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EVALUATION OF MECHANICAL BEHAVIOR OF AL-ALLOY/AL_2O_3 METAL MATRIX COMPOSITES WITH RESPECT TO THEIR CONSTITUENTS USING TAGUCHI TECHNIQUE

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ABSTRACT: *The ductility of Al-alloy/Al2O3 metal matrix composites is much lower than that of un-reinforced Al-alloy. The ultimate tensile of Al-alloy/Al2O3 metal matrix composites is only marginally higher than yield strength indicating that the work hardening rate past yielding is low. In the as-cast condition, Al is present both in solid solution with the matrix and precipitated as Al12Mg17 phase along the grain boundaries. MgO and MgAl2O4 are also formed along the grain boundaries. There is also possibility of forming intermetallics such as Al5Cu2Mg8Si6 and Al4CuMg5Si4. The ductility decreases with increasing amount of reinforcement in Al-alloy/Al2O3 metal matrix composites. The decrease in the particle size increases the yield strength, ultimate tensile strength, hardness, and ductility (tensile elongation). The larger ceramic particle size is detrimental to composite strength. Al2O3 particles aggregated to form coarse clusters in the matrix. The degree of agglomeration increases with the Particulate volume fraction in the case Al 6063 and Al 7072 matrix alloys.*

Keywords: Al-Alloys, Alumina, Metal Matrix Composites, Taguchi Technique

1 INTRODUCTION

Alumina Al2O3 is found as the mineral corundum. It is characterized by its high hardness [1]. It is widely used as windows for instruments, high temperature parts, and wear resistance parts.

Chawla et al [2] explained that the fracture of particle reinforced MMCs is dependent on the particle strength and particle/matrix interface strength. The toughness decrease slightly with decreasing particle size, the effect of particle size is less because decreasing particle results in a lower inter-particle spacing. Ceshini et al. [3] have carried the tensile test on two particle reinforced metal matrix composite, AA6061/20 vol.% Al203 particles and AA7005/10 vol. % Al203 particles. The average size of particles in the 6061/ Al203 is 35µm and in 7005/ Al2O3 is 17µm. They observed that there was increase in Young's modulus (38% for 6061/ Al203, 17% for 7005/Al203) and UTS (17.4% for 6061/ Al203, 5.7% for 7005/ Al203) compared to unreinforced alloys.

The present work was focused on the effects of matrix microstructure and reinforcement (in terms of % volume fraction and particle size) on the properties of alumina (Al2O3) reinforced Al-alloy composites. Different Al-alloys have been designed to vary the matrix microstructure. The Al-Al2O3 metal matrix composites were characterized in terms of matrix microstructure (using different Al-alloys), % volume fraction of reinforcement (Al2O3), and particle size of reinforcement by Taguchi Techniques.

Table- 1: Chemical composition of alloys

Alloy	Composition determined spectrographically, %								
	Al	Si	Fe	Cu	Ti	Mg	Mn	Zn	Cr
6061	97.	0.6	0.61	0.021	0.05	0.92	0.044	0.07	0.005
6063	98.	0.2	0.32	0.004	0.03	0.52	0.007	0.07	<0.000
7072	97.	0.3	0.46	0.013	0.00	0.39	0.008	0.85	0.012

2. MATERIALS AND METHODOLOGY

The matrix materials used in the present work are Al 6061, Al 6063 and Al 7072. The reinforcement material is Al2O3 at 12%, 16% and 20% volume fraction of the composites with average size 10µm, 20µm, and 30µm. The chemical composition of alloys is given in Table 1. The properties of the matrix materials are given in Table 2. The matrix alloys and composites were prepared by stir casting process.

Table-2: Mechanical properties of matrix materials

Matrix Material	Density g/cc	Modulus of Elasticity GPa	Poisson Ratio	Ultimate Tensile strength, MPa	Elongation %
Al 6061	2.7	68.9	0.33	241	22
Al 6063	2.7	68.9	0.33	172	22
Al7072	2.72	68	0.33	168	15

2.1 Stir Casting Process

Stir casting is a liquid state method of composite materials fabrication, in which a dispersed phase (ceramic particles, short fibers) is mixed with a molten matrix metal by means of mechanical stirring (figure 1). The liquid composite material is then cast by conventional die casting method.

