Effect of SiCp reinforcement on mechanical properties of Al 6061 by Powder Metallurgy

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Abstract. Silicon carbide reinforced aluminium have been developed since past 3 decades for many structural and automotive applications especially for manufacturing gears due to their excellent characteristics such as light weight, high strength, good wear resistance and other mechanical properties. Gears are transmission components that requires high wear resistance as well as self-lubrication properties while performing the needed operations. The present research elucidates the addition of particle reinforcement with Al6061 with particle size 50 µm and different weight percentages of Silicon carbide (SiCp) such as 3, 6 and 9 for gear blank application. The addition of SiCp with Al6061 enhance its properties and provides prolonged use of gear for many applications. In this study, the gear blank has been produced via traditional powder metallurgy method by adding Zinc stearate as binding agent. The compacted green part was further processed with sintering process with 500°C in muffle furnace. The sintered gear blank was examined for mechanical properties such as hardness and surface roughness according to ASTM standards. The influence of SiCp with Al6061 were evaluated by incrementing the SiCp. It was seen that there was an increase in the hardness showing the dispersion of hard particles SiCp throughout the structure. Further, the surface roughness varied depending on the process and heat treatment of compacted composites. This study gives better understanding about the effect SiCp reinforcement on mechanical properties of Al6061 metal matrix.

Keyword: Al6061; SiCp; Hardness; Surface roughness; Powder metallurgy

1. Introduction
The applications of Metal Matrix Composites (MMC) are growing rapidly throughout many industries such as aerospace, automotive, chemical plants, healthcare, defense, marine and many more. The MMCs are considered as best alternatives for conventional materials because of its unique and enhanced physical, chemical and mechanical properties. Some of the notable mechanical properties such as high elastic modulus, damping capacity, wear resistance, corrosion resistance, and thermal stability are...
possessed by MMCs compared to unreinforced alloys. The tailor made MMCs could add the required properties within it and fulfill the need of industries. One of the best examples of MMC in automotive industry had been experimented in Fiat. Fiat Chrysler Automobiles examined and compared the mechanical properties of Aluminium with sandwich composites and Aluminium metal through conducting and evaluating various tests such as tensile tests, surface roughness measurement, hardness tests, joining mechanisms of composite structures, adhesive properties and failures, metallurgy of cross section. It was proved that mechanical properties and strength of MMCs were superior to that of plain Aluminium [1-3, 14-18].

Exploration of lightweight materials in components which are subjected to high force and stresses is still a challenging task. Aluminium and its alloys are extensively used for light weight and high strength applications because of its lower density. Amongst aluminium alloys, age hardening series (2xxx, 6xxx and 7xxx) are widely used as base matrix alloy as these age hardened alloys have improved mechanical properties through different ageing treatments. Aluminium alloy 6061 metal matrix is a highly used 6000 series in aluminium alloy, in view of its typical properties such as medium to high strength, high toughness, excellent in machinability and workability. Particulate Reinforced Composites are widely used these days because of its easy formability/machinability, lower cost and possibility of further/secondary processing. Addition of particulate reinforcement especially hard ceramic particles with base aluminium metal matrix composites exhibited elevated properties. The unique thermal properties of aluminium composites are metallic conductivity measured as coefficient of expansion can be tailored down to zero, adding to their prospects in aerospace and avionics. [1, 4-6, 19-21]

Silicon Carbide (SiCp) has good affinity with aluminium matrix and can serve as a potential choice for formation of composites in many practical applications in aerospace, automotive and electronics sectors. Extended investigation was performed about abrasive wear study over Al 2014-SiC MMC with 20% weight fraction and 50 μm of mesh size compared with different forms of ductile iron tested with similar conditions in Pin-on-Disc configuration. The investigation proved that composites are having better wear properties comparing with ductile iron. Dunia Abdul Saheb (2011), had conducted a series of experiments by varying the weight fractions of SiC, and alumina (5%, 10%, 15%, 20%, 25%, and 30%). Variations were also investigated in graphite composition (2%, 4%, 6%, 8%, and 10%) containing aluminium as the matrix material. It was observed that there was an increase in hardness with increase in weight percentage of ceramic materials. The maximum hardness was observed at 25% weight fraction of SiC and at 4% weight fraction of graphite. The characteristics of Aluminium matrix composites reinforced by silicon carbide particle (below 74 μm and above 53 μm) through stir casting. The hardness, wear resistance and tensile strength of reinforced material were found to be higher than the unreinforced one. The microstructure studies revealed the presence of some non-uniform distribution and clustering of SiCp. [7, 8, 23]

