Investigation on Mechanical and Fatigue behaviour of Aluminium Based SiC/ZrO2 Particle Reinforced MMC

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Abstract: The study is the work on Aluminium Metal Matrix Composites (MMC's), which have wider applications in automobile, aerospace and defense industries, hi-tech engineering and power transmission due to their lightweight, high strength and other unique properties. The Aluminium Matrix Composites (AMC's) refer to a kind of light weight high performance Aluminium centric material system. AMC's consist of a non-metallic reinforcement which when included into aluminium matrix offers an advantage over the base material. Reinforcements like SiC, B₄C, Al₂O₃, TiC, TiB₂, TiO₂ are normally preferred to improve mechanical properties of such composites. Here Aluminium 6061 is preferred as matrix material, while silicon carbide (SiC) and Zirconium di-oxide (ZrO₂) is selected as reinforcement compounds. Conventional Stir casting procedure is employed to fabricate the necessary composites compositions, which are I. Al:SiC::100:5 and II. Al:ZrO₂:SiC::100:3:2. Experimental results depict that the composition II provides higher hardness of 53.6 RHN as opposed to 45.8 RHN of composition I. In tensile strength composition II demonstrates 96.43 N/mm² as opposed to 67.229 N/mm² tensile strength of composition II. The fatigue test indicate a expected number of life cycles to failure of 10⁵ cycles for composition II and over 10⁴ cycles for composition I, at stress ranges of 79.062 MPa and 150.651 MPa respectively.

Keywords: Stir casting, Hardness, Tensile strength.

1. Introduction

D.L. McDanels et al. highlighted that Aluminium and its alloys have attracted most attention as base metal in metal matrix composites [1]. B. Ralph et al and Suryanarayanan et al. focused on Aluminium MMC's are widely used in aircrafts, aerospace, automotive industries and various other applications [2, 3, 4 & 5]. Few researchers have discussed the requirement of reinforcements as: The reinforcements should be stable at a given working temperature and remain inert too. The most commonly used reinforcements are Silicon Carbide (SiC) and Aluminium Oxide (Al₂O₃). SiC reinforcement increases the tensile strength, hardness, density and wear resistance of Al and its alloys [6, 7, 8, 9 & 10]. Sedat Ozdenet et al. investigated the impact behavior of Al and SiC particle reinforced in AMC under different temperature conditions. The impact behavior of composites was found to be affected by clustering of particles, particle cracking and weak matrix-reinforcement bonding respectively [11]. John Dixon et al investigated that on addition of Al₂O₃ and SiC particulates into the Aluminium matrix showed increased yield strength, ultimate tensile strength, hardness and decreased elongation (ductility) of the composites in
comparison with those of the matrix. Increasing wt% of Al₂O₃ and SiC increased their strengthening effect and SiC is the most effective strengthening particulate, for higher strength, hardness, & grain size reduction. At the same time it decreases ductility & toughness [12]. Srinivasan et al have done machining investigations on metal matrix composites [13, 14].

The study is aimed to introduce Zirconium di-oxide (ZrO₂) with the above discussed Silicon Carbide (SiC), using stir casting technique and thereby evaluating their strengths in two compositions namely: I. (Al+5%wt. SiC) and II. (Al+3%wt. ZrO₂+2%wt. SiC).

2. Materials and Methods

a). Aluminium(Al) {Metal Matrix}
Aluminium 6061 is a precipitate-hardened aluminium alloy, containing magnesium and silicon as its major alloying elements. Annealed 6061 (6061-O temper) has maximum tensile strength no more than 120 MPa (18,000 psi), and maximum yield strength no more than 55 MPa (8,000 psi). The material has elongation (stretch before ultimate failure) of 25 – 30%.

b). Silicon Carbide [SiC]
Silicon carbide is a compound of silicon and carbon with chemical formula Si-C. It is primarily used in abrasives, refractories, ceramics, and numerous high-performance applications due to its high melting point of 2730°C. It has low density, high strength, low thermal expansion, high thermal conductivity, high hardness, high elastic modulus, excellent thermal shock resistance, superior chemical inertness.

c). Zirconium di-oxide [ZrO₂]
Zirconium di-oxide (ZrO₂) sometimes known as zirconia is a white crystalline oxide of Zirconium. With a high melting point of 2715°C, it is desired as a reinforcement material and its solubility in water is negligible.

d). Stir casting technique parameters
Stir casting is made through the setup which is shown in Figure 1. This specific study aims to throw light on the performance and selection of better composite amongst the combinations of Aluminium metal matrix with Silicon Carbide (Al+SiC) and Aluminium metal matrix with Zirconium di-oxide and silicon carbide (Al+ZrO₂+SiC) compositions.

