CHAPTER- 6

MECHANICAL PROPERTIES

6.1 INTRODUCTION

The strong demand for weight reduction in car and aircraft fabrication urges the optimization of the design of products employing low weight materials. The replacement of conventional materials by lighter metals such as aluminium alloys is, therefore, highly desirable. However, aluminium alloys are not sufficiently stiff or strong for many purposes and their reinforcement is necessary. Aluminium based functionally graded materials (FGMs) are outstanding candidates for these applications owing to the high ductility of the matrix and the high strength of the hard reinforcing phases. The attraction for such materials is also due to very high specific modulus, strength to weight ratio, fatigue strength and wear resistance [125-128]. The presence of reinforcing particles produces very attractive properties non-attainable by other materials [129]. Recent work demonstrated the possibility of producing complex components by using discontinuously reinforced aluminium based FGMs by employing different processing methods such as isothermal forging leading to materials characterized by lower damage levels by controlling the processing parameters such as temperature and strain rate [130-131]. It is clear that it is possible to achieve super plasticity at high strain rates in conventional materials by making a strong reduction in grain size. This can be obtained by using a process such as centrifugal casting, in which the samples are subjected to a severe plastic deformation leading to a strong grain refinement. Al-FGM billets consist of two distinct zones, a particle-enriched zone and a particle-depleted zone that can be routinely obtained by centrifugal casting (CC). The different densities of the particles and the melt cause controlled segregation under the action of the centrifugal force in a manner similar to the segregation observed in sand castings under the influence of a gravitational force. When the centrifuged mixture is solidified, the segregated structure can be preserved in the casting.
The extent of particle segregation as well as the relative locations of the particle-enriched and the particle-depleted zones within the casting are determined mainly by the melt temperature, melt viscosity, cooling rate, densities of the silicon carbide particles and molten aluminum alloy, particle size and the magnitude of the centrifugal acceleration. By proper selection of the above listed processing parameters, the silicon carbide reinforcement content and the distribution across the diameter of the centrifugal casting billet can be adequately varied.

6.2 EXPERIMENTAL STUDIES

6.2.1 SPECIMEN PREPARATION

Prior to the various characterization studies, the shrinkage cavities that were located at the top of all the ingots were first removed. This was followed by sectioning the ingot into 10-mm thick cylindrical shaped specimen along the deposition direction by electrical discharge cutting machine (EDM). The small cutting gap of 0.3 mm produced by the cutting machine aided in maintaining the continuity of the gradient and in reducing wastage. All the specimens required for quantitative assessment of Young’s modulus, ultimate tensile strength, compression strength, yield strength and tensile testing were obtained from the respective 10 mm cylindrical specimens. The specifications for both tensile and compressive tests are shown in the Fig 6.1.

6.2.2 TENSILE TEST

The three test specimens were machined and selected according to the distance from the centre of the ingots (0-10, 10-20 and 20-30 mm). The tensile properties of the materials viz, ultimate strength and ductility were evaluated using a standard 40 ton capacity servo hydraulic universal testing machine shown in Fig. 6.2.
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Fig 6.1: (Tension and Compression specimen)

Fig 6.2: Universal Testing Machine (UTM)

Fig 6.3: Tensile Testing

Fig 6.4: Tensile Al/FGM Specimen after break
In tension test the test specimen is in a direction parallel to the applied load as shown in fig 6.3. In a stress-strain graph the initial portion of the curve is a straight line and represents the proportionality of stress to strain according to Hooke's law and this point is known as limit of proportionality. Beyond this point Hooke's law is not obeyed although the material remains elastic i.e. the strain completely disappears after the removal of load. If the material is loaded or stressed up to this point the material will regain its original shape at the removal of the load. At this point metal yields and on further increasing the load slightly, the strain increases rapidly till the neck is formed. When this point is reached deformation or extension continues even with lesser load and ultimately the specimen brakes or fractures. Elastic limit is the maximum stress that can be applied to the material without producing a permanent plastic deformation when the load is removed.

Yield point is the maximum stress at which the specimen is deformed without a noticeable increase in load.

Ultimate tensile strength is the maximum stress that a test specimen can bear before fracture and is based on original area.

The procedure used for measuring the tensile strength is described below.