Some of the MMC fabrication techniques are Stir casting, Spray Deposition, Powder Metallurgy (P/M), Chemical Vapor Deposition, etc. Among the variety of manufacturing processes available for MMCs, powder metallurgy technique is widely accepted as a promising route over other techniques which offers greater precision, rapid, economical and high-volume production, eliminating most or all of the finish machining operations required for castings. P/M avoids casting defects such as blow holes, shrinkage and inclusions. The multiphase composites, non-equilibrium materials such as amorphous, microcrystalline or metastable alloys are also processed by P/M technique. The desired chemical composition for the final product is found to be controllable in Powder Metallurgy. The failure behaviour of Al-SiC MMC was investigated by Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD) for the P/M processed sintered composites. It has been observed that there was an increase in strength, ductility, brittleness of the composites with increase in the temperature. Al–Si alloy prepared by powder metallurgy with different porosity levels to identify the impact of wear properties during material removal. The amount of porosity, shape and sizes of pores have influence during material removal. It has been observed that the wear rate increases with surface porosity while experimenting dry sliding wear behaviour with AISI 52100 bearing steel ball. Aluminium based MMC reinforced with 1% wt of Mg and with/without adding 1% of lubricant Acrawac has showed that the addition of lubricant Acrawac provides reasonable green density of compaction of the specimens. [9-13, 22, 24-25]
Most of the earlier investigations had concentrated on fiber reinforced polymer composites characterization, gear manufacturing and performance testing. Only a few researchers had shown interest in developing a specimen based mechanical property characterization of aluminium MMC. The main objective of this research work is to investigate the effect of the addition of silicon carbide particle reinforcement with base aluminium alloy for the suitability of light weight spur gear production with higher production rate dealing with the development and mechanical testing of Al/SiCp spur gear blank using powder metallurgy technique.

2. Materials and Methods

2.1. Materials

Initially, a MMC material spur gear blank was fabricated using Aluminium metal powder and silicon carbide reinforced particle with various wt. % of 3, 6 and 9 with grain size of 50 μm. From the literature survey, the reinforcement percentage is limited with 3, 6 and 9 wt. % in order to find out workability, green part strength and collapsibility, matrix-reinforcement grain attachment, density deviation, formability nature. Increasing the weight fraction of reinforcement may make the composite as brittle due to hardness properties of SiC [16]. The wear behaviour of gear blank will be affected in case of excessive weight fraction of reinforcement. Particle size is one of the influencing factor for the outcome of green part such as yield strength and other characteristics, a decrease in particle size increases the production difficulty. There is a possibility of undesirable clustering of particles. At the same time increase in particle size may affect the performance of the composite. Considering these factors in this research, grain size of 50μm was selected to make gear blank. The properties of aluminium powder and silicon carbide powder used in experiments are tabulated in Table 1. Zinc stearate with properties given in Table 2 was applied as lubricant for improving bonding between the powders. Zinc stearate is frequently used as metallic lubricants for minimising compaction tool wear through the reduction of ejection force. Aluminium powder (99.7 wt. % of Al, 0.17 wt. % of Fe and 0.1313 wt. % of Si), 50 μm ceramic SiC particles (SiCp) of 3, 6 and 9 wt. % and 1 wt. % of zinc stearate were homogeneously mixed.

| Sl.No. | Properties         | Al  | SiC |
|-------|--------------------|-----|-----|
| 1     | Young’s Modulus (GPa) | 71  | 414 |
| 2     | Poisson’s ratio     | 0.345 | 0.192 |
| 3     | Density (kg/m³)     | 2700 | 3145 |
| 4     | Melting Temperature (°C) | 660 | 2700 |

| Sl.No. | Properties         | Unit |
|-------|--------------------|------|
| 1     | Density (kg/m³)    | 1095 |
| 2     | Melting Temperature (°C) | 130  |

EN24T was considered as die material to fabricate spur gear blank in this research due to its excellent high load bearing capacity. EN 24T is a surface hardened alloy steel which extensively applied into wear resistance and load bearing conditions.

2.2. Die modeling and fabrication

A simple type of press die was considered in this research for making spur gear blank. The 3D CAD model of die mentioned in Fig.1 (with detailed description in Fig. 2) was designed through CATIA V5.0. The specifications of punch – die is mentioned in Table 3.
Table 3. Die Specification

| Male die (Punch)          | Female die (Hole)          |
|---------------------------|---------------------------|
| Height: 45mm              | Height: 20mm              |
| Outer Diameter: 50mm      | Bore diameter: 20mm       |
| Punch diameter: 20mm      | Outside diameter: 50mm    |
| Punch height: 19mm        |                           |

Figure 1. Male and Female Die Design

Figure 2. Die drawing description (All dimensions are in mm)

The P/M process for manufacturing the gear blanks have been done by following process flow:

1. Sieve Analysis
2. Powder Blending
3. Compacting
4. Sintering
5. Testing
2.3. Sieve Analysis

The sieve analysis is initial step for the preparation of the powder for the powder blending. It is a general procedure to segregate the sizes of granular particles. The distribution of powder particle in the material influence its behaviour. Sieve analysis is performed to remove the particles of greater size.

