Evaluation of mechanical properties of aluminium alloy (LM25) reinforced with fused silica metal matrix composite

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Aluminium alloys are broadly used as a main matrix element in composite materials. The present work is aimed to fabricate and evaluate the microstructure, tensile properties, hardness and impact strength of aluminium matrix composites consists of aluminium alloy LM25matrix and fused silica-SiO₂ particulates as the reinforcement (size 150-250µm) in the matrix. The reinforcement added in ranges from 4 to 12 wt% in steps of 4%. The composites were casted by stir casting route. The reinforcement of SiO₂ particulates boosts the mechanical properties of the composites. The microstructure and mechanical properties of the fabricated MMCs were evaluated. The mechanical properties like tensile, hardness and impact strength have improved than that of unreinforced alloy.

Keywords: Aluminium alloy LM25, SiO₂, Stir casting, MMC, Mechanical properties, Microstructure analysis

Aluminium alloy materials were found to be the best alternative because of its unique capacity of designing the materials to give required properties¹. Due to its light weight, it has been in the internet of researchers for enhancing the technology. The aluminium alloys are broadly used in a very desirable combination of properties, combined with the ease with which they may be produced in a great variety of forms and shapes². Aluminium alloys are preferred as engineering material for variety of applications such as automobile, aerospace and mineral processing industries; owing to their lower weight and excellent thermal conductivity properties³. Advanced engineering materials, composites have high wear resistance, which is used in electrical contact brushes, cylinder liners, artificial joints, helicopter blades, etc. Compared to monolithic materials, wear resistance can be gradually enhanced by introducing a secondary phase(s) into the matrix material⁴. Composite materials are finding increasing no of applications such as, automotive, aerospace, nuclear energy generation and structural applications, because of their improved mechanical and tribological properties. Metal matrix composites are new materials which are attracting considerable industrial interest and investment worldwide⁵. The superior properties of the particulate-reinforced Al-based MMCs make these materials attractive for applications in the automobile, defense and leisure industries. The wear resistance of unreinforced Al-alloys is relatively poor⁶-⁷.

Hence, their applications as structural and automobile parts are often limited. Fortunately the strength, fracture, toughness and wear resistance can be improved drastically by the incorporation of hard particulates such as fused silica⁸. The SiC particles, used in aluminium matrix composites, are harder than tungsten carbide, that’s why many researchers have recommended SiC metal matrix composites typically, contains continuous or discontinuous fibers, whiskers, or particulates dispersed in a metallic alloy matrix. These reinforcements provide the composite with properties not attainable in monolithic alloys⁹-¹⁰. The interface between the matrix and the reinforcement plays a very important role for deciding and explaining the toughening mechanism in the metal matrix composites and the bond in between the interface should not be either strong or weak¹¹. Metal matrix composites produced by stir casting technique have more advantages compare with other methods. Addition of TiB₂ improves the wear resistance of aluminium composites¹². Mechanical properties of quartz particulate reinforced LM6 alloy matrix composites. They reported that the tensile strength and young’s modulus was decreased and hardness was increased, when the volume fraction of reinforcement was increased¹³,¹⁴. Therefore, aim of
this study is to investigate the effects of mechanical and structural due to the addition of fused silica with Al-LM25 at different ranges from 4 to 12 wt% in steps of 4%.

Material and Methods

Matrix material

Materials used in this work are aluminium LM25 alloy for the matrix material and fused silica (SiO$_2$) as a particulate reinforcement added in three different percentages. Chemical compositions of LM25 is given in Table 1.

LM25 alloy can be cast in permanent or sand mould and possesses excellent castability, good corrosion resistance, good wear resistance and greater machining and welding characteristics$^{15}$. Many researchers have developed various composite materials by using different types of matrix, reinforcement size, shape and volume as well as suitable processing techniques depending upon the requirement and application. In order to achieve the optimum properties of the metal matrix composite, the distribution in the matrix alloy of second phase must be uniform, and the wettability or bonding between these substances should be optimized$^{16}$. In specific, particulate reinforced MMCs have recently found special interest in specific strength and specific stiffness at room and elevated temperatures$^{17}$. Aluminium metal matrix composites are the most promising materials for wear and structural applications because of its low density, low cost and ease of fabrication$^{18}$.

