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Characteristics on Heat Treatment of AA6063 Aluminum Extrusion Based ZrO2 Molecule Reinforced MMC

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Abstract

In the current study, a characteristic has been carried out on the influences of Zirconium dioxide (ZrO2) content and casting temperature on mechanical properties and fracture behavior of AA6063 Al/ZrO2 composites. AA6063 aluminum extrusion Metal Matrix Composites (MMC) reinforced with 5, 10 and 15 vol % ZrO2 were fabricated at various casting temperatures, viz. 750, 850 and 950^{o}C via the stir casting method. Based on the acquired results, optimum amount of reinforcement and casting temperature were measured by evaluating the density and mechanical properties of the elements. Hardness and tensile tests were carried out in order to find the mechanical properties of the elements. Fracture surfaces of the samples were also studied to find the main fracture mechanism(s) of the elements. The results indicate that all samples fractured due to the structure interdendritic cracking of the matrix extrusion. Reinforcing the Al matrix extrusion with ZrO2 molecules, improved the hardness and ultimate tensile strength of the extrusion to the maximum values of 70 BHN and 232 MPa, respectively. Hence, the highest mechanical properties were obtained by the specimen including 15% of ZrO2 produced at 750^{o}C.

Keywords: Elements/Molecule, Composites, Fracture, Heat treatment, Zirconium dioxide (ZrO2)

1. Introduction

Metal Matrix Composites (MMC) represent a new generation of engineering materials due to their heat treatment of mechanical and physical properties in which a strong ceramic reinforcement is incorporated into a metal matrix to improve its properties including strength, stiffness, wear resistance, excellent corrosion resistance and high elastic modulus [Singla & Mediratta, 2013]. MMC combine metallic properties of matrix extrusions (tensile stress and toughness) with ceramic properties of reinforcements (high strength and high modulus), leading to greater strength in shear stress and compression and higher service temperature capabilities. Therefore, MMCs tend to replace conventional materials in various fields of application such as automotive, aeronautical, aerospace, mechanical engineering, as well as in other industries because of its own properties [Kok, 2005].

As the ceramic reinforced aluminum matrix composites have important applications in many fields of the industry, in the present study, Al–ZrO_2 composites were fabricated by the stir casting method with different volume percents of ZrO_2 content (as the reinforcement phase), and casting temperatures. Subsequently, the effects of these two parameters on mechanical properties (tensile and hardness stress tests) were studied. Also, fractography is drawn between Stress Corrosion Cracking (SCC) to evaluate the fracture behavior of the aforementioned elements. Molecule reinforced aluminum Metal Matrix Composites (MMC) can be fabricated by using conventional material manufacturing methods with improved mechanical and physical properties. These properties include improved strength, high elastic modulus, creep strength, fatigue strength, hardness and wear resistance, corrosion resistance and low thermal expansion.

Among the fabrication processes for aluminum Metal Matrix Composites (MMC) elements, the stir-casting technique has been developed to fabricate a wide range of these materials due to its low cost, simplicity and high production rate [Jiang & Wang, 2015]. However, the improper control of some process parameters in this technique commonly produces the elements with defects such as void fraction, weak bonding between reinforcement and matrix, non-uniform distribution of the particles, large reinforcement free zones, which may result in decreasing mechanical properties [Kumaravel, Mohanraj, Channankaiah, 2015]. Although a great deal of work has been conducted on the aluminum Metal Matrix Composites (MMC), there is limited information over the effect of manufacturing variations on fracture behavior of these materials.

2. Materials and methods

In this study, AA6063 aluminum Extrusion was used as the matrix material while Yttria (Y2O3) stabilized zirconia (ZrO2) powder (ZrO_{2_3} mol% Y_2O_3, D_{50}=0.79 mm) was used as the reinforcement and the elements were produced using a vortex method. In order to fabricate the elements, the aluminum extrusion was melted at 750°C, 850°C and 950°C, using a furnace and an impellors which was made of graphite. The melt was stirred at a constant speed of 300 rpm for 13 min and the different amount of zirconia (ZrO2) molecules (0, 5, 10, and 15 vol %) were added into the molten extrusion. Stirring was carried out for 2 more minutes and the molten composites were poured inside a metallic mold (Sphere inscribed cylindrical shape with 15 cm height and 15 mm diameter).

