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Tensile Properties and Fracture Behavior of 6061/Al_2o_3 Metal Matrix Composites Fabricated by Low Pressure Die Casting Process

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Abstract

In the present work, the low-pressure die casting process has been implemented to fabricate 6061/ Al_2O_3 metal matrix composites. This process avoids the transport of clustered Al_2O_3 particles into the die cavity. The yield strength and fracture strength increase with increase in volume fraction of Al_2O_3 , whereas ductility of 6061/Al_2O_3 composites decreases. The skewness in the tensile properties is reduced owing to the solution treatment of the 6061/ Al_2O_3 composites. The formation of intermetallic particles $MgAl_2O_4$, $Al_5Cu_2Mg_8Si_6$ or $Al_4CuMg_5Si_4$ was also observed in the composites. The fracture mode is ductile in nature.

Keywords: Low pressure die casting process, 6061, alumina, tensile properties, fracture.

Introduction

A particle reinforced metal matrix composite consists of a uniform distribution of strengthening ceramic particles embedded within a metal matrix. In general, these materials exhibit higher strength and stiffness, in addition to isotropic behaviour at a lower density, when compared to the un-reinforced matrix material [1]. Composites reinforced by carbides, borates, nitrides and oxides have been successfully fabricated by either powder metallurgy (P/M) technique or casting methods [2]. The metal matrix composites are currently being used for the aerospace and automotive applications [3].

The mechanical properties of aluminium alloys reinforced with ceramic particulates are known to be influenced by the particle size and the volume fraction. It is also generally found that 0.2% proof stress and ultimate tensile strength tend to increase, and toughness and ductility decrease with increasing volume fraction of particulate or decreasing particle size [4].

Stir casting method is a relatively low cost liquid processing present to produce MMC. Besides being simple, flexible, and attractive, as compared with other techniques, it also allows very large size components to be fabricated and is also applicable to large quantity production. Stir casting route also ensures that undamaged reinforcement materials are attained. Moreover, this type of processing is now in commercial use for particulate Al-based composites [5].

The objective of the present work was to study the influence of microstructure (as-cast and heat treatment conditions), volume fraction of alumina reinforcement on the tensile properties, and fracture behaviour of 6061 aluminium alloy metal matrix composite reinforced with alumina (Al_2O_3). In the present work, the low-pressure die casting process was implemented with double the pressure that conventionally employed for unreinforced Al-alloys. The pressure was raised to lift the alumina particles along with the matrix alloy and to provide uniform distribution of alumina particles in the composite.

Experimental Procedure

The matrix alloys and composites were prepared by the low-pressure die casting process in Tapasya Casting Private Limited – Hyderabad. The chemical composition of 6061 alloy is given in Table 1. The properties of the 6061 alloy are given in Table 2. The volume fractions of Al_2O_3 reinforcement are 10%, 20% and 30%. The particle size of Al_2O_3 reinforcement is 10 μm.

Table 1: Chemical composition of alloys.

Alloy	Composition determined spectrographically, %								
	Al	Si	Fe	Cu	Ti	Mg	Mn	Zn	Cr
6061	97.6	0.62	0.61	0.021	0.053	0.98	0.044	0.072	0.0051

Table 2: Mechanical properties of matrix materials.

Matrix Material	Density, g/cc	Modulus of Elasticity, GPa	Ultimate Tensile strength, MPa	Elongation, %
6061	2.7	68.9	124	30
6061(T4)	2.7	68.3	296.6	17

Preparation of Melt and Metal Matrix Composites

Al alloys were melted in a resistance furnace. The crucibles were made of graphite. The melting losses of alloy constituents were taken into account while preparing the charge. The charge was fluxed with coverall to prevent dressing. The molten alloy was degasified by tetrachlorethane (in solid form). The crucible was taken out of the furnace and modified with sodium. Then the liquid melt was allowed to cool down just below the liquidus temperature to bring the melt semi solid state. At this stage, the preheated (1000^0C for 1 hour) alumina particles were added to the liquid melt. The molten 6061 alloy and alumina particles are thoroughly stirred manually. After sufficient manual stirring, the semi-solid liquid melt was reheated to a fully liquid state in the resistance furnace followed by automatic mechanical stirring using a mixer to make the melt homogenous for about 15 minutes at 200 rpm. The temperature of the melt was measured using a dip type thermocouple. The preheated cast iron die was filled with dross removed melt by the compressed (2.0 bar) argon gas. The schematic representation of low-pressure die casting is shown in figure 1.

