix and offered a higher level of resistance in the dislocation movement. The load transferred from the soft matrix to the hard particles, which increased the tensile properties of composites [2425]. The addition of 14% Al_2O_3 particles of size 1 µm resulted in significantly higher values of both R_m (301 MPa) and $_T$ (3.10%) of Al_2O_3 reinforced Al7010 matrix composites, attributed to the uniform dispersion of Al_2O_3 particles without intensive agglomeration. Whereas, Al_2O_3 reinforced Al7010 matrix composite, incorporating 21% Al_2O_3 particles of size 1 µm, demonstrated the minimum values of both R_m and $_{T.}$ A 43% reduced value of R_m and a 46% reduced value of $_T$ were offered by this sample compared to composite with 14% Al_2O_3 particles of the same size. This is because of the vigorous agglomeration of the Al_2O_3 particles, observed throughout the fabricated composite.

Table 2: Tensile properties of Al_2O_3 reinforced Al7010 matrix composite.

Sample IDs	R_m (MPa)	$R_{P0.2}$ (Mpa)	$_T$ (%)	R_A (%)	Rm × $_T$ (Mpa.%)
1 µm14%	301	249	3.10	2.33	933.10
1 µm21%	172	167	1.69	1.10	290.68
15 µm14%	349	275	3.41	2.54	1190.0
15 µm21%	213	193	2.10	1.71	447.30

The composite, incorporating 14% Al_2O_3 particles of size 15 µm, showed the maximum values of both R_m and $_T$. This sample offered a 16% improved value of R_m and a 10% improved value of $_T$ compared to composite with 14% Al_2O_3 particles of size 1 µm. On the other hand, the addition of Al_2O_3 particles of size 15 µm in volume fractions of 21% resulted in a 41% reduced value of R_m and a 32% reduced value of $_T$ compared to 14% Al_2O_3 particles of size 1 µm. These moderate values of tensile properties are attributed to the agglomeration of Al_2O_3 particles of a moderate level. The composite sample, having 14% Al_2O_3 particles of size 15 µm, demonstrated optimum combination of tensile properties among all samples.

3.3 Impact Toughness:

Toughness determines the amount of energy absorbed by a material before fracture [25]. Variations in impact toughness of all Al_2O_3 reinforced Al7010 matrix composite samples are plotted in Figure 5. Similar to the tensile properties, the Al_2O_3 reinforced Al7010 matrix composites, incorporating 14% Al_2O_3 particles demonstrated much better impact toughness values than composites having 21% Al_2O_3 particles. The composite with 14% Al_2O_3 particles of size 1 µm exhibited a moderate impact toughness value (6.9 J), whereas composite with 21% Al_2O_3 particles of the same size showed very poor impact toughness value (3.9 J). The excellent impact toughness value of composite with 14% Al_2O_3 particles can be due to the uniform dispersion, excellent interfacial bonding, and minor agglomeration of particles, whereas the poor impact toughness value of the sample with 21% Al_2O_3 particles might be due to the intensive agglomeration of particles, occurred due to relatively greater volume fractions of Al_2O_3 particles. The agglomeration sections provided crack initiation sites for fracture under impact load.

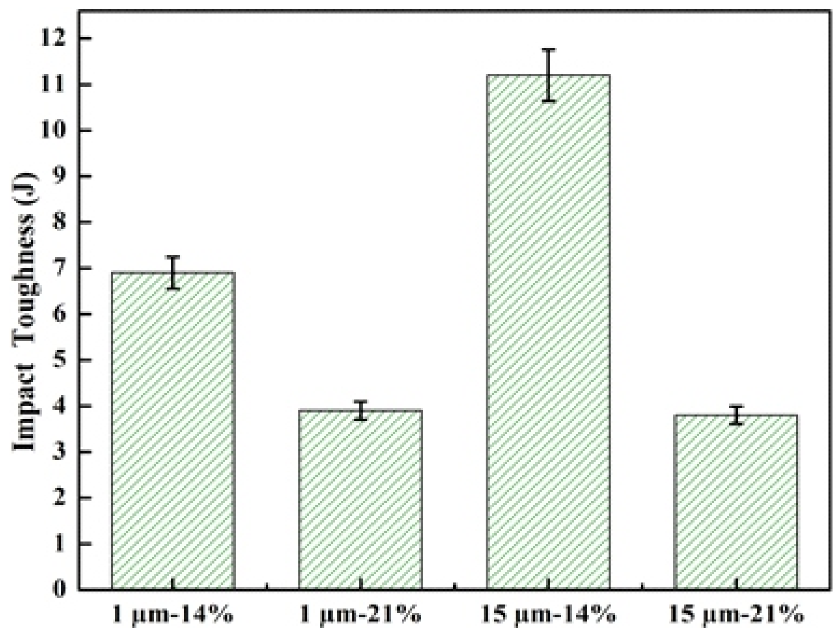

Figure 5: Variations in impact toughness values of Al_2O_3 reinforced Al7010 matrix composite.