To determine the density of the fabricated specimens, a density test system was used to measure density according to the Archimedes method. After grinding and polishing the specimens, the hardness tests were carried out with a load of 306.56 N to find the hardness values of the mentioned samples. Samples were tested in an ESEWAY DV RB-M testing unit with the HB (Brinell Hardness Test) method. At least five indentations were made for each hardness measurement and the average hardness values are reported. Sphere inscribed cylindrical samples of height 150mm and diameter 15mm were machined using an Electronic Distance Measurer (EDM) device from the composite specimens. In order to measure tensile strength of the samples, tensile tests were conducted at room temperature according to ASTM.B557 [Chen, Shu, Zude Zhao, Zhao, Wang, Yuan, 2012], using an INSTRON 1195 test unit. Also, Scanning Electron Micro-scope (SEM, Camscan MV2300) was employed to study the fracture surface of the fractured samples.

3. Results and discussion

3.1. Density measurements

The experimental densities of the compo-sites versus the volume fraction of Zirconium dioxide (ZrO_2) molecules are shown in Fig.1. It can be seen that the density increases with the Zirconium dioxide (ZrO_2) content at 750°C. This behavior is consistent with the mixture rule in which the total density increases with the volume percent of the second phase [Zhang, Gu, Jin, 2004]. For the elements, cast at 850°C, increasing the volume content of zirconia (ZrO_2) led to increase in the density up to 10%. Then, density followed a decreasing trend which is due to the effects of high temperature and sintering at high content of reinforcement. Moreover, tensile stresses originated from thermal expansion coefficient mismatch between Metal Matrix Composites (MMC) and rigid reinforcement would normally form defects such as void fraction and dislocations around the particles [Baghchesara, Abdizadeh, Baharvandi, 2010].

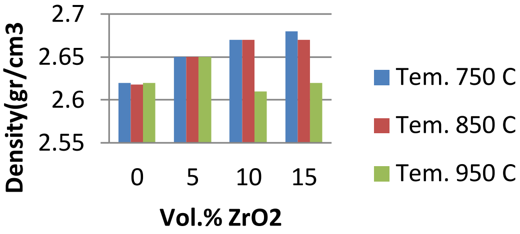

Fig.1 The density results of the Al extrusion and the element specimens containing 0, 5, 10 and 15 vol % ZrO2 fabricated at 750, 850 and 950°C

As seen in this figure, increasing the temperature to 950°C increased the density of composite up to 5 vol % ZrO_2. At this condition, temperature plays an important role to increase the wet ability of molecules. However, there is a minimum value of 10 vol % ZrO_2, which may be attributed to air entrapment due to high fluidity and turbulence (high speed stream) of the melt at high temperature. In general, the density of the element is obtained at this temperature by two important factors: high temperature and volume content of the second phase. In contrast, in the composite with 15 vol % of zirconia (ZrO2), the density is increased, since the effect of second phase content is more significant than the effect of temperature.

3.2. Hardness test

The hardness variation of samples with the ZrO2 (vol %) is mentioned in Fig. 2. The hardness of all elements is higher than the AA6063 aluminum extrusion one (45 HB), due to the presence of ZrO2 molecules. Also, it can be attributed to the higher hardness stress of zirconia (ZrO2) molecules compared to aluminum extrusion. In fact, the hardness of element depends on the hardness stress of the reinforcement and the matrix. Hardness properties of the composite element fabricated at

750°C were improved by increasing the amount of Zirconium dioxide (ZrO2) molecules in accordance with the density variation at this temperature. The coefficient of thermal expansion (CTE) of ceramic particles is less than that of aluminum extrusion. So, an enormous amount of dislocations are generated at the particle matrix interface during solidification process, which further increases the metal matrix hardness stress.

