TENSILE FRACTOGRAPHY OF ARTIFICIALLY AGED AL6061-B₄C COMPOSITES

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Abstract—Presence of B₄C reinforced particles in Al6061 alloy and various weight percentages of (2, 4 and 6) on the hardness and tensile behaviour is studied in the present work. Under different aging temperatures the influence of artificial aging on the mechanical properties was also assessed. Brinell macro hardness and mechanism of tensile fracture behavior have been discussed. Failure mode of fracture surface is studied to determine the parameters which influence the crack growth characteristics. Lower temperature aging and addition of B₄C particles shows improvement in hardness by 170% and tensile strength by 90% due to the precipitation of finer secondary solute rich phases of alloying elements. Fracture surface analysis for composite shows mixed mode fracture and void nucleation growth failure.

Keywords—Metal Matrix Composites (AMMC’s), Boron carbide, Stir casting, Aging, Microstructure

I. INTRODUCTION

Aluminum- magnesium-silicon alloys (Al-Mg-Si; also denoted as 6xxx series), are medium strength, heat treatable alloys with good formability and corrosion resistance. The 6061Al alloy has been studied extensively because of their technological importance and farther increase in strength obtained by precipitation hardening [1]. Aluminium matrix composites reinforced with ceramic particles such as SiC, B₄C, Al₂O₃ and TiC are the most commonly used materials in automobile and marine industries, have been paid more consideration because of high strength, high modulus and low density. The aluminium MMCs reinforced with B₄C particulates are harder, tougher, more fracture resistant, lighter in weight and possess higher fatigue strength and reveal substantial improvements in properties over other materials [2-5]. In the metal matrix composites, the presence of reinforcement particles in aluminium alloy accelerating the aging process and thus attain to higher...
strength. This leads to more nucleation sites for the fine precipitates. [6-9].

According to the literature, the aging sequence of several researchers, the variation of the hardness versus aging temperature and time can be correlated to the phase transformations during aging treatment. The increase in the mechanical properties during aging is due to the vacancy assisted diffusion mechanism in under aged and peak aged conditions [10-13]. The formation of GP zones depends upon the aging temperature, which distorts the matrix lattice planes [14]. This distortion of the lattice planes hinders the dislocation movement as long as the coherency exists in the lattice [15-16]. Several works have been reported on the use of two- step (double) stir casting as a means of improving cast metallic matrix [5]. All these studies brought out differences in microstructures of aluminium metal matrix composites (AMCs) produced through different routes such as, (a.) direct casting (no stirring), (b.) manual stirring, and (c.) two step mixing. It was evident from these reported literatures that the two step mixing gives the best uniform distribution of the SiC particulates. It was also suggested that production of AMCs without the use of two step stirring results in less dispersion of the particulates and higher porosity levels which might be in excess of the acceptable limits. Thus the present work emphasizes on investigation of the effect of reinforcement and artificial aging on microstructure and fracture behavior of Al6061-B$_4$C composites.

II. MATERIALS AND METHODS

The base matrix chosen in the present study is the aluminium 6061 (0.52% Si, 0.95% Mg, 0.55% Fe, 0.24% Cu, 0.14% Mn and 0.25% Cr) because it is one of the most extensively used 6000 series aluminium alloys. The boron carbide reinforcement particles used for preparation of composite is brought from Boron Carbide India limited, Mumbai. The reinforcement materials are having irregular shape. Scanning Electron Microscope (SEM) and X-Ray Diffraction (XRD) plot of the same shown in Fig.1 confirms the presence of the B$_2$C particles. Al6061- B$_4$C composites were fabricated by two stage stir casting technique by altering the amount of boron carbide particles in the range 2-6 % wt.

![Fig.1(a) SEM micrographs of boron carbide particles and (b) XRD plots of B$_4$C particles.](image)

Hardness tests were carried out in a Brinell hardness testing machine with steel ball indenter of diameter 5mm and a load of 250 kgf (SAROJ Brinell Hardness Testing Machine, Model:-B/3000/00, Sl# 13/06/08- India). Tensile properties dictate how the material will react to forces being applied in tension. Tensile specimen is prepared according to ASTM-E8M standards. The specimen prepared for above test is subjected to age hardening heat treatment. Specimens are soaked at 558°C for duration of 2h, then immediately quenched in water at room temperature. The quenched specimens were artificially aged in the furnace at 100, 150 and 200°C for various durations of time. According to the Al-Mg-Si phase diagram melting of ternary eutectic Mg$_2$Si-(Al)-(Mg) phase takes place at 558°C. The presence of Mg$_2$Si is a strengthening intermetallic phase and dissolves completely at 558°C during solutionizing and precipitates during age hardening to maximize the strengthening effect. These secondary precipitated phases result in particle strengthening and coherency of the crystal structure of the particle and the matrix. It
is reported that the samples of Al6061 composite, with the solution heat-treated at 558°C, exhibit better strength [9].

