Synthesis and Characterization of SiC<sub>p</sub> Reinforced Magnesium Alloy Based Metal Matrix Composite Through Vacuum Assisted Stir Casting Process

Anil Kumar ¹, Santosh Kumar ² and N. K. Mukhopadhyay ³

¹Research Scholar, ²,³Professor
¹,²Department of Mechanical Engineering, Indian Institute of Technology
³Department of Metallurgical Engineering, Indian Institute of Technology,
(Banaras Hindu University), Varanasi, Uttar Pradesh, India.

Abstract

Development of light weight material is one of the challenging task for all the engineers and scientist. The magnesium as a light weight material has limited application in pure form due to high corrosion and average mechanical properties. The alloying element has tendency to improve corrosion as well as mechanical properties of the magnesium alloy. The particle reinforced metal matrix composites of magnesium alloy is one of the solution to improve utility of the magnesium. This paper present the characterization of SiC particulate reinforced metal matrix composites, where commercial magnesium alloy (AZ91) is used as a matrix material. The microstructural examination using optical microscope and scanning electron microscope (SEM) has been performed for the composite prepared using stir casting method in inert atmosphere. The mechanical properties like tensile and hardness were examined. The yield strength, ultimate strength and tensile facto-graph are also evaluated in this study.

Keywords: Magnesium alloy, composite, particle reinforcement

INTRODUCTION

The production of metal matrix composite has been enhanced since last three decade, because metal matrix composite offer more attractive properties than their monolithic counterparts. The demand for lightweight materials has been increased in all field of engineering applications like automobile aerospace, sports, electronics and medical fields. Acrylonitrile butadiene styrene and polycarbonate and carbon fibre are the lighter non-metallic structural materials [1], but non-metal cannot solve problems, where heat transfer is required. The light metals are magnesium, aluminium and titanium due to their capability of reducing the weight of component in comparison with steel. Magnesium is one of the promising light weight material (lightest of all structural metal), which is even lighter than Aluminium and currently underutilized for engineering applications. The density of Magnesium is 1.74 g/cm³, which is approximately 70% lighter than steel and 35 % lighter than Aluminium [2].Products made from lightweight magnesium are therefore easier to lift and move. This makes them more energy-efficient and more user-friendly.

Magnesium is the lightest structural metal but its application is limited due to high corrosion in open atmosphere and poor mechanical properties [3], to compensate this magnesium alloy are used in structural applications. Magnesium alloy exhibit high specific resistance with good castability, excellent machinability and some other advantages in relation to weight reduction and energy saving [4]. The metal matrix composite of magnesium alloy seems to provide advantage of magnesium alloy (light weight) and enhancement of mechanical properties. Magnesium and magnesium alloy are have great importance in the field of automobile and aerospace industries [5].

The addition of particulate reinforced in to the magnesium alloy can significantly improve the stiffness and strength at room and elevated temperature [6-8]. Magnesium alloy MMCs are reinforced by various ceramics particle, metals and carbon nano-tubes. Ceramics particle such as SiC, Al₂O₃, TiC, MgO etc. are highly preferred reinforcements [9-13].

The production of metal matrix composite have been fabricated using different available technologies such as stir casting [14] gas infiltration [15], power metallurgy [16,17], squeeze casting [18], spray deposits [19], injection moulding [20] and in situ-technique[21]. The stir casting process is one of the most economical process for production of magnesium alloy based MMCs.

EXPERIMENTAL PROCEDURES

Materials

Commercial magnesium alloy AZ91D was used as the metallic matrix for producing metal matrix composites. The chemical composition of as received AZ91D magnesium alloy has been tabulated in table1. The elemental composition of AZ91 were evaluated with help of optical Emission Spectroscopy.

Table 1. Elemental Composition of alloy AZ91

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>99.600</td>
<td>0.129</td>
<td>0.073</td>
<td>0.045</td>
<td>0.032</td>
</tr>
<tr>
<td>Al</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Zn</td>
<td>0.026</td>
<td>0.020</td>
<td>0.020</td>
<td>0.017</td>
<td>0.007</td>
</tr>
<tr>
<td>Fe</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>Sn</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>Pb</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>Ti</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>Cu</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>MgO</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>SiC</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>TiC</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>MgO</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>SiC</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>TiC</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
</tbody>
</table>
In order to fabricate metal matrix composite with magnesium alloy AZ91, SiC particle with average particle size of 20 micron were added as a reinforcements. The AZ91 magnesium alloy were melted in metallic crucible hanged in an electric resistant furnace at temperature 700°C. Four different weight percentage of SiC particle (3, 6, 9 and 12 percent) were added to the matrix material through stir casting techniques. The melt was held at this temperature for 20 minutes and then stirred mechanically for 15 minutes. The melt was poured in to die through bottom pouring facility in inert atmosphere to avoid porosity in the composite.