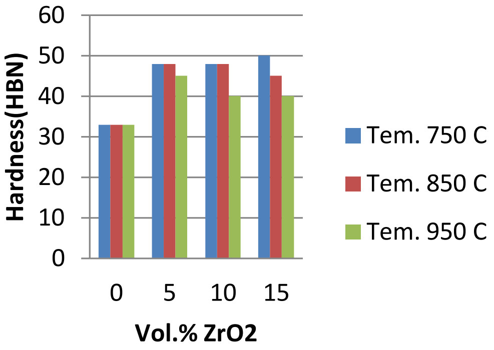

Fig.2 The hardness results of the Al extrusion and the composite specimens containing 0, 5, 10 and 15 vol % ZrO2 fabricated at 750, 850 and 950 °C

The higher the amount of particle matrix interface, the more is the hardening due to dislocations [Das & Das, 2007]. The hardness stress was enhanced with the content of Zirconium dioxide (ZrO2) up to 5 vol% at 850°C and remained constant by increasing the amount of Zirconium dioxide (ZrO2) up to 10 vol%. However, the hardness stress values were reduced as the amount of ZrO2 was increased over 10 vol%. This behavior can be attributed to the effect of reinforcement content as a factor which raises the hardness and volume content of voids.

Therefore, the range of 0–5 vol %, the reinforcement content is the rule factor, while in the range over 10 vol % the important factor which controls the hardness stress variations is voids content. Moreover, the constant values of hardness stress between 5 and 10 vol % of ZrO2 can be due to the opposite effects of reinforcements and voids which neutralize each other. Furthermore, by increasing the temperature to 950°C, the hardness stress values are lower than the ones at 750°C and 850°C which may be due to the defect formation as a result of high fluidity of the melt at high temperature.

3.3. Tensile test

The effect of Zirconium dioxide (ZrO2) content on Ultimate Tensile Strength (UTS) of the samples, for each casting temperature is depicted in Fig. 3. The strengthening is a result of two major contributions, indirect strengthening and direct strengthening [Hashim, Looney, Hashmi, 2002].

The tensile strength shows an improvement with increasing the content of Zirconium dioxide (ZrO2) at 750°C which could be the result of increasing dislocations density and their pile-ups behind the uniform distributed ZrO2 molecules [Jiang & Wang, 2015].

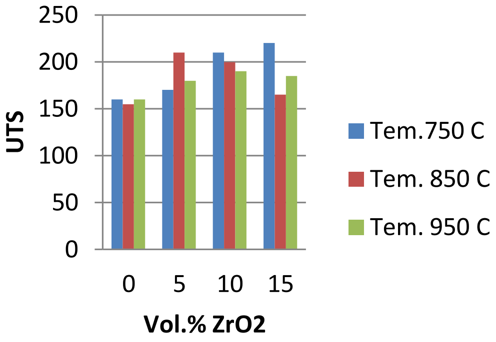

Fig.3 The UTS results of the Al extrusion and the composite specimens containing 0, 5, 10 and 15 vol % ZrO2 fabricated at 750, 850 and 950 °C

The, increasing Zirconium dioxide (ZrO2) volume percent resulted in an increase in ultimate tensile strength. Indirect strengthening results from the changes in the matrix microstructure that takes place due to the presence of reinforcement particles. In the Al–ZrO2 composites, indirect strengthening arises from an increase in dislocation density due to the coefficient of thermal expansion mismatch between ZrO2 and Al extrusion (as illustrated, CTE plays an essential role in density, hardness stress and tensile tests).

The density of these thermally induced dislocations also increases with increasing volume fraction of ZrO2, so the indirect strengthening contribution increases with increasing ZrO2 content [Jamaati, Toroghinejad, 2010]. This gradual enhancement seems to be due to work hardening behavior. Aluminum Metal Matrix Composites (MMC) can deform plastically. But, the deformation of reinforcing molecules generally remains elastic due to the much higher yield stress. So the stress concentration within the molecules would be very high. In the process of load transfer, the matrix transfers the load to the ZrO2 molecule. So if the boundary is assumed to be strong, ceramic particles prevent plastic deformation of the matrix and this leads to the direct strengthening contribution and higher work-hardening rate [Karunesh & Manjunath, 2016].