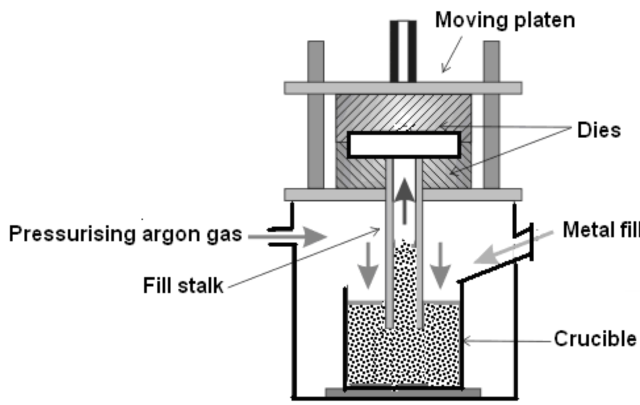

Figure 1: Low-pressure die casting process.

Heat Treatment

Prior to the machining of composite samples, a solution treatment was applied at 500^0 C for 1 hour, followed by quenching into cold water. The materials were then naturally aged at room temperature for 100 hours (figure 2).

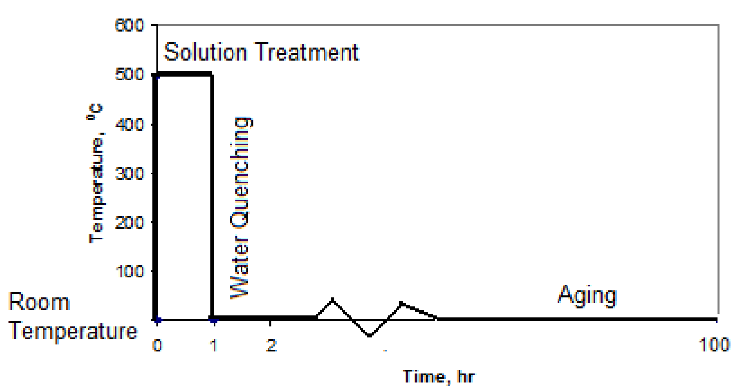

Figure 2: Heat treatment of 6061/Al_2O_3 composite.

Tensile and Fatigue Tests

The as-cast and heat treated samples were machined to get dog-bone specimen for tensile test. The shape and dimensions of the tensile specimen are shown in Figure 3. The universal testing machine (UTK-E: PC based) was used for the tensile test. The specimens were loaded hydraulically. The loads at which the specimen has reached the yield point and broken were noted down. The extensometer was used to measure the elongation.

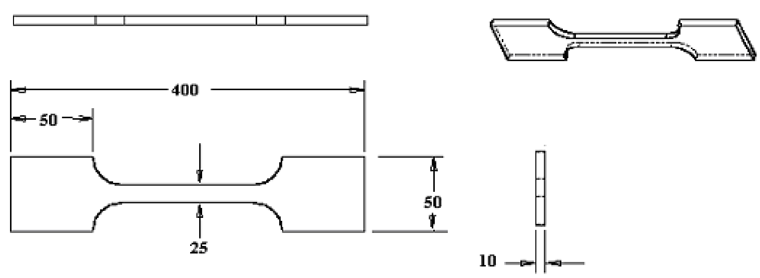

Figure 3: Tensile specimen, all dimensions are in mm.

Optical and Scanning Electron Microscopic Analysis

The microscopic structures of the cast composite samples were revealed by the optical microscopy. The polished specimens were ringed with distilled water and etched with 0.5% HF solution. Fracture surfaces of the deformed/fractured (under tensile loading) test samples were examined in a scanning electron microscope (SEM) to determine the macroscopic fracture mode and to establish the microscopic mechanisms governing fracture. Samples for SEM observation were obtained from the tested specimens by sectioning parallel to the fracture surface and the scanning was carried in IICT (Indian Institute of Chemical Technology - Hyderabad) S-3000N Toshiba. EDX spectrum analysis was carried out to find the formation of interfacial compounds in the composites.