- The tension tests were conducted as per the ASTM E8-82 standards.
- The average cross section of the specimen was determined using a micrometer.
- The upper end of the specimen was firmly gripped in the fixed head of universal testing machine using fixing shackles. The specimen was placed such that punch marks faced in front of the machine.
- The extensometer was firmly attached to the specimen so that the axis coincides with that of specimen. The testing machine and extensometer was adjusted to read zero. The lower end of the specimen was gripped taking care not to disturb the fixing of the extensometer.
- Suitable loads were selected in steps of 100 N and strains were noted. The load was applied at low speed taking simultaneous observation of load and strain without stopping the machine.
- The broken specimen was removed from the machine (fig 6.4), and was observed for the failure characteristics. The dimension of smallest section was
measured, the parts were held together and gauge length, length between the shoulders, and diameters was measured.

All calculations were made and a graph of stress v/s strain is plotted. The readings were made to obtain data for plotting a tensile test diagram. This diagram shows the relationship between the force applied to the specimen and its resulting deformation. The ductility of the specimens was evaluated in terms of percentage elongation for both (30μm and 5μm) specimens. Five specimens were tested and an average value of the ultimate tensile strength and ductility are reported. It was found that in all the cases there was just a little scatter in the results and each value did not deviate more than 2% from the average value.

6.3 RESULTS & DISCUSSION

Table 6.1 shows the experimental data of Al/SiC FGMs as a function of distance from the centre of the ingot. Adding SiC to the Al alloy results in increased yield strength, Ultimate tensile strength, Young’s modulus, compression strength and decreased elongation.

**Table 6.1 Mechanical properties of Al/SiC FGMs function of distance from the centre of the ingot**

<table>
<thead>
<tr>
<th>SiC particle size</th>
<th>Distance from base of ingot</th>
<th>Density (gm/cc)</th>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Young's Modulus (GPa)</th>
<th>Compression strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>μm</td>
<td>mm</td>
<td>2.63</td>
<td>146</td>
<td>269</td>
<td>74.2</td>
<td>340</td>
<td>18.5</td>
</tr>
<tr>
<td>30</td>
<td>00-10</td>
<td>2.77</td>
<td>193</td>
<td>310</td>
<td>77.2</td>
<td>396</td>
<td>13.6</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>2.82</td>
<td>213</td>
<td>326</td>
<td>85.2</td>
<td>408</td>
<td>09.2</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>2.62</td>
<td>143</td>
<td>272</td>
<td>73.2</td>
<td>332</td>
<td>16.9</td>
</tr>
<tr>
<td>50</td>
<td>00-10</td>
<td>2.72</td>
<td>182</td>
<td>309</td>
<td>77.8</td>
<td>361</td>
<td>11.3</td>
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<tr>
<td></td>
<td>10-20</td>
<td>2.92</td>
<td>225</td>
<td>331</td>
<td>87.2</td>
<td>421</td>
<td>07.8</td>
</tr>
</tbody>
</table>
6.3.1 DENSITY

The density of the FGMs is plotted in Fig. 6.5 and listed in Table 6.1. Since the density of SiC (3 gm/cc) is higher than that of the Al alloy (2.7 gm/cc), the addition of SiC leads to an increase in the density of the material. The SiC particulate concentration varies from minimum at centre of ingot to maximum at outer side and hence the density is increasing along with distance from the centre of the ingot. Smaller diameter SiC reinforced FGM shows higher density at the centre but lower at outer wall than the larger diameter SiC reinforced FGM. This is due to the larger particulates have more tendency to move in outward direction. Because of this higher SiC concentration, higher will be the density of FGM.
6.3.2 YIELD STRENGTH

Addition of SiC to the Al alloy shows an increasing yield strength as shown in the fig 6.6. The yield strength is increasing along the distance from centre of the ingot towards outer surface. At the centre of the specimen smaller size particulate reinforced FGM shows better results than the larger particulate reinforcement FGM. But towards outer surface of the specimen larger particulate FGMs show better results than the smaller particulate reinforcement.

6.3.3 ULTIMATE TENSILE STRENGTH

The results of tensile test for the three specimens taken from the three regions 0-10mm, 10-20 mm and extreme end of the respective FGMs are shown in Table 6.1. Comparing the UTS obtained from these regions for both the FGMs (30 µm size particle and 50 µm size particle) synthesized, it was found that the UTS of high and low SiC ends are respectively, 330, 325 275 and 265 Mpa, as shown in fig 6.7.
The results of Young’s modulus computations are shown in Fig.6.8. The results reveal significantly different Young’s modulus values at either ends of the two FGM ingots synthesized. For 30 μm SiC and 50 μm SiC reinforcement the Young’s modulus was found to increase as a function of distance from the centre of the ingot.
6.3.4 COMPRESSION STRENGTH

The results of compression strength measurement are shown graphically in Fig. 6.9. The results show an increase in compression strength with an increase in distance from the centre of the ingot for both the FGMs. Moreover, it can be noted that the average values clearly exhibit an increasing trend, although standard deviations for some of the density measurements are large.