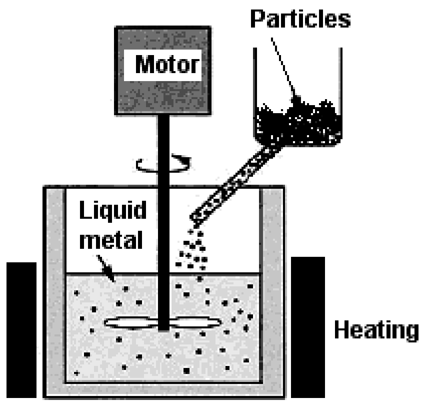

Figure 1: Charge preparation in the stir casting process

2.2 Selection of the Quality Characteristics

The quality characters, which were selected to influence the mechanical properties of the metal matrix composites, are: yield strength, ultimate tensile strength, tensile ductility (%elongation), hardness and bending force.

2.3 Selection of Process Parameters

The parameters, which influence the performance of the metal matrix composites properties, are:

- Aluminum alloy type: Al 6061, Al 6063 and Al 7072
- Volume fraction of reinforcement:12%, 16% and 20%
- Particle size of reinforcement: 10µm, 15µm and 20µm

The objectives at the end were developing good metal matrix composite properties. The factors to include in the investigation should be the ones thought relevant to the objective of producing good metal matrix composite. The important parameters were optimized by Taguchi's method [4-5]. Taguchi techniques offer potential saving in test time and cost.

2.4 Selection of Levels for Control Parameters

Control parameters are those parameters that a manufacturer can control the design of the product, and the design of process. The levels chosen for the control parameters were in the operational range of the metal matrix composites process. Each of the four control parameters was studied at three levels. The chosen control parameters are summarized in Table-3.

Table – 3: Parameters and Levels

Factor	Symbol	Level–1	Level–2	Level–3
Aluminum alloy	A	6061	6063	7072
Volume fraction	V	12%	16%	20%
Particle size	P	10µm	20µm	30µm

2.5 Assignment of Parameters in OA

The orthogonal array (OA), L9 was selected for the present work. The parameters were assigned to the various columns of O.A. The assignment of parameters along with the OA matrix is given in Table – 4. One interaction among matrix alloy and volume fraction of reinforcement (AxV) was also considered.

Table- 4: Orthogonal Array (L9) and control parameters

Treat No.	A	V	P	AxV
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

2.6 Preparation of Al-Alloys and Composites

Al alloys were melted in an oil-fired furnace. The charge was fluxed with coverall to prevent dressing. The molten alloy was degasified by tetrachlorethane (in solid form). The crucibles were made of graphite. The preheated reinforcement particles were added to the liquid melt. The molten alloy and reinforcement particles are thoroughly stirred using a mixer to make the melt homogenous. The melt was reheated to the required pouring temperature in a muffle furnace. The temperature of the melt was measured using a dip type thermocouple. The dross removed melt was finally gravity poured into the preheated mould.

2.7 Conduction of Tests

The following tests were conducted on the metal matrix composites:

- Tensile test for yield strength, ultimate tensile strength and %elongation
- Hardness test
- Microstructure analysis
- Scanning electron microscopy

The samples were machined to get dog-bone specimen (figure 2) for tensile test. The computer-interfaced UTM (Universal Testing Machine) was used for the tensile test. The loads at which the specimen has reached the yield point and broken were noted down. The extensometer was used to measure the elongation. The load v/s deflection graph was also obtained for each specimen from the computer attached to the machine. Two specimens were used for each trial.