Reinforcement material

Ceramic materials are generally used to reinforce aluminum alloys like SiC, TiC, TiB$_2$, ZrB$_2$, AlN, Si$_3$N$_4$, Al$_2$O$_3$, and SiO$_2$. Among these reinforcing ceramic particles, fused silica (SiO$_2$) is particularly attractive material$^{19}$. Pure and fused silica is commonly called quartz. Quartz is a hard mineral which is available in abundant. It provides excellent hardness when incorporated into the soft lead alloy, thereby making it suited for applications where hardness is desirable. It also imparts good corrosion resistance and high chemical stability$^{20}$. It is a mineral which having a composition of SiO$_2$, it is the most common among all the materials, and occurs in the combined and uncombined states$^{21}$. It is estimated that 60% of the earth’s crust contains SiO$_2$-Sand, clays, and rocks are largely composed of small quartz crystals. In the pure form, SiO$_2$ is white in color$^{22}$.

Preparation of composite

In stir casting route method of composite materials fabrication, a dispersed phase (ceramic particles, short fibres) is mixed with a molten metal matrix by means of mechanical stirring. The liquid composite material is casted by conventional casting methods and may also be processed by conventional metal forming technologies. The stir casting methodology is relatively simple and low cost$^{23}$.

The synthesis of the metal matrix composite used in the present work was carried out by stir casting route. A three phase crucible furnace up to 800°C with temperature controller is used for melting as shown in Fig. 1. For each melting process 300-400 g of alloy is used. Al alloy was used in the form of ingots. Three different weight fractions of SiO$_2$ particle in the range from 4%, 8% and 12% by weight are used. The cleaned metal ingots are melted to the desired temperature of 750°C in graphite crucibles. Cover flux were added into the molten metal in order to minimize the oxidation. Glass particulates are preheated to around 400°C for 30 min were then added to the molten metal and mechanically stirred continuously for uniform dispersion up to 6 to 8 min$^{24}$.

During stirring, magnesium was added in small quantities to increase the wettability of glass particulates. The preheated glass particulates dispersion was achieved in accordance with the stir casting route. This stir casting route makes the particles dispersed randomly. The melt then poured into the sand moulds. The moulds for the plate type of castings120×120×30 mm which were prepared using

<table>
<thead>
<tr>
<th>Elements in wt%</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Ni</th>
<th>Zn</th>
<th>Pb</th>
<th>Sn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM 25</td>
<td>6.987</td>
<td>0.360</td>
<td>0.063</td>
<td>0.21</td>
<td>0.42</td>
<td>0.003</td>
<td>0.005</td>
<td>0.008</td>
<td>0.064</td>
<td>0.005</td>
<td>0.1</td>
<td>Bal.</td>
</tr>
</tbody>
</table>
silica sand with 5% bentonite as binder and 5% moisture and finally they were dried in an air furnace. The pouring temperature was maintained at 650°C. It means when the molten metal temperature decreased from 750°C to 650°C, it was suddenly decanted to the sand moulds. The melt was allowed to solidified in the moulds. The stir casting process is shown in Fig. 2.

Experimental Procedure

Tensile testing

Tensile test was used to determine the mechanical properties of the processed SiO2 particulate reinforced LM25 alloy composites. To investigate the mechanical behaviour of the composites, tensile tests were carried out with the help of Universal tensile testing machine having tensile load range of maximum 5 ton, gear rotational speed of 1.25, 1.5 and 2.5 mm/min is used, specimens are prepared as per ASTM E8 standards, dimensions are shown in Fig. 3(a). The tensile properties of the alloys were determined by performing the tension test on standard flat tensile specimens. A typical tensile test specimen as per ASTM standard is shown in Fig. 3(b).

Hardness testing

ASTM E18: Standard methods for Rockwell hardness and Rockwell superficial hardness of metallic materials. A standard specimen size for Rockwell hardness test is 25.6×25.6×6.5 mm. The hardness test was done in a Rockwell Hardness Tester with B scale is used. The hardness of composites was tested by using Digital Rockwell Hardness Tester. Hardness values of different weight % of the processed composites are determined for different weight fraction % of silica particulate containing aluminium alloy LM25. Rockwell hardness test specimens are shown in Fig. 4.

Impact testing

The impact test was conducted in Charpy impact tester having 140° pendulum drop angle, pendulum weight of 22 kg, pendulum impact energy of 300 J and pendulum striking velocity of 5 m/s. The test specimens are made as per ASTM E23 standard as shown in Fig. 5(a). For each sample impact test was carried out and readings are taken. Impact strength values of different types of the processed composites are determined. The photographic view of the impact test specimens are shown in Fig. 5(b).
The impact value of a material can also change with temperature. Generally, at lower temperatures, the impact energy of a material is decreased. The size of the specimen may also affect the value of the Charpy impact test because it may allow a different number of imperfections in the material, which can act as stress risers and lower the impact energy.