Results and Discussion

Three samples were tested for each trial. The average values of yield strength, fracture strength, and tensile elongation are presented in the form of graphs. Skewness of the distribution test results was determined.

Undeformed Microstructure

Alumina Al_2O_3, is known to be stable in pure aluminium, but reacts with magnesium in Mg-containing Al-alloys to form MgO and $MgAl_2O_4$ (spinel). MgO may form at high magnesium levels and lower temperatures whereas the spinel form even at very low magnesium levels [6]. It is not surprising that Al_2O_3 is not thermodynamically stable in most aluminium alloys. There is also possibility of forming intermetallics such as $Al_5Cu_2Mg_8Si_6$ and $Al_4CuMg_5Si_4$. These are brittle in nature. 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 [7].

The various intermetallics can be revealed in the microstructures shown in figure 4a. In the present work, the microstructure of as-cast composites is found to be multiphase. The intermetallics are brittle in nature. Such brittle phases might have been formed because of reaction between the matrix and reinforcement, and during solidification. In the as-cast condition, Al is present both in solid solution with the matrix and precipitated as $Al_{12}Mg_{17}$ phase that is present at and along the grain boundaries. A non-uniform distribution of Al_2O_3 particulates through the 6061 metal-matrix with evidence of clustering, or agglomeration is observed. Al_2Cu, Mg_2Si, MgO and $MgAl_2O_4$ are also seen along the grain boundaries. EDX spectrum (figure 5a) shows isolated magnesium-rich particles (suspected to be $MgA1_20_4$ spinel or magnesium oxide (MgO)). The EDX spectrum shown in figure 5b depicts the possibility of formation of intermetallic particles $Al_5Cu_2Mg_8Si_6$ or $Al_4CuMg_5Si_4$.

The grains are also found to be refined due to the heat-treatment. After heat treatment to the T4 condition, most of the coarse intermetallic phases such as (Al_2Cu, Mg_2Si) are dissolved to form $Al_5Cu_2Mg_8Si_6$ or $Al_4CuMg_5Si_4$ compound; however residual amounts remain (figure 4b). The agglomerations appear to be well bonded to the matrix. Due to solution treatment the oxide film at the interface between matrix and reinforced particles turns into fine particles ($MgAl_2O_4$).

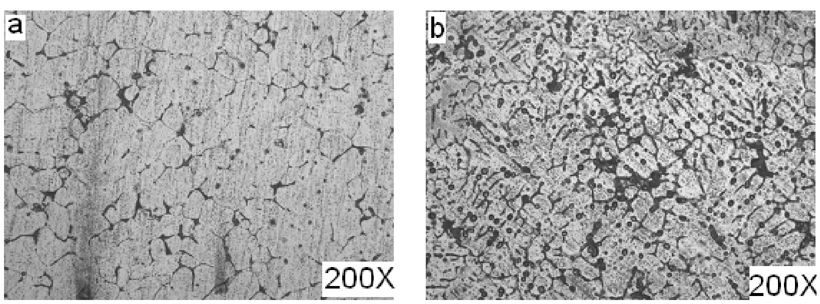

Figure 4: Microstructure of 6061/Al_2O_3 composite (a) As-cast, and (b) heat-treated.

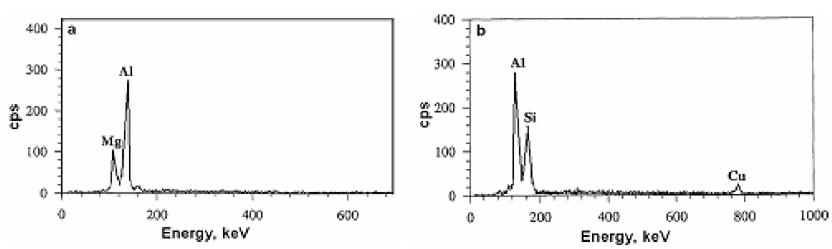

Figure 5: EDX spectrum shows the major elements that present in the interfacial reaction products. (a) $MgA1_20_4$ spinel or magnesium oxide (MgO), and (b) $Al_5Cu_2Mg_8Si_6$ or $Al_4CuMg_5Si_4$