III. RESULTS AND DISCUSSION

A. HARDNESS MEASUREMENT

Peak hardness values obtained in as cast and different aging temperatures at 100, 150 and 200°C as shown in Table 1. Increase in hardness values were observed in as cast condition with the addition of boron carbide particles when compared to the unreinforced alloy. The hardness value increases with increase in weight percentage of boron carbide particles. Increased content of boron carbide particles (2, 4 & 6% wt.) in the matrix alloy leads to higher dislocation densities during solidification due to the thermal mismatch of the matrix alloy and the reinforcement. The matrix deforms plastically to accommodate the smaller volume expansion of the reinforcement particles leading to increased dislocation density. Enhancement in dislocation densities results in higher resistance to plastic deformation and responsible for additional increase in hardness of composites [17].

Similar to base alloy, the Al6061 matrix composite is very sensitive to age hardening irrespective of lower or higher aging temperature. It is evident that composites exhibit accelerated rate of aging kinetics as compared to unreinforced matrix alloy. Aging kinetics gets accelerated in the composites with increase in wt. % of reinforcements. Aging is accelerated due to the presence of areas with a high concentration of dislocation close to Al6061 matrix & B\textsubscript{4}C reinforcements interface. These high density locations provide heterogeneous nucleation sites for the precipitation & high diffusivity path for the diffusion of alloying elements [18]. Compared to base alloy, composites show drastic increase in the hardness in as cast & treated conditions. At the same time increase in weight percentage of B\textsubscript{4}C in the composites gives positive effect on hardness value. Lower aging temperature shows increase in hardness of base alloy as well as composites as compared to higher temperature aging. Lower temperature aging contributes to the increased hardness by increasing the number of intermediate zones during precipitation, increase in the number of finer inter-metallic’s & decreased interparticle distances. Higher the aging temperature, lower is the time required to attain peak hardness [9]. From the above results it can be concluded that heat treatment has a profound influence on the hardness of matrix alloy as well as composites.

B. TENSILE STRENGTH

Tensile test is carried out on as cast and peak aged specimens. The average value of the three readings in as cast and peak aged conditions is tabulated in Table 2. There is a marginal increase in the ultimate tensile strength (UTS) with the addition of reinforcements when compared to unreinforced alloy in as cast condition. The reinforcement particles control the mechanical properties of the composites due to the strong interface, which transfers and distributes the load from the matrix to the reinforcement exhibiting increased elastic modulus and strength. The UTS in composite or base alloy is very sensitive towards age hardening. There is a minimum of 60% additional increase in the UTS by age hardening over untreated specimen. From Table 2, it is clear that higher the weight percentage of reinforcement in the composite and lower the aging temperature better is the ultimate tensile strength. The increase in strength is due to the combined effect of difference in co-efficient of thermal expansion between matrix and B\textsubscript{4}C particulates and precipitation behavior of solute rich secondary phases.
The effect of reinforcement content on the percentage elongation is shown in Fig. 2. It is observed that, as the boron carbide content increases, the percentage elongation of the composite material decreases. Quantitatively as B₄C content is increased from 0 to 6%, there is a reduction in percentage elongation of 50%. There is an embrittlement effect due to the hard B₄C particles which causes increased local stress concentration sites. These B₄C particles resist the passage of dislocations either by creating stress fields in the matrix or by inducing large differences in the elastic behavior between the matrix and the dispersoid.

A. FRACTURED SURFACE ANALYSIS OF Al6061 ALLOY AND AL6061-B₄C COMPOSITES.

It is found from Fig. 3, that the fracture mode is predominantly dimple rupture. Numerous cuplike depressions or dimples are observed. Dimples are the results of formation and coalescence of micro-voids that nucleate at localized strain region (2nd phase particles, inclusions, grain boundaries, dislocations etc.). In Fig.3, it is found that some micro-voids formed at grain boundary and other locations.

In Fig.4 fracture surface of aged specimen is shown after tensile test. Here numbers of dimples are more and smaller in size indicating the formation of micro-voids (dimples after coalescence) at numerous precipitated particles at peak aging. Therefore, the dimples are evenly distributed with smaller in size.