Microstructure analysis

The composites were produced using a sand casting technique. They investigated the variation in % composition, hardness, tensile strength and microstructure properties of composites. The tensile strength and hardness of the composite are increased with increasing the % of reinforcement. The microstructure revealed the formation of silicon dendrites and the dispersion of the glass particle. Microstructural analysis was carried out using optical microscope is shown in Fig. 6. The specimens for metallographic examination were sectioned to the required sizes from the metal matrix composites. The specimens are ground, polished, and etched as per ASTM standards. The burs and edge protrusions are removed by polishing on a grit abrasive coated belt grinder. The specimens were ground on 400, 600 and 1000 grit SiC emery paper. Subsequently, the ground samples were mechanically polished using one micron diamond based polishing compound. The polished specimens were washed with distilled water and etched using 0.5% hydrofluoric acid solution. Microscopic study was also carried out using image analyzer software.

Results and Discussion

Tensile test results

Results obtained from the tensile tested samples with the reported tensile properties for each weight fraction of SiO₂ percentage addition to the LM25 alloy matrix. The results of tensile test for three various percentages of fused silica particulate in LM25 alloy are given in Table 2. The graph plotted between ultimate tensile strength versus three different weight fraction percentages of fused silica particulates is shown in Fig. 7. Ultimate tensile strength increases with increasing wt% of fused silica up to 8 wt% which means up to 26.5%. It is because that the compressive strength of the SiO₂ particulate is higher than the ultimate tensile strength of LM25 alloy matrix. So the ultimate tensile strength is decreasing with more addition of SiO₂ particulate and it evidenced from the literature citation.

The graph plotted between yield strength versus three different weight fraction percentages of fused silica particulates is shown in Fig. 8. Yield strength increases with increasing wt% of fused silica up to 8 wt% which means up to 45.1%. It is because the increase of yield stress shows that there was good interfacial strength. Weak interfacial bonds may result in decrease in yield stress of the composite. The graph plotted between elongations versus three different weight fraction percentages of fused silica particulates is shown in Fig. 9. Elongation increases with increasing wt% of fused silica up to 8 wt%.

<table>
<thead>
<tr>
<th>Sl.No</th>
<th>Weight fraction % of SiO₂</th>
<th>Ultimate tensile stress (MPa)</th>
<th>Yield stress (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>130</td>
<td>91</td>
<td>3.000</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>163</td>
<td>116</td>
<td>5.400</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>177</td>
<td>166</td>
<td>7.275</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>152</td>
<td>146</td>
<td>4.175</td>
</tr>
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</table>
which means up to 58.7%. It's because the reinforcement particles donate the strength by holding the molecules in the matrix and thereby resisting the deformation of the material and it evidenced from the literature\textsuperscript{31}.

From the graphs, it is observed that the MMCs tensile properties are increased with increasing the dispersoid content up to 8 wt% and then decreases with increasing the wt% of dispersoid content. Increase in tensile properties is attributed to increase in grain boundary area due to grain refinement, at the interface and effective transfer of applied tensile load to the uniformly distributed well bonded reinforcement. In most cases, ceramic reinforced MMCs have superior mechanical properties to the unreinforced matrix alloy because these MMCs have high dislocation densities due to dislocation generation as a result of differences in coefficient of thermal expansion. The reason for the reduction in tensile properties in MMCs is due to increase of closed pores content with increasing quartz particulate content would create more sites for crack initiation and hence lower down the load bearing capacity of the composite.

**Rockwell hardness test results**

Results obtained from the hardness test samples for each weight fraction of SiO\textsubscript{2} addition with the LM25 alloy matrix. It is observed that the hardness of LM25 alloy is 62.26 and then hardness increases with increasing wt% of SiO\textsubscript{2} particulate up to 8 wt% which means up to 11.9% and then decreases with increasing wt% of silicon dioxide particulate. It is because the increase in hardness from 0 to 8 wt% can be explained according to literature\textsuperscript{32} as the suppression of the columnar and dendritic growth and the formation of small equated grains Rockwell hardness test result given in Table 3.