Tensile Properties

Figure 6 illustrates the influence of volume fraction of Al_2O_3 (reinforcement) on the on the yield strength of 6061/Al_2O_3 Metal matrix composites. . The yield strength is defined as the stress corresponding to a plastic strain of 0.2%. The graphs indicate that the yield strength increases with increase in volume fraction of Al_2O_3 in the composite. With increasing volume fraction, more load is transferred to the reinforcement which also results in a higher yield strength. This behavior is in agreement with the work carried by Yung et al [8]. There is an increase of 82% yield strength in the reinforced composite over the as-cast 6061 alloy and an increase of 24% yield strength in the heat treated composite over the heat treated 6061 alloy when the metal matrix alloy 6061 is reinforced with 30% volume fraction of Al_2O_3. The yield strength increases after solution treatment. Upon cooling, dislocations form at the matrix/reinforcement interface owing to the thermal mismatch. The tangled dislocations around the agglomeration of the alumina particles 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 [9]. 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. The area between the upper line and the lower line in figure 6 represents the strengthening effect due to dislocations. If the agglomeration appears to be bonded to the matrix, the agglomeration can contribute to the strengthening of the composite. The degree of agglomeration increases with the increase in volume fraction.

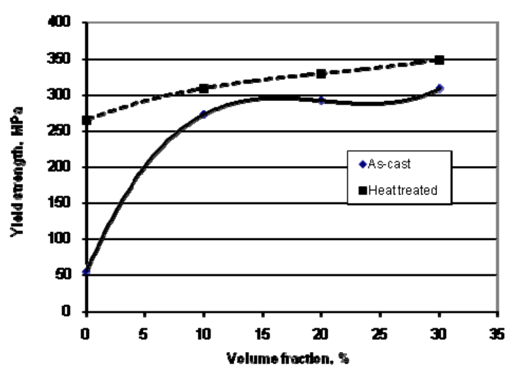

Figure 6: Variation of yield strength with volume fraction of Al_2O_3 (a) As-cast, and (b) heat-treated.

Skewness characterizes the degree of asymmetry of a distribution around its mean. Positive skewness indicates a distribution with an asymmetric tail extending toward more positive values. Negative skewness indicates a distribution with an asymmetric tail extending toward more negative values. The equation for skewness is defined as:

$$\text{Skewness} = \frac{n}{(n-1)(n-2)} \sum \left(\frac{x_i - \bar{x}}{s} \right)^3$$

where,

s is the standard deviation

n is the number of tests

$\bar{x}$ is the mean value of yield strengths

The skewness of yield strength of the 6061/Al_2O_3 composite is shown in figure 7. The skewness is varying from negative to positive and again to negative in the as-cast condition of composites where as it is only positive in the solution treatment condition of the composites. The skewness in the yield strength of composites can be attributed to the characteristics of low-pressure die casting process and the distribution of alumina particles on account of volume fraction in the composite. The oscillation behavior of the skewness is switched by the solution treatment of 6061/Al_2O_3 composite. The skewness of yield strength in the solution treated condition is only positive because all the test samples were heat treated at the same time and under the same environment.

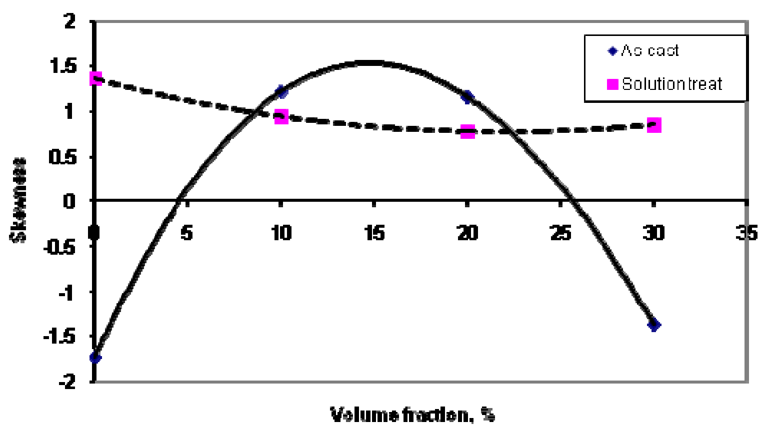

Figure 7: Skewness of yield strength.