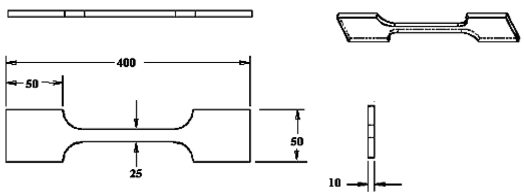

Figure 2: Tensile specimen, all dimensions are in mm

The hardness measurements employed a Rockwell indenter with a steel ball (Diameter of 0.159 cm) at 60 kg load according to the specifications of ASTM E-18.

Microscopic analysis of selected specimens of the cast composite materials was performed by optical microscopy. An image analyzer was used to examine the distribution of the reinforcement particles within the aluminum matrix. The specimen to be observed under the microscope is placed in a plastic capsule and allowed to set for some time. The mold is then polished on various grits of sand paper and finally with alumina solution according to standard procedures. The polished specimens were ringed with distilled water and etched with 5% HF solution. The specimens were then viewed under an optical microscope. Scanning electron microscope (SEM) is carried out to characterize the fine-scale topography and establish the microscopic mechanisms governing fracture. Samples for SEM observation were obtained from the failed specimens by sectioning parallel to the fracture surface and the scanning was carried on S-3000N Toshiba scanning electron microscope.

Table-5: Experimental results

Treat No.	Yield strength, MPa		UTS, MPa		Elongation, %		Hardness, HRF	
	Trial -1	Trial -2	Trial -1	Trial -2	Trial -1	Trial -2	Trial -1	Trial -2
1	276.6	272.4	308.3	315.5	5.3	5.5	61.6	63.5
2	236.6	239.6	311.1	328.6	5.1	5	62.4	62.8
3	259.2	257.7	322.3	331.2	4.3	4.5	59.7	58.1
4	236.6	239.6	282.6	298.3	4.8	4.6	63.4	62.8
5	226.6	229.2	263.9	284.5	4.5	4.3	62.9	63.3
6	252.4	249.9	345.2	339.4	4.3	4.4	62.1	61.3
7	211.2	216.4	250.5	255.6	4.3	4.5	57.6	56.8
8	258.6	269.9	334.5	328.7	4.4	4.4	72.6	71.4
9	226.7	232.5	342.6	335.2	4.0	4.2	68.9	69.8

3. RESULTS

The experiments were scheduled on random basis to accommodate the manufacturing impacts (like change in pouring temperature of liquid melt, stirring, etc). The experimental values to characterize the mechanical behavior of Al-Al2O3 metal matrix composites are given in Table 5.

3.1 Effect of parameters on the yield strength

Table – 6 gives the ANOVA (analysis of variation) summary of raw data. The Fisher's test column establishes all the parameters (A, V, P, and AXV) accepted at 90% confidence level. The percent contribution indicates that the metal matrix composite (MMC) parameter, A (matrix alloy composition) contributes 21.83% of variation, MMC parameter, V (% volume fraction of Al2O3) aids 3.79% of variation, MMC parameter, P (particle size of Al2O3) influences 53.22% of variation, and interaction between parameters A and V contributes 13.26% of variation.

Table-6: ANOVA summary of the yield strength

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	1539.1	1424.4	1428.2	1414.9	2	707.5	24.49	21.8
V	1432.4	1468	1491.3	293.3	2	146.7	5.07	3.8
P	1579.8	1401.1	1410.8	3366.0	2	1683.0	58.26	53.3
AxV	1487.4	1403.1	1501.2	940.0	4	235.01	8.13	13.3
Error	----	----	---	202.2	7	28.9	1.0	7.9
T	----	----	----	6216.6	17	------	------	100

Table-7: ANOVA summary of the tensile strength

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	1917	1814	1847	923	2	461.6	5.14	4.68
V	1711	1851	2016	7773	2	3886.7	43.31	47.8

P	1972	1898	1708	6172	2	3086	34.39	37.7
AxV	1850	1830	1898	398	4	99.5	1.11	0.25
Error	----	----	---	628	7	89.7	1.00	9.59
T	----	----	----	6216	17	-------	------	100