The compositions were as follows: I. (Al + 5% wt. Of SiC) and II. (Al + 3% wt. Of ZrO₂ + 2%wt of SiC) respectively. The stir casting technique begins with the Aluminium being loaded into the furnace chamber and preparing to melt. The setup reaches a temperature of 1035°C in 45 minutes of loading. Meanwhile the reinforcement SiC particles are preheated at a temperature of 600-605°C with a time limit of 45 minutes. A powder substance named Coverall AR (Cover flux) is added to the molten Aluminium in order to ward of impurities and collect them prior to adding the reinforcements respectively. Nearly one-thirds of the base metal is found to be collected in this activity. On addition of the SiC particles (5%wt.), the stirring action is applied on the mixture at 1060 rpm which is raised to 1437 rpm with Aluminium being at a temperature of 1036°C at that time. Stirring action is continued for 180 seconds and it rises flames in the furnace. Now the molten mixture is manually carried from the tilted furnace and poured in to the suitable die (dimensions being 20mm and gauge length of 250mm). The method is also used to fabricate the second composition of Al + 3% ZrO₂ + 2% SiC respectively.
3. Results and Discussion

a) Based on Material Hardness

The hardness of the composites is determined by the Rockwell hardness test. Figure 2 shows the Rockwell hardness locations in the test specimen. The Rockwell test determines the hardness by measuring the depth of penetration of an indenter under a large load compared to the penetration made by a preload. When testing materials, indentation hardness correlates linearly with tensile strength [2]. Most commonly the Rockwell scale used is C Scale which is defined for aluminium, brass and soft steels but going with ISO standards, we adopt and employ the T Scale with 1/15 inch dia. Indenter as defined in ISO 6508-1: Metallic materials - Rockwell hardness test-Part I: Test
method (scale T). The use of ASTM E18: Standard methods for Rockwell hardness and Rockwell superficial hardness of metallic materials is suggested. The Rockwell hardness measurements of the specimens are presented in Table. 1.

**Table 1 Hardness Measurements**

| Location | Al+SiC | Al+ZrO$_2$+SiC |
|----------|--------|-----------------|
| 1        | 41.1   | 50.7            |
| 2        | 45.8   | 49.7            |
| 3        | 42.9   | 53.6            |
| 4        | 44.8   | 47.5            |

Fig. 2. Rockwell Hardness at locations.

The table indicated that the hardness of Aluminium with 3%ZrO$_2$ and 2%SiC is high enough than the Aluminium and 5% SiC composition. It is to be noticed that the hardness at location 2 has only a difference of 3.9 and can be attributed to the region of cup formation. Therefore it is wise to suggest Al with ZrO$_2$ and SiC composition (3% ZrO$_2$ seem to improve hardness property) for high hardness requiring applications.

**b) Tensile strength Test Parameters**

In order to determine the most suitable composition for applications requiring high tensile load capacity, the tensile test is conducted. Values on the two composition's tensile strength and other load capacity such as ultimate tensile strength, ultimate load, breaking stress and breaking load, yield load are obtained from the Stress Vs. Strain plot [Fig.4 & 6]. The Load Vs. Displacement plot [Fig. 3 & 5] gives the values of Max. Displacement, % elongation, % reduction in area, displacement at ultimate load (mm) respectively. The base parameters chosen for both the compositions are from Table 2 given below.
Table 2 Input parameters of Tensile Strength Test

| Input parameters (Composition 1 and 2) | Unit | Measurement Value |
|---------------------------------------|------|-------------------|
| Specimen diameter                     | mm   | 8.61              |
| Final diameter                        | mm   | 8.45              |
| Cross sectional area                  | mm²  | 58.45             |
| Test temp                             | °K   | 312               |
| Test speed                            | mm/min | 1.00            |
| Original gauge length                 | mm   | 50.00             |
| Final gauge length                    | mm   | 52.47             |

Based upon the ISO 6892-1:2009- Metallic materials - tensile testing - Part I: Method for tensile testing, the test was conducted and the output results obtained were given in Table 3 Tensile strength of composites are less than that of matrix alloy, this could only be attributed to the addition of Zirconium di-oxide to the Aluminium metal matrix as it seems to harden the composite much better than a single composition which is SiC alone.