The graph plotted between the average hardness values versus weight fraction of SiO\textsubscript{2} particulate added to LM25 alloy is shown in Fig. 10. As dispersoid content is increased, there is a tendency for the hardness to increase because dispersoids provide more nucleation sites for precipitation. As expected, increasing the SiO\textsubscript{2} content up to 8 wt% causes the

<table>
<thead>
<tr>
<th>SI.No</th>
<th>Weight fraction % of SiO\textsubscript{2}</th>
<th>Hardness in HR15T Sample</th>
<th>Average Hardness in HR15T</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>60.4</td>
<td>62.26</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>65.7</td>
<td>67.76</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>70.4</td>
<td>70.67</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>67.5</td>
<td>65.43</td>
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hardness of the MMC to increase since the SiO₂ of particulates are so much harder than the matrix alloy.

**Impact strength test results**

The results obtained from the impact test samples for each weight fraction of silicon dioxide addition with LM25 alloy matrix. It is observed from Table 4 the impact strength values are increased with addition of wt% of silicon dioxide up to 8 wt% which means up to 17.2% in the alloy matrix.

The graph plotted between impact strength versus weight fraction percentage of SiO₂ particulate addition to LM25 alloy is shown in Fig. 11. In the SiO₂ particulate reinforced composites, the weight fraction of SiO₂ affects the amount plastic deformation that the matrix can absorb. This leads more quickly to SiO₂ reinforcement fracture, matrix SiO₂ particle delamination, and SiO₂ particle spalling. As a consequence, volume impact abrasive wear increases at a more rapid rate for the composite materials as the hardness increases.

**Microstructure analysis test results**

The microstructural analysis was carried out in optical microscope. Microstructure of the three different weight percentage of SiO₂ particulate reinforced matrix alloy at magnification of 100X is shown in Figs 12-15. In Fig. 12, it is observed the microstructures of the pure Al matrix. It is clear that there is no dark spot area in the microstructure which means no addition of SiO₂ particles.

Figure 13 shows that the microstructures are taken from different fields of 4% fused silica added metal matrix composite. The distribution of composite particles is even as the percentage of composite is lower and mixing is effective. The metal matrix shows that the silica particles occupy the grain boundaries of Al-Si dendritic grains. Some particles with higher grain size occupy the metal matrix in aluminium solid solution. The microstructure of aluminium metal matrix shows the Al-SiO₂ eutectics in primary alpha aluminum solid solution.

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Weight fraction % of SiO₂</th>
<th>Impact strength (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1.53</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>1.6</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>1.85</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>1.8</td>
</tr>
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</table>

Fig. 11 — Impact strength at various wt% of SiO₂ MMC
Figure 14 shows that the microstructures are taken from different fields of 8% fused silica added metal matrix composite. The higher addition of particulates leads to the agglomeration of the particles in certain pockets. The distribution of composite particle is isolated as the percentage of composite is higher and mixing is ineffective but at some locations the composite particles have uniformly distributed. It shows that the silica particles occupy grain boundaries. Some particles with finer grain size occupied the grain boundary voids. But higher grain size occupies the metal matrix in aluminium solid solution. The microstructure of aluminium metal matrix shows the Al-Si eutectics in primary alpha solution. The metal matrix shows Al-Si eutectics in primary alpha solution. The Rockwell hardness is increased with addition of reinforcement material influence the microstructure of the composites. The factors which affect the properties of the material they are reinforcement particle size and weight fraction percentage. It will significantly improve the composite properties.

Conclusions

Aluminium matrix composite was successfully synthesized by the stir casting method and its microstructure, tensile properties, hardness and impact strength were analyzed. The following conclusions may be drawn from this study:

(i) The tensile strength increased up to 8 wt% of fused silica particulate in alloy matrix which means up to 26.5%. After those values were decreased with increasing wt% of SiO₂. Because of the ultimate tensile strength is decreasing with more addition of SiO₂ particulate.

(ii) The Rockwell hardness is increased with increased addition of fused silica particulates up to 8 wt% which means up to 45.1% and then decreases with increasing wt% of SiO₂. It is due to there is a tendency for the hardness to increase because dispersoids provide more nucleation sites for precipitation.

(iii) The impact strength also increased with addition of fused silica particulates up to 8 wt% which means up to 58.7% and then decreased. The weight fraction of SiO₂ affects the amount plastic deformation that the matrix can absorb.

(iv) Microstructures of the composites were improved than that of unreinforced alloy. The additions of reinforcement material influence the microstructure of the composites. The factors which affect the properties of the material they are reinforcement particle size and weight fraction percentage. It will significantly improve the composite properties.

References