3.2 Effect of parameters on the tensile strength

The summary of ANOVA (analysis of variance) for the ultimate tensile strength (UTS) is shown in Table 7. The Fisher's test column confirms only three parameters (A, V, and P) accepted at 90% confidence level influencing the variation in ultimate tensile strength. According to the analysis of variance, there are two strong parameters, which influence UTS. Looking at the ANOVA table, parameter, V (% volume fraction of Al2O3) has the largest effect (47.78%), parameter, P (particle size of Al2O3) the second largest effect (37.70%). Parameter, A (matrix alloy composition) has the least effect on the ultimate tensile strength. The interaction between matrix alloy composition and volume fraction of Al2O3 (AXV) has no significance on the ultimate tensile strength.

3.3 Effect of parameters on the ductility

The ANOVA summary of ductility measured in terms of tensile elongation is given in Table 8. The Fisher's test column ascertains only three parameters (A, V, and P) accepted at 90% confidence level influencing the variation in the ductility (tensile elongation). The parameter, A (matrix alloy composition) contributes 47.29% of variation, the parameter, V (% volume fraction of Al2O3) aids 31.77% of variation, and the parameter P (particle size of Al2O3) influences 9.75% of variation. The interaction between parameters AXV is not significant over the variation in the ductility of composites.

Table-8: ANOVA summary of the ductility

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	29.7	26.9	25.8	1.35	2	0.68	34.0	47.3
V	29.0	27.7	25.7	0.92	2	0.46	23.0	31.8
P	28.3	27.7	26.4	0.31	2	0.16	8.0	9.75
AxV	27.8	27.6	27.0	0.06	4	0.02	1.0	-0.7
Error	----	----	---	0.13	7	0.017	1.0	11.9
T	----	----	----	2.77	17	------	-----	100

3.4 Effect of parameters on the hardness

The ANOVA summary of hardness is given in Table 9. The Fisher's test column ascertains all the parameters (A, V, P, and AXV) accepted at 90% confidence level influencing the variation in the hardness. The percent contribution indicates that the metal matrix composite (MMC) parameter, A (matrix alloy composition) contributes 21.06% of variation, parameter, V (% volume fraction) aids 20.58% of variation, parameter, P (particle size) influences 34.06% of variation, and interaction between parameters A and V contributes 20.70% of variation.

Table-9: ANOVA summary of the hardness

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	368	376	397	75.23	2	37.62	50.84	21.1
V	366	395	380	73.56	2	36.78	49.70	20.6
P	393	390	358	120.75	2	60.38	81.59	34.1
AXV	390	363	388	75.45	4	18.86	25.49	20.7
Error	----	----	---	5.17	7	0.74	1.0	3.6
T	----	----	----	350.16	17	--	-	100

4 DISCUSSION AND VALIDATION

The influence of control parameters (viz: matrix alloy, volume fraction and particle size of Al2O3) on the mechanical properties are discussed. The validation is confirmed through the behavior of constituent elements in the matrix alloy, mechanism of microstructural phenomena and arguments made by the other researchers.

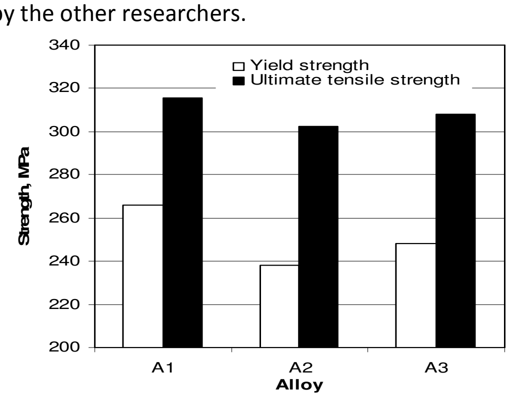

Figure 3: Influence of matrix alloy on the yield and ultimate tensile strengths of Al-alloy/Al2O3 composite

4.1 Effect of matrix alloy composition on the mechanical properties

Alloy -1 is Al 6061. Alloy -2 is Al 6063. Alloy – 3 is Al 7072. The mechanical properties of matrix alloys are given in Table-2. Figure 3 shows the influence of matrix alloy on the yield strength (YS) and ultimate tensile strength (UTS) of Al- Al2O3 composites. It can be seen that the Al 6061 exhibits very large YS; Al

6063 very low YS; and Al 7072 intermediate strength. The same kind of trend as observed with the yield strength is also experienced with the ultimate tensile strength (UTS). The only difference is that the UTS values are marginally higher than the yield strength values.