MICROSTRUCTURAL OBSERVATION
The die cast composites with different percent of SiC particles were sectioned in to small pieces for mechanically gridding and polishing. The mirror polished sample etched with suitable etchant for 5 second to determine the related microstructure. The etchant was prepare by mixing ethyl glycol, distilled water and nitric acid in the ratio of 75:24:1. The grinding paper which is used for grinding/polishing are 120,320, 500, 1000, 1200, 1500, 2000 and 2500 grit size of SiC abrasive paper. The MMC specimen finally polished on velvet cloths with diamond paste (Mono-crystalline) of 1 micron size.

The obtained microstructure sample were examined by a Leica optical microscope (OM) equipped with leica application suite. Further scanning electron microscope equipped with EDS was used to examine the sample's surface topography and elemental composition.

MECHANICAL TESTING
1. Tensile Testing
The tensile test of SiC particulate reinforced metal matrix composites were performed to estimate the mechanical properties of vacuum assisted stir die cast composites. The tensile sample were prepared from composites with different percentage of SiC particle as well as commercial magnesium alloy AZ91. The gauge length of tensile sample was 20 mm and gauge diameter 8 mm according to the ASTM E8/E8M standard. The tensile tests were carried out at room temperature on Instron-4208 universal testing machine under the initial strain rate of 0.005 s.

1. Hardness Test
The hardness test for all the composite has been performed to estimate the distribution homogeneity of reinforcement particles as well as variation of hardness with different percentage of reinforcement. The Vickers micro-hardness test were performed across section of polished composites by applying a load of 1.0 kgf with dwell time of 10 second. The macro hardness test also have been performed on the composite using load of 3kgf with dwell time of 10 second. LECO's LV Series Macro-Vickers Hardness machine is used for testing hardness.

RESULT AND DISCUSSION
1. Microstructure
The optical microstructure of unreinforced AZ91 and SiC particle reinforced composite with different volume fraction of SiC particle have been illustrated in figure 1. The β- phase are represented by red arrow, α- phase represented by blue arrow and porosity are represented by yellow arrow in figure 1. The reinforced particle are represented by green arrow. The increase in the percentage of the SiC particle lead to the decrease in grain size of the magnesium alloy. From the microstructure it is cleared that on addition of SiC reinforcement there is grain refinement of the stir casted composite.

The distribution of different percentage of SiC particle were clearly shown in FE SEM microstructure of the composite which are shown in figure 2. The distribution of SiC particle in magnesium alloy were almost uniform as per SEM micrographs. A sound casting are also observed as no gas inclusion and porosity were seen in cast microstructure of magnesium alloy composites.

2. Mechanical properties
2.1 Yield Strength
Yield strength of the composite observed to be increasing on increase in volume fraction of SiC particle in magnesium alloy (AZ91) composite. The various strengthening mechanism can contribute to increase Yield strength of the metal matrix composite i.e. (a) Generation of geometrically necessary dislocation to accommodate thermal and elastic modulus mismatch between the matrix and reinforcement (b) Load- bearing effects due to the presence of reinforcement (c) Orowan strengthening (d) Hall- Petch effect due to grain size refinement. The Yield strength of the composite \(\sigma_{comp,y}\) can be given by [22]

\[
\sigma_{comp,y} = \sigma_{mo} + \Delta\sigma
\]

Where \(\sigma_{mo}\) = Yield strength of unreinforced matrix
\(\Delta\sigma =\) Total improvement in Yield strength

The total value of \(\Delta\sigma\) is estimated by equation (1) [23]

\[
\Delta\sigma = \sqrt{(\Delta\sigma_{CTE})^2 + (\Delta\sigma_{EM})^2 + (\Delta\sigma_{Load})^2 + (\Delta\sigma_{Orowan})^2 + (\Delta\sigma_{Hall-Petch})^2} \quad (1)
\]
$\Delta \sigma_{CTE}$ and $\Delta \sigma_{EM}$ are the stress increment due to coefficient of thermal expansion and elastic modulus mismatch between the reinforcements and the metallic matrix respectively. These two values can be calculated by the Taylor dislocation strengthening relation [22-24]

$$\Delta \sigma_{CTE} = \sqrt{3} \beta G_m b \sqrt{\rho_{CTE}}$$

and

$$\Delta \sigma_{EM} = \sqrt{3} \alpha G_m b \sqrt{\rho_{EM}}$$

Where $\delta$ and $\beta$ are the strengthening coefficient, $G_m$ is the shear modulus of the matrix, $b$ is the Burger vector.