Fig. 4 SEM micrographs of fracture surface of heat treated Al6061 alloy peak aged a 100°C.

Fig.5 shows fracture surface SEM microstructure of as cast Al6061-6% B₄C composite. Considerable decrease in dimple density is observed in comparison with Al6061alloy. In a localized region fracture may be due to tear or shear, resulting in the formation of elongated dimples. Further, it is noticed that some of the dimples are shallow and these may be due to coalescence of micro voids by shear as shown in Fig.5 (b).

Whereas, in the case of peak aged sample at 100°C (Fig.6) the fracture mode is dimple rupture. Dimples are formed when numerous nucleation sites are activated resulting in the formation of micro-voids and thereafter coalescence of these micro-voids. Nucleation sites may be inclusions, 2nd phase particles, grain boundary dislocation pile-ups etc. Fracture surface is significantly influenced by the distribution of these particles/defects. Non-uniform distribution of such particles/defects with various sizes results the formation of dimples of different sizes. In few places, quasi-cleavage fracture also noticed.
Quasi-cleavage is localized and exhibits characteristics of both cleavage and plastic deformation (Fig. 6b). Generally, de-cohesive rupture may be due to several mechanisms. In the present case, it may be due to the rupture of protective films surrounding B₄C.

**TABLE I**

HARDNESS OF Al6061- B₄C (0, 2, 4 & 6% wt.) AS CAST AND PEAK AGED CONDITION.

<table>
<thead>
<tr>
<th></th>
<th>As cast condition (without Heat treatment)</th>
<th>Peak aged condition at 100°C</th>
<th>Peak aged condition at 150°C</th>
<th>Peak aged condition at 200°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al6061 alloy</td>
<td>50</td>
<td>85</td>
<td>74</td>
<td>65</td>
</tr>
<tr>
<td>Al6061-2% B₄C</td>
<td>60</td>
<td>110</td>
<td>107</td>
<td>95</td>
</tr>
<tr>
<td>Al6061-4% B₄C</td>
<td>65</td>
<td>126</td>
<td>115</td>
<td>100</td>
</tr>
<tr>
<td>Al6061-6% B₄C</td>
<td>74</td>
<td>134</td>
<td>123</td>
<td>105</td>
</tr>
</tbody>
</table>

**TABLE 2**

ULTIMATE TENSILE STRENGTH OF ALLOY AND ITS COMPOSITES IN AS CAST AND PEAK AGED CONDITIONS

<table>
<thead>
<tr>
<th></th>
<th>As cast condition (without Heat treatment)</th>
<th>Peak aged condition at 100°C</th>
<th>Peak aged condition at 150°C</th>
<th>Peak aged condition at 200°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al6061 alloy</td>
<td>145</td>
<td>227</td>
<td>211</td>
<td>199</td>
</tr>
<tr>
<td>Al6061-2% B₄C</td>
<td>158</td>
<td>248</td>
<td>231</td>
<td>218</td>
</tr>
<tr>
<td>Al6061-4% B₄C</td>
<td>165</td>
<td>255</td>
<td>241</td>
<td>225</td>
</tr>
<tr>
<td>Al6061-6% B₄C</td>
<td>173</td>
<td>261</td>
<td>248</td>
<td>229</td>
</tr>
</tbody>
</table>

**conclusions**

- 20-40% improvement in hardness was observed in as-cast composites compared to the base alloy.
- Al6061 alloy and Al6061-B₄C composites positively respond to age hardening treatment with considerable improvement in mechanical properties.
- Slower precipitation kinetics and higher peak hardness is noticed at lower aging temperature for both base alloy and the composites.
- An increase in peak hardness of 90-110% aged at 200°C and 140-175% (2-6 wt.% B₄C) aged at 100°C is observed in significant duration for the composites in comparison with untreated Al6061 alloy.
- Marginal increase (20%) in ultimate tensile strength (UTS) is noticed in as cast Al6061-B₄C composite compared to as cast Al6061 alloy.
- During aging there is 80% increase in UTS of composites over untreated base alloy.
- Peak aged tensile fracture surface of base alloy and its composite material fails by mixed mode of fracture.

**REFERENCES**

[1] Fatih Toptan,, Ayfer Kilicarslan,, Ahmet Karaaslan,, Mustafa Cigdem,, Isil Kerti,, “Processing and microstructural characterisation of AA 1070 and