Figure 4 shows the effect of matrix alloy composition on the ductility (measured in terms of % elongation) and harness of metal matrix composites. The variation in the ductility of composites is largely effected by the change in matrix alloy composition. The ductility of Al-Al2O3 composites is much lower than that of un-reinforced Al-alloy. It can be seen that the Al 6061 attributes very large variation in the ductility; Al 7072 very low ductility; and Al 6063 intermediate ductility of the composites. It can be seen that the Al 6061 exhibits very low hardness values; Al 7072 very high hardness values; and Al 6063 intermediate hardness of the composites. There is an interaction effect of the alloy composition and volume fraction of Al2O3 on the hardness of the composites (figure 5). The interfacial interaction between matrix alloy and alumina can contribute to the hardening of the composites.

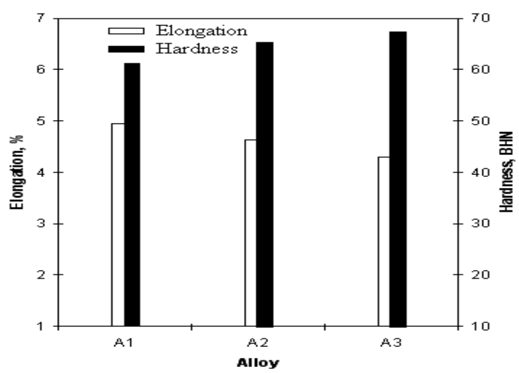

Figure 4: Influence of matrix alloy on the ductility and hardness of Al-alloy/Al2O3 composite

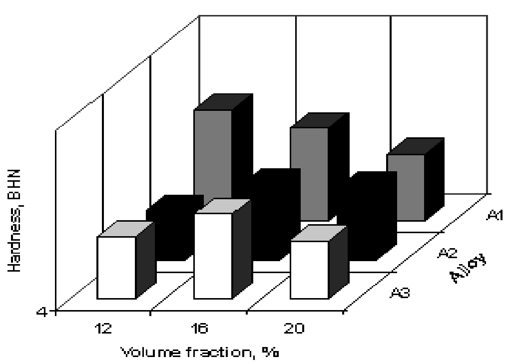

Figure 5: Effect of interaction between matrix alloy and volume fraction on harness of Al-alloy/Al2O3 composite

The elements of Si, Fe, Cu, Mn, and Ni, in Al-alloys are known to increase tensile properties by forming precipitates such as Al2Cu, and NiAl3 during the fabrication process [7]. The contents of alloying elements such as Si, Fe, and Cu in Al 6061 are higher than those in Al 6063 and Al 7072. Therefore, it is expected that the yield strength, and UTS of Al 6061 is higher than those of Al 6063 and Al 7072

The ductility is in the decreasing order of matrix alloys Al6061, Al 6063 and Al 7072, whereas the hardness is in the increasing order of matrix alloys Al6061, Al6063 and Al7072. Alumina Al2O3, is known to be stable in pure aluminum, but reacts with magnesium in Mg-containing Al-alloys to form MgO and MgAl2O4 (spinel). MgO may form at high magnesium levels and lower temperatures whereas the spinel will form even at very low magnesium levels [8]. It is not surprising that Al2O3 is not thermodynamically stable in most aluminum alloys. There is also possibility of forming intermetallics such as Al5Cu2Mg8Si6 and Al4CuMg5Si4. These are brittle in nature. The Mg content in Al 6061, Al 6063, and Al 7072 is respectively 0.920%, 0.520%, and 0.396%.