$\rho_{CTE}$ and $\rho_{EM}$ represent the dislocation density because of the coefficient of thermal expansion and elastic modulus mismatch respectively.

The geometrically necessary dislocation density due to elastic modulus mismatch $\rho_{EM}$ can be given as [25]

$$\rho_{EM} = \frac{\gamma^m m}{b \lambda}$$

Where $\gamma^m$ the shear strain and $\lambda$ is the local strength scale of

---

**Figure 1.** Optical Micrograph (a) 3% SiC in AZ91 (b) 6% SiC in AZ91 (c) 9% SiC in AZ91 (d) 12% SiC in AZ91

---

**Figure 2.** Scanning Electron Micrograph (a) 3% SiC in AZ91 (b) 6% SiC in AZ91 (c) 9% SiC in AZ91 (d) 12% SiC in AZ91
the deformation field and \( \lambda \) can be defined as [26]

\[
\lambda = d \left[ \frac{1}{V_r} \right]^{3} - 1
\]

Where \( d \) is the smallest dimension of the reinforcement and \( V_r \) is the volume fraction of the reinforcement.

The geometrically necessary dislocation density due to CTE mismatch, \( \rho_{CTE} \) can be given as [27]

\[
\rho_{CTE} = \frac{B V_r \varepsilon_{CTE}}{b (1 - V_r) d}.
\]

Where \( B \) is a geometric constant and \( \varepsilon_{CTE} \) is the misfit strain due to the different CTE mismatch value of the metallic matrix and reinforcements. \( \varepsilon_{CTE} \) can be given as

\[
\varepsilon_{CTE} = (C_m - C_r) \Delta T = \Delta C \cdot \Delta T
\]

Where \( C_m \) and \( C_r \) represent the CTE of the metallic matrix and reinforcements, respectively. \( \Delta T \) is the temperature change.

Effective load bearing capacity is highly dependent upon the interfacial bonding between the matrix and the reinforcement. According to modified shear log model, the improvement in Yield strength due to load-bearing effect (\( \Delta \sigma_{Load} \)) can be expressed by [28]

\[
\Delta \sigma_{Load} = \frac{\sigma_{\text{ref}} \varepsilon_{S_r} S_r}{2}
\]

Where \( \varepsilon_{S_r} \) is the aspect ratio of the reinforcements. For particulate reinforcement \( S_r = 1 \) [29]

Orowan strengthening plays very important role in improvement of the yield strength in case of Nano-Composite. Improvement in yield strength due to Orowan-Ash by equation [26]

\[
\Delta \sigma_{Orowan} = \left( \frac{0.13 C_m b}{\lambda} \right) \log \frac{d_r}{2b}.
\]

Improvement in Yield strength due to grain size strengthening can be described by the Hall-Petch equation [30]

\[
\Delta \sigma_{Hall-Petch} = KD^{-\frac{1}{2}}
\]

Where \( K \) is the constant and \( D \) is the grain size of the metallic matrix.

The Yield strength of the magnesium alloy (AZ91) and its composite reinforced with different percentage of SiC particulate are shown in figure 3

The strength of the composite depends on the interfacial bonding between matrix material and reinforced particle. If bonding between matrix and reinforcement is good enough then only magnesium alloy (AZ91) matrix can transfer stress from soft matrix to hard reinforcement SiC particle. The hard SiC particle generally protect softer matrix and so the strength of the matrix increases with increase in volume fraction of the reinforcement

2.2 Ultimate Tensile Strength

The ultimate tensile strength of magnesium alloy (AZ91) was found to be 187.67 MPa, which is higher than SiC particulate reinforced composite.

The UTS of the 3% composite was lower than UTS of the magnesium alloy as shown in figure 4 and the UTS increases as the percentage of reinforcement increases. However UTS of 12% SiC reinforced composite are higher than unreinforced alloy. The difference of UTS in AZ91/SiC composite is due to its processing technique, which is stir casting. For the as cast AZ91 composite UTS usually lower than that of cast AZ91[31] because of addition of any secondary hard phase particle reduces tensile strength. Under the tensile load strong internal stress lead to formation of cracks in secondary phase and particle coated with secondary phase. Both SiC particle and secondary phases are very brittle, so the interface between SiC particle and large secondary phase cannot bear large strain. However as the volume percentage of SiC particle increases, the large secondary phases at SiC particle surfaces reduced significantly and the size of secondary phase were also refined. This lead to the increase in the strength and elongation as the volume fraction of SiC particle increases[32]

The variation in UTS with variation in particle content are shown in figure 4. The highest value of UTS at 12% of SiC particle.