![Graphical representation of variation of compression strength of Al/silicon carbide FGMs.](image)

**Fig. 6.9:** Graphical representation of variation of compression strength of Al/silicon carbide FGMs.

6.3.5 DUCTILITY

As for ductility, the results showed a drastically decreasing trend in percentage of elongation with an increase in distance from the base of the ingot for both the FGMs (30 and 50 µm), but the higher particle size reinforced FGM showed drastic reduction in ductility (fig 6.10).
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Fig. 6.10: Graphical representation of variation of ductility of Al/silicon carbide - FGMs.

6.4 FRACTURE STUDIES

In the whole range of FGMs investigated under SEM (fig 6.11), all types of the specimens (three specimens each for both smaller and larger particulate reinforced) exhibit ductile type fracture behaviour. Primary dimples originated from the reinforcement particles, whereas micro-voids of smaller size grew from matrix finer precipitates. From systematic analyses of the broken specimens, it was observed that
the reinforcement particles exposed on the fracture surface were generally broken and are shown in the figures 6.12 and 6.13. Micro-voids were thus considered to form due to reinforcement fracture under load. On the contrary, at higher SiC end the particles exposed on the fracture surface were unbroken and fragments of matrix or of interface reaction products were visible at higher magnification. Particle-matrix interface debonding thus acted as a preferential mechanism of fracture nucleation.

It is well known that under tensile straining condition, the ductility of discontinuously reinforced FGM is heavily affected by the progression of reinforcement damage [132-134]. In addition, a clear correlation exists between the evolution of damage in FGMs and the achievable tensile strength [135]. From current knowledge it is, therefore, supposed that the increase in ductility as well as the slight improvement in strength are brought about by a lower damage sensitivity induced by the high testing temperature. From concurrent analysis of fracture surfaces, it was evaluated that, the rise in ductility at high temperature corresponded to a shift in damage behavior from crack nucleation induced by particle cracking toward formation of voids due to preferential decohesion of reinforcement particles from matrix at interface sites. Experimental data also supported the hypothesis that this trend is time dependent, the mentioned slight increase in strength being systematically observed only at tests at the lowest strain rate.
Fig. 6.12: SEM Fractographs of the FGM (30 μm particulate reinforced FGM)
Fig 6.13: SEM Fractographs of the FGM (50 µm particulate reinforced FGM)
6.5 DISCUSSION

As mentioned above, it was found that the average particle size is gradually distributed in the FGMs fabricated by the centrifugal method, and the average particle size at outer region is greater than that in the inner region. It was also found that the particle size gradient in the FGMs become steeper by increasing the G number or by decreasing the mean volume fraction. In the following, the effects of the G number and mean volume fraction of particles on the particle size distributions are discussed. Obviously, the centrifugal force changes as the position on the cylindrical specimen changes. The motion of particles at each position and the variation of centrifugal force will not be taken into account in this study.

A decrease in elongation towards the outer side of the specimen for both 30 µm and 50 µm particulate reinforced Al/SiC-FGM was observed, while the yield stress, UTS, compression and the Young’s modulus increase with the distance from the centre, which depends on the actual SiC particle size in the matrix. This decrease in elongation is due to the formation of SiC clusters in the outer wall of the composites, when the reinforcement concentration accumulation depends on matrix-to-reinforcement particle size ratio. This critical concentration of reinforcements is higher for the composites containing 30µm SiC particulate, as confirmed by the structural investigations. Among the characteristics studied, the yield strength seems to be least sensitive to reinforcement clustering, since its dependence on the reinforcement content shows the most monotonic trend over the whole range of reinforcement concentrations. A comparison of the data for the FGMs reinforced with 50 µm SiC and 30µm SiC was made. The gradation leads to the conclusion that small SiC particles provide a higher increase in the yield strength and the ultimate tensile strength, while the FGMs containing large 50 µm SiC particles possess higher elongation to fracture and Young’s modulus. The obtained results showed that using reinforcements with small particle size provides higher strength, comparable Young’s modulus and elongation to fracture and obviously better fabricability of the material if the reinforcement concentration does not exceed the critical value. Therefore, it is preferable to use small-size reinforcements for optimization of the properties of the
material where low reinforcement concentrations are sufficient. However, in cases where an increase in Young’s modulus is the main criteria that has to be implemented into the material goal, large reinforcement particles should be preferred, because of the higher critical content of the reinforcements.

The increase in the mean particle size of the reinforcement leads to a poor reinforcement distribution those results in a lowering of the mechanical characteristics. A linear decrease of the characteristic with increasing mean particle size is observed.