Figure 6: *M*icrostructure of 6061/Al2O3 composite

Figure 7: *M*icrostructure of 6063/Al2O3 composite

Figure 8: *M*icrostructure of 7072/Al2O3 composite

The various intermetallics can be revealed in the microstructures shown in figures 6-8. In the as-cast conditions, the matrix is multiphase. The intermetallics are brittle in nature. Such brittle phases can form at various stages of composite processing, reaction between the matrix and reinforcement, and during solidification [8]. Even small quantities of brittle second phases, particularly if these are located along the matrix-reinforcement interface, are well-documented to affect the toughness and tensile ductility of metal matrix composites [9].

In the as-cast condition, Al is present both in solid solution with the matrix and precipitated as Al12Mg17 phase that is present at and along the grain boundaries. A non-uniform distribution of Al2O3 particulates through the Al-alloy metal-matrix with evidence of clustering, or agglomeration is observed. MgO and MgAl2O4 are also seen along the grain boundaries. The phases Al2Cu, Mg2Si, Al5Cu2Mg8Si6 and Al4CuMg5Si4 are also observed in the microstructures.

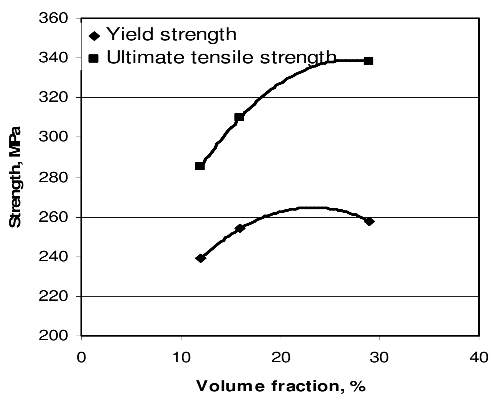

Figure 9: Influence of volume fraction on the yield strength of Al-alloy/Al2O3 composite

4.2 Effect of volume fraction on the mechanical properties

Figure 9 illustrates the influence of % volume fraction of Al2O3 (reinforcement) on the on the yield strength and ultimate tensile strength of Al- Al2O3 Metal matrix composite. The graphs indicate that the yield strength and ultimate tensile strength increase with increase in % volume fraction of Al2O3 in the composite. With increasing volume fraction, more load is transferred to the reinforcement which is also results in a higher yield strength, and ultimate tensile strength [10]. This behavior is in agreement with the work carried by Yung et al [11]. The tangled dislocations are also observed around the agglomeration of the alumina particles. It suggests that the agglomeration could contribute a reinforcement effect in the Al-alloy matrix. According to previous literatures, the yield strength of the Al-alloy is related the particulate – dislocation interaction by means of the Orowan bowing mechanism. Residual dislocation loops are left around each particle after a dislocation passes the particles. The Orowan bypassing of particles by dislocations can increase the material's strength. In metal matrix composites, the reinforcing phase typically is much stiffer than the matrix. The ultimate tensile of Al- Al2O3 composite is only marginally higher than yield strength. The yield strength, and ultimate tensile strength increase with the work hardening rate. The work hardening rate increases with increasing volume fraction of reinforcement (and decreased matrix volume).

The effect of volume fraction of Al2O3 on the ductility and hardness of the composites is shown in figure 10. The decrease in ductility can be attributed to the grain boundary embrittlement, as resulted from grain boundary agglomerated particles, would weaken the ductility of the composites. The high stress concentration at the tip of the cracked can also contribute to a decrease in the ductility (tensile elongation) in the composite. The effect of volume fraction on the hardness of the composites is also illustrated in figure 13. The hardness of the composites increases when the volume fraction of Al2O3.