2.3. Vickers Hardness

The Vickers number \((HV)\) is calculated using the following formula:

\[
HV = 1.854(F/D^2),
\]

Micro and macro Vickers hardness were investigated to know the homogeneous distribution of SiC particles within magnesium alloy (AZ91). A rectangular cross-section (15 mm x 30 mm) of each fabricated composite has been used to

![Figure 3. Yield Strength of Magnesium Alloy](image)

![Figure 4. Ultimate Tensile strength with different percentage of SiC](image)
measure the Vickers hardness. The micro Vickers hardness value examined throughout the cross-section at different point of the composite. There is slight variation in hardness value at different point of the cross-section, it shows uniform distribution of SiC particle within magnesium alloy matrix. Figure 5 show the variation in micro hardness value of magnesium alloy (AZ91) reinforced with SiC particle with percentage variation 3%, 6%, 9% and 12%. The microhardness at different position of the sample are different. Figure 5.a show the variation of micro-hardness value at 3% of SiC particulate reinforcement. Figure 5.b,5.c and 5.d show the variation in micro-hardness at volume faction of 6%, 9% and 12% of the SiC particulate respectively.

**Figure 5.** Vickers Hardness Value at different position of the composite (a) 3% SiC in AZ91 (b) 6% SiC in AZ91 (c) 9% SiC in AZ91 (d) 12% SiC in AZ91

**Figure 6.** Comparison of average micro -Vickers hardness of composites with AZ91

**Figure 7.** Comparison of average macro -Vickers hardness of composites with AZ91

**Figure 8.** Tensile facture of the composite (a) 3% SiC in AZ91 (b) 6% SiC in AZ91 (c) 9% SiC in AZ91 (d) 12% in AZ91
The average value of micro-hardness are shown in Figure 6 for different volume fraction of the SiC reinforcement. The micro Vickers hardness value increases on increasing the volume fraction of SiC particulate reinforcement. The figure 7 shows the macro Vickers hardness value at the 3 kgf for different volume fraction of SiC particulate reinforcement. The macro Vickers hardness value also increases on increasing the volume fraction of SiC particle reinforcement.

The higher value of Vickers hardness at 3kgf load indicate that now more number of particle resist indentation. The enhancement in hardness of the composite with increase in volume fraction SiC particle reinforcement is due presence of interactive influence of the SiC particle phase which restrict the localized matrix deformation during indentation.

3. Fracture behavior

The tensile fracture surfaces of AZ91/SiC particulate composite were analyzed by SEM and morphology of fractured surfaces are shown in Figure 8.a -8.d with different percentage of SiC particulates. The Tensile fracture behavior of the magnesium matrix are found as combination of brittle and ductile like features in the cases of AZ91/SiC composites. The dimple size in the fractured surface decreases as the percentage of SiC increases. Fractured surface morphology of the composite also reveal that small size dimple, cracks, shrinkage porosity and cleavage fracture increases with increase in volume fraction of the reinforcement.

CONCLUSIONS

The following conclusions are extracted from the experimental analysis and characterization of AZ91/SiC metal matrix composites.

1. On addition of hard reinforcement the yield strength of the materials (AZ91) decreases but yield strength increases as the percentage of SiC particulate increases. The highest value of yield strength is 105.44 M Pa for AZ91/SiC composites.

2. The ultimate tensile strength is also increases with increase in percentage of reinforcement. The highest value of ultimate tensile strength is 193.96 M Pa for 12% SiC reinforced composite.

3. The micro Vickers hardness value is not uniform throughout the surface of the composite, but the average micro hardness value increases with increase in percentage of SiC particulate in AZ91 metal matrix. The highest value of micro Vickers hardness is 107 HV for 12% SiC/AZ91 composite.

4. The macro Vickers hardness value is higher than micro Vickers hardness because at higher load (i.e.3 kgf) the indentation area was more and in this case more number of the reinforced particle resist indentation.

5. The facto-graphy of the tensile sample reveals that the composite materials is more brittle and less ductile because the dimple was very small in size and more number of cracks and cleavage fracture.

REFERENCES