Figure 8 shows the effect of volume fraction on the fracture strength (ultimate tensile strength). The fracture strength follows the same trend as the yield strength of 6061/ Al_2O_3 composite. The fracture strength is only marginally higher than the yield strength. This indicates that the work hardening rate past yielding is low. Chawla and Shen [10] reported that the work hardening rate was a simple function of lower matrix volume (the matrix volume decreases with increase in volume fraction of reinforcement). There is negative skewness of fracture strength in the as-cast composites and positive skewness of fracture strength in solution treated composites on account of plastic deformation (figure 9).

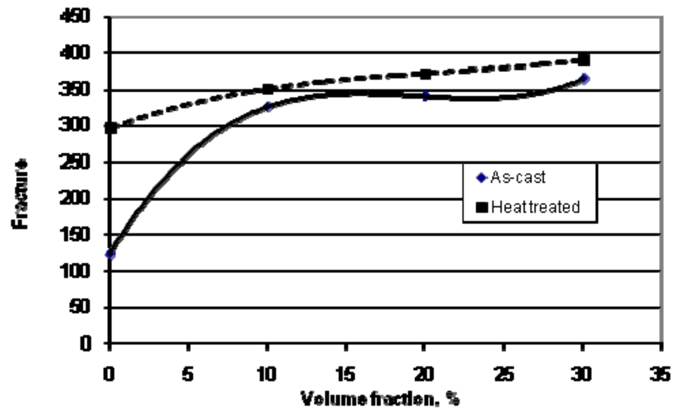

Figure 8: Variation of fracture strength with volume fraction.

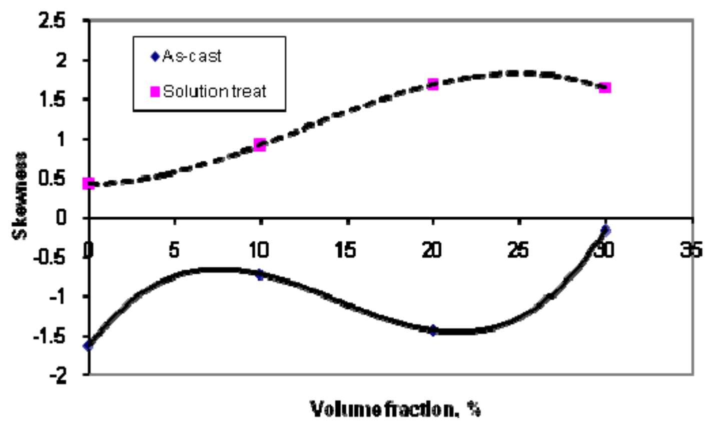

Figure 9: Skewness of fracture strength.

The influence of volume fraction of Al_2O_3 on the ductility (measured in terms of tensile elongation) is shown in figure 10. The decrease in the ductility can be attributed to the beginning of void nucleation and growth in advance with increasing amount of Al_2O_3 reinforcement. Chawla and Shen [10] verified that the microplasticity took place in the metal matrix composites due to stress concentrations in the matrix at the poles of the reinforcement and/or at sharp corners of the reinforcing particles. The skewness in the tensile elongation of as-cast composites is oscillatory from positive to negative where as the skewness in the tensile elongation of solution treated composite is positive only (figure 11).

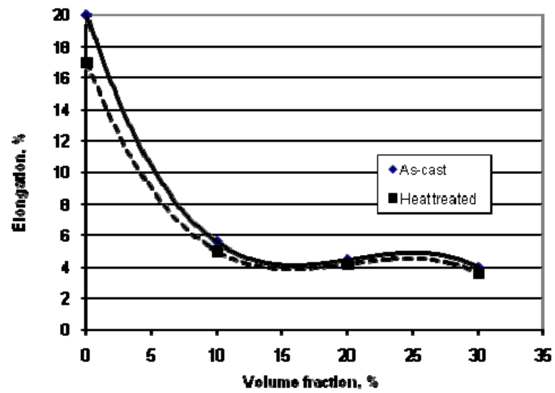

Figure 10: Variation of tensile elongation with volume fraction.