Table 3 Output Results of Tensile strength Measurements

| Output Results                  | SiC   | ZrO₂+SiC |
|---------------------------------|-------|----------|
| Ultimate load (kN)              | 3.50  | 5.60     |
| Ultimate tensile strength (N/mm²) | 67.229 | 96.43    |
| Yield load (kN)                 | 2.11  | 3.34     |
| Breaking load (kN)              | 1.91  | 3.26     |
| Breaking stress (N/mm²)         | 36.96 | 55.96    |
| Maximum Displacement (mm)       | 2.93  | 4.04     |
| % Elongation                    | 4.80  | 5.45     |
| % Reduction in area             | 4.37  | 3.68     |
| Displacement at Ultimate Load (mm) | 2.56  | 3.49     |

Fig. 3. Load vs. Displacement in Composition 1
Fig. 4. Stress vs. Strain in Composition 1

Fig. 5. Load vs. Displacement in Composition 2

Fig. 6. Stress vs. Strain in Composition 2
Thus it is implied by the Tensile test data that the addition of Zirconia (3% wt.) along with Silicon Carbide (2% wt.) does show improved capabilities in tensile strength than the sole addition of Silicon Carbide (5% wt.) respectively.

4. Fatigue Test

The fatigue test on the composites involve the process of determination of suitable stress range, strain range, expected number of cycles to failure and displacement during operation, and is a measure of the composite’s capability. The Tension/Compression (+/-) operations is expected to replace conventional rotating tests in fatigue. The compositions I and II tested at 15.00 Hz and 20.00 Hz respectively with gauge length load control of 0.001mm, indicating the precision of control. The test gives out the load stable cycle of 214 and 81214 for compositions I and II with last load cycle being 12964 and 86485 for the same above compositions. The stress range for composition I is found out to be 150.65 MPa and 79.06 MPa for that of composition II respectively.

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5. Conclusion

The experimental work aimed in fabrication, testing and identifying mechanical behavior and some fatigue characteristics of the two compositions based on Aluminium as metal matrix and the corresponding reinforcements being

I. 5%wt. of SiC and
II. 3%wt. of ZrO2 with 2%wt. of SiC.

The hardness, tensile and fatigue studies on these compositions has revealed that the addition of partial amounts of Zirconia and Silicon carbide rather than a whole lot of Silicon carbide alone, is beneficial in the significant improvement of both hardness, tensile and fatigue strengths of the composites in comparative study.

This could only be attributed to the addition of Zirconium di-oxide to the Aluminium metal matrix as it seems to harden the composite much better than a single composition which is SiC alone.

The tensile strength test reveals the data on % elongation, %reduction in area, break load, yield load, ultimate load etc. which highlights the fact that although composition II (ZrO2+SiC) displays greater elongation than composition I (SiC), the % reduction in area of the former is significantly lesser than the later, which again can be attributed to the presence of Zirconia and Silicon Carbide together, making the composite demonstrate a higher ultimate tensile strength of 96.143 N/mm² compared to 67.229 N/mm² of the later.

The fatigue tests indicate that composition II (Al with ZrO2 and SiC) functions to higher stable cycle (81214) than composition I (Al with SiC) with 214 as stable cycle and also composition II operating at much lesser stress range of 79.062 MPa as opposed to 150.651 MPa of other composition. Therefore it is suggested that the composition II viz. (Al with 3%wt. ZrO2 and 2%wt. SiC) be employed in applications requiring high tensile strength while displaying a higher yield load of 3.640 kN compared to 2.110 kN and higher breaking load of 3.26 kN compared to 1.91 kN, higher hardness and higher load stable cycle respectively.

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