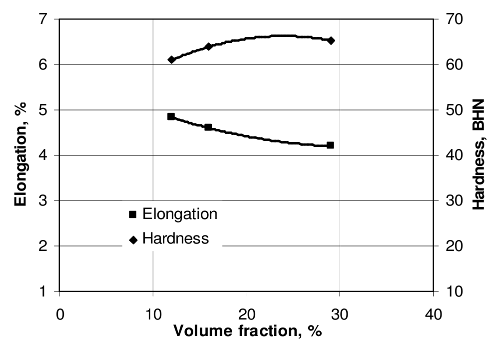

Figure 10: Influence of volume fraction on the ductility of Al-alloy/Al2O3 composite

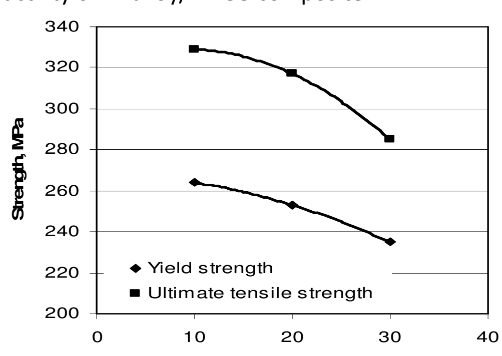

Figure 11: Influence of particle size on the yield and ultimate tensile strengths of Al-alloy/Al2O3 composite

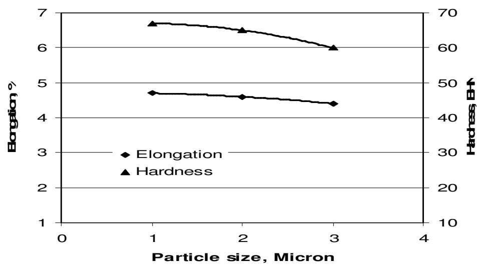

Figure 12: Influence of particle size on the ductility and hardness of Al-alloy/Al2O3 composite

4.3 Effect of particle size of reinforcement on the mechanical properties

Figure 11-12 illustrate the effect of particle size of Al2O3 on the yield strength, ultimate tensile strength, ductility (tensile elongation), and hardness. The decrease in the particle size increases the yield strength, ultimate tensile strength, ductility (tensile elongation), and hardness. This is because, the small particle size means a lower inter-particle spacing so that nucleated voids in the matrix are unable to coalesce as easily. Also, the larger ceramic particle size is detrimental to composite strength. This is on account of the strength distribution of a ceramic particulates population obeys weibull statistics. The agglomeration could contribute a reinforcing effect in the aluminium matrix. The inhomogeneous distribution of reinforcement reduces the effective amount of particulates for strengthening [11].

The large particles of Al2O3 particles can readily react with the magnesium as compared to small Al2O3 particles. At relatively large particle sizes of Al2O3, a significant amount of particle cracking takes place during tensile testing of the composites. A higher work hardening rate is also been observed with decreasing particle size [12].

5. CONCLUSIONS

The matrix alloy Al 6061 gives large values of yield strength, ultimate tensile strength and ductility but low hardness to the Al-alloy/Al2O3 metal matrix composites. The matrix alloy Al 7072 provides greater hardness to the Al-alloy/Al2O3 composites than the Al 6063 alloy. Al2O3 particles aggregated to form coarse clusters in the matrix. The degree of agglomeration increased with the particulate volume fraction in the case Al 6063 and Al 7072 matrix alloys. Alumina Al2O3 reacts with magnesium to form MgO and MgAl2O4 (spinel). The intermetallics such as Al5Cu2Mg8Si6 and Al4CuMg5Si4 are also formed. These are brittle in nature in Al-alloy/Al2O3 composites. The yield strength, and ultimate tensile strength increase with increase in % volume fraction of Al2O3 in the composites whereas the ductility decreases with increase in volume fraction. The hardness of the composites did not increase when the volume fraction of Al2O3 in the composite exceeded 16%. The decrease in the particle size increases the yield strength, ultimate tensile strength, ductility (tensile elongation), and hardness of Al-alloy/Al2O3 metal matrix composites. The agglomeration has contributed a reinforcing effect in the aluminium matrix. The inhomogeneous distribution of reinforcement reduces the effective amount of particulates for strengthening.

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