2.4. Powder Blending

Powder blending in P/M is the process of mixing of composite powder particles together homogeneously. In this research, the 50 µm particle size of Al 6061 and SiCp are mixed together for homogeneity of gear blank material. The homogeneity of composite powder was exhibited in the final gear blank with uniformly distributed physical and mechanical properties. The composite powder was blended together for 2 hours for homogeneous distribution of reinforcement throughout out the matrix. After power blending was done the composite powder further proceeded to power compaction. The powder blending process was mentioned in Fig.3.

![Figure 3. Powder Blending](image1)

2.5. Powder Compaction

The powder that has to be compacted was taken and filled in the cavity of the die in which the compaction has to be performed. The quantity of powder that has to be filled in the cavity of the die was decided by the calculation made with the help of the density of the material and the volume of the component made. Density of the green part formed from the compacting process depends on the amount of load that was applied during the compacting process. In this work, the load of about 50 tons was applied for making every green part. The surface finish of the component is dependent on the surface of the die cavity. Ejection of the green part from the cavity is very important. The ejector system should be properly designed so that the component will be ejected properly from the die cavity without any damage to the green part.

![Figure 4. Powder Compaction](image2)
2.6. Sintering Process

The compacted powders were ejected carefully from die and the green part of gear blanks were further moved to sintering process. The sintering has to be done by keeping the ceramic material at the base of the part that has to be sintered. The green part which came as the final output of the compaction process has less strength. In order to improve the mechanical properties and hardness, the green part has to be sintered. In this work, sintering was performed with the help of muffle furnace. The furnace should be a closed type to avoid the atmospheric reactions. Sintering should be done at the temperature of about 80% of the melting point of the material that has the lowest melting point. Among the materials, Aluminium has the lowest melting point. So, the sintering temperature has been selected as 500°C. Sintering is done by heating the green part to the temperature of 500°C and then need to maintain the temperature for about an hour. After that it has to be cooled in the furnace itself in the steady rate. The sintered part will be of high strength and was ready for the examination. During sintering process, the green parts were placed in the muffle furnace. Gradually the temperature of the furnace was increased. This temperature was maintained for nearly one hour and then it is allowed to cool slowly in the furnace. The complete cooling of the sample will take nearly around 20 hrs. Fig. 5 shows the sintering process.

3. Mechanical Testing

Mechanical characterization was carried out using the developed material to verify the mechanical properties such as hardness, toughness, wear resistance and strength. The mechanical behaviour of Al/SiCp spur gear blank was evaluated by hardness and surface roughness as per ASTM standards. The Rockwell hardness number was evaluated (ASTM E18) using sintered Al/SiCp spur gear blank samples.

3.1. Hardness test

In this work, Rockwell hardness has been chosen for conducting the hardness test. Based on the matrix material i.e. Aluminum, 1/16” ball indenter, and hardness scale as ‘B’ were chosen. 100 kg was selected as the applied load as per the matrix material. The following steps were taken to find the Rockwell hardness number,

- 1/16” ball indenter was fixed in the hardness tester. Then, gear blank sample was placed. Load was applied manually using a lever given in the bottom side of tester. The loading was made till the inner small dial came to the 3 indicated by red dot.

- Then, the gear blank was loaded automatically by operating the lever provided in tester due to which dial showed some fluctuation. When the dial came to the rest position, gear was unloaded slowly; this again caused fluctuation in the dial. Dial position gave the Rockwell hardness value for the respective component. Similarly, these steps were followed for the rest of the gear blanks. Hardness value was noted and tabulated in Table 4. Fig.6 indicates hardness measurement of gear blank.
3.2. Surface Roughness measurement

Surface roughness measurement is used to identify the nature of surface as an outcome of fabrication or machining or forming process. In this work, the surface roughness was measured by using the surface roughness tester called Surfcorder. The surface roughness tester has an adjustable probe which will be extended and retracted. The component whose surface roughness has to be measured was kept in the probe side. The surface tester should be placed in the same height as that of the component. Then the surface tester was switched on and the probe travels along the surface of the component. The irregularities in the surface or the roughness of the surface were measured by the probe and then the values of the roughness were plotted as the graph. Then, the value of the roughness was displayed. Fig.7 indicates the surface roughness measurement and surface roughness values are mentioned in table 5.

| Samples              | Hardness (HRX) |
|----------------------|----------------|
|                      | Trial 1 | Trial 2 | Trial 3 |
| 3% sic composition   | 81      | 80      | 86      |
| 6% sic composition   | 97      | 93      | 100     |
| 9% sic composition   | 110     | 112     | 114     |

**Figure 6.** Hardness measurement of gear blank

**Figure 7.** Surface Roughness measurement
4. Results