The highest impact toughness value was offered by the sample, incorporating 14% volume fractions of Al_2O_3 particles of size 15 µm attributed to the negligible agglomeration, uniform dispersion, and excellent interfacial properties of Al_2O_3 particles. On the other hand, composite with 21% Al_2O_3 particles of size 15 µm showed poor impact toughness value quite identical to composite with 21% Al_2O_3 particles of size 1 µm. This is associated with the vigorous agglomeration of Al_2O_3 particles, which provided crack initiation sites for fracture under impact load.

3.4 Micro Vickers Hardness

Variations in micro Vickers hardness of Al_2O_3 reinforced Al7010 matrix composites are plotted in Figure 6. The highest micro Vickers hardness value (125 VHN) was achieved after the addition of 14% Al_2O_3 particles of size 1 µm. This improvement might be attributed to the hindrance provided by Al_2O_3 particles in the movement of dislocations [25]. As the volume fractions of 1µm sized Al_2O_3 particles increased to 21%, it reduced the hardness value to 103 VHN. This reduction might be attributed to the intensive agglomeration of Al_2O_3 particles [26]. Composite, incorporating 14% Al_2O_3 of size 15 µm exhibited a slightly better hardness value (116 VHN) than composite having 21% Al_2O_3 particles of size 1 1µm. Increasing volume fractions of 15 µm sized Al_2O_3 particles to 21% resulted in almost identical hardness value (117 VHN) to composite having 14% Al_2O_3 particles of the same size. These variations in hardness values are in good agreement with the work of James et al. [27,28].

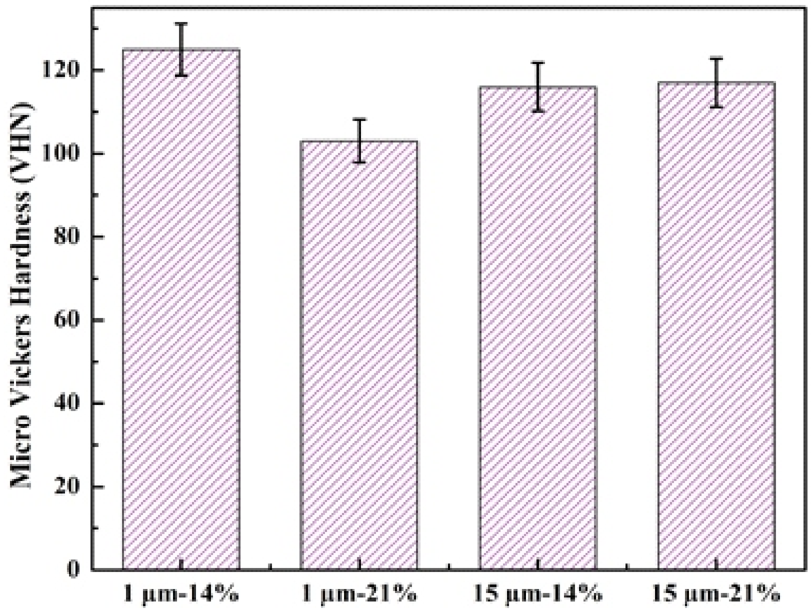

Figure 6: Variations in micro Vickers harness values of Al_2O_3 reinforced Al7010 matrix composite**.**

4. Conclusions:

Microstructural and mechanical properties of Al_2O_3 reinforced Al7010 matrix composites, fabricated by stir casting were investigated. Following were the extracted conclusions;

A homogeneous dispersion, superior interfacial bonding between Al_2O_3 particles and Al7010 matrix, and negligible agglomeration were observed in composites, incorporating 14% Al_2O_3 particles of size 1 µm and 15 µm. On the other hand, intensive agglomeration and poor morphological properties were offered by *composites, containing* 21% Al_2O_3 particles of size 1 µm and 15 µm.

Much better tensile properties were provided by the composites, having 14% Al_2O_3 particles than composites incorporating 21% Al_2O_3 particles. The highest values of R_m (349 MPa) and $_T$ (3.41%) were offered by the composite, incorporating 14% Al_2O_3 particles of size 15 µm. On the other hand, the lowest values of R_m (172 MPa) and $_T$ (1.69%) were provided by the composite, incorporating 21% Al_2O_3 particles of size 1 µm.

The maximum impact toughness value (11.4 J) was achieved after the incorporation of 14% Al_2O_3 particles of size 15 µm, whereas the minimum impact toughness value (3.8 J) was achieved after the addition of 21% Al_2O_3 particles of the same size. All the composites exhibited almost identical micro Vickers hardness values.

An optimum combination of morphological and mechanical properties was achieved after the addition of 14% Al_2O_3 particles of size 15 µm.

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