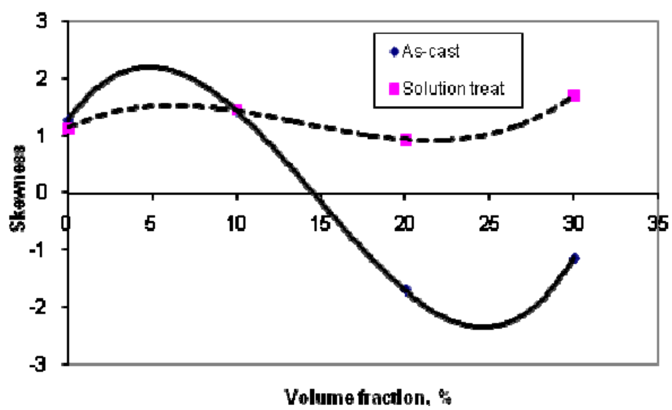

Figure 11: Skewness of tensile elongation.

Fracture Behavior

The influence of alumina particles clustering, agglomeration and the interfacial reactions between matrix and alumina particles of the composites are analyzed by examining SEM fracture surfaces of the tested specimens. Two factors appear which control the ductility of the composites are distribution of alumina particles and deformation behavior of the metal matrix.

The 6061 metal matrix contains the alloying elements, which were added to enhance the mechanical properties of the composites. These alloying elements would react with the metal matrix and the reinforcement particles to form various intermetallic phases in the composite. These intermetallic phases (which are brittle in nature) act as void nucleation sites during the plastic deformation of the composites by their rupture. debonding between the matrix and reinforcement also occurs during the plastic deformation of the composites.

The fracture of Al_2O_3 particles is not seen in Al 6061/Al_2O_3 metal matrix composite fabricated by the low-pressure die casting process. The fracture is only due to the matrix failure and the particle/matrix interface rupture (figure 12a). The fracture due to tensile loading is ductile in nature. The fracture process in high volume fraction (more than 20%) aluminium Al_2O_3 composites is very much localized and the failure path in these composites is through the matrix due to the matrix cracking, matrix cavitation and the decohesion and rupture of interfaces. Arsenault [11] reported that the cracking of Al_2O_3 particles was a rare event when the size of the particle was less than 10μm.

Shakeri and Wang [12] studied the effects of different aging process on ductility, fracture, and interfacial properties in 6061/ Al_2O_3 metal matrix composites. They observed that the number of broken particles decreases and the frequency of interface and near-interface debonding increases by increasing aging time (figure 12b).

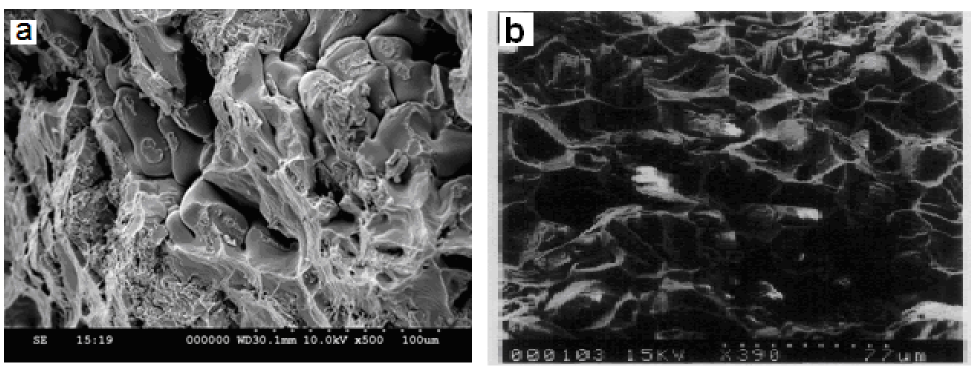

Figure 12: SEM tensile fracture surface of 6061/ 30% Al_2O_3 composite (a) present work and (b) previous work (after Shakeri and Wang [23]).

Conclusions

The low-pressure die casting process avoids the transport of clustered Al_2O_3 particles into the die cavity. The yield strength and fracture strength increase with increase in volume fraction of Al_2O_3 , whereas ductility of 6061/Al_2O_3 composites decreases. The skewness in the tensile properties is reduced owing to the solution treatment of the 6061/ Al_2O_3 composites. Due to solution treatment the oxide film at the interface between the matrix and reinforced particles turns into the fine particles ($MgAl_2O_4$). The formation of intermetallic particles $Al_5Cu_2Mg_8Si_6$ or $Al_4CuMg_5Si_4$ was also observed in the composites. The fracture mode is ductile in nature.

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