Also, for the elements cast at 850^{o}C and 950^{o}C the maximum tensile strength was achieved by the ones containing 5–10 vol % ZrO2. However, the composites containing 15 vol % ZrO2, showed the decreasing trend of tensile strength which is mainly due to the formation of porosities as a result of high ZrO2 content and also air entrapment during high temperature casting. According to Fig. 1 and 3, among composites with the different amounts of Zirconium dioxide (ZrO2) cast at various temperatures, the one which has maximum density shows the highest strength (15 vol % ZrO2, 750^{o}C). Therefore, it can be concluded that element with 15 vol % ZrO2 content, cast at 750^{o}C, represent maximum tensile strength and can be considered as the optimum fabrication conditions.

3.4. Fracture behavior and Fractographic observation

In general, the fracture modes of Metal Matrix Composites (MMC) can be controlled by a number of material and processing parameters such as the type, shape, volume fraction and distribution of the molecules, as well as the matrix and interface properties which may include the solute segregation, precipitation effect, void fraction amount, interfacial bonding strength, original sample surface roughness, etc.

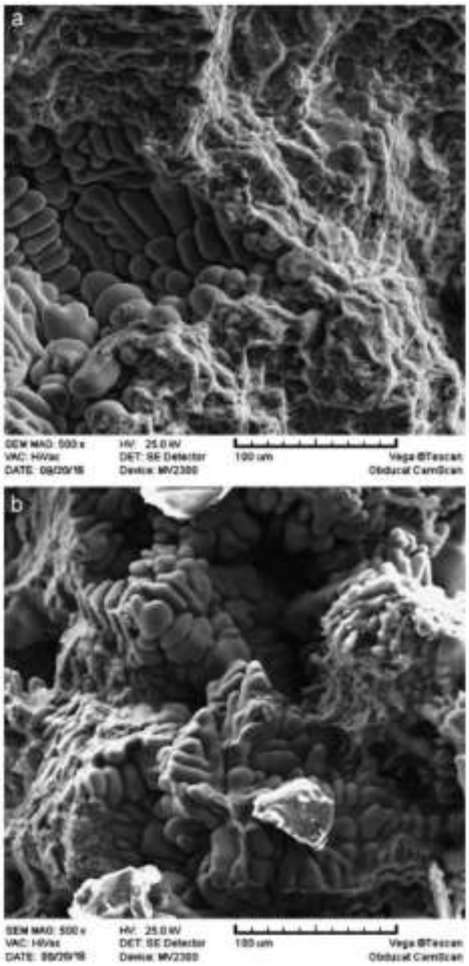

Fig. 4 Scanning Electron Micro-scope of fracture surfaces of composites fabricated at 750^{o}C containing (a) 5 and (b) 15 vol % ZrO2.

Most of these parameters will be strongly influenced by the processing and thermal treatment history. Failure in particulate reinforced MMCs is believed to be due to three different sources, namely, the matrix/ reinforcement interfacial de-cohesion, reinforcement fractured and failure in the matrix [Lee, Sue, Lin, 2000].

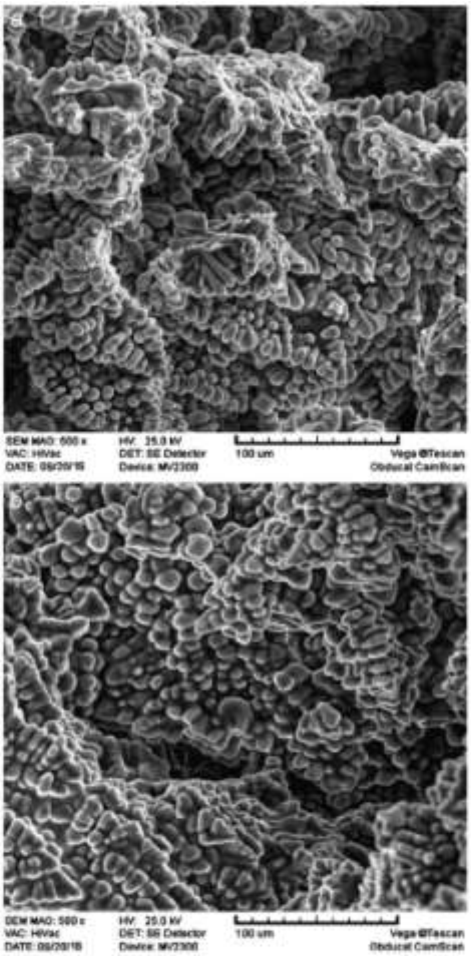

Fig.5 Scanning Electron Micro-scope of fracture surfaces of composites fabricated at 850^0C containing
(a) 5 and (b 15 vol % ZrO2.

To determine the fracture mechanism(s) in samples with minimum and maximum volume fraction of reinforcement particles, microscopic observations were made on the fractured samples containing 5 and 15 vol % of ZrO2.

Figs. 4–6 show the SEM fracture surfaces after tensile testing for the element poured at 750^{o}C, 850^{o}C and 950^{o}C, respectively. Fracture surface observations of the samples show that the main controlling fracture mechanism is interdendritic cracking. This failure mode is identical for the AA6063 unreinforced extrusion which has been recently investigated [Tahamtan, Boostani, 2010]. During solidification of the composite, the ZrO2 molecules and extrusions elements (Si), are rejected to the solid/liquid interface and segregate to the interdendritic regions [Quazi, Fazal, Haseeb, Yusof, Masjuki & Arslan, 2015].

The micro-cracks propagate along interdendritic aluminum silicon eutectic and silicon molecule resulted in failure of the specimen which implies that the fracture of this element is dominated by failure of the matrix extrusion.

However, some areas of the elements fracture surfaces consist of dimples which may be a result of the void nucleation and subsequent merging elements by strong shear stress deformation and fracture process on the shear stress plane [Fard, Akhlaghi, 2007]. The dimpled rupture occurs mostly by voids initiation at heat treatment such as hardness and ultimate tensile strength were improved, comparing with the un rein-forced extrusion. Composite containing 15 vol % ZrO2 fabricated at 750^{o}C showed the maximum value of the hardness stress and ultimate tensile strength in comparison with other specimens which could be attributed to the presence of ZrO2 molecules, dislocations density increasing and their pile ups behind the uniform distributed ZrO2 molecules

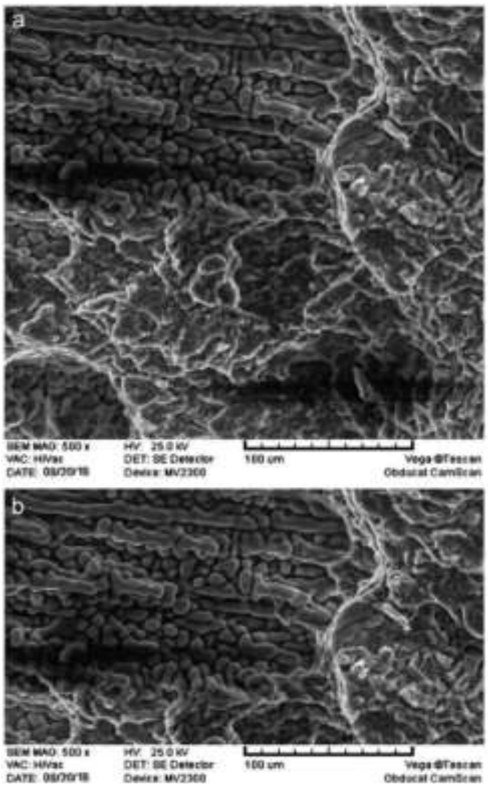

Fig. 6 Scanning Electron Micro-scope of fracture surfaces of composites fabricated at 950^{o}C containing
(a) 5 and (b) 15 vol % ZrO2.

4. Conclusions

Fracture surface observations of the samples shows that the failure of the AA6063/ZrO2 composite is similar to the unreinforced AA6063 extrusion one which was controlled by interdendritic cracking of the matrix. In addition, a number of dimples were observed on the fractured surfaces of all samples which could be a result of the void nucleation and subsequent coalescence during the fracture process. Thus, it can be concluded that the optimum fabrication conditions of the composite processing was provided with 15 vol % ZrO2 and casting at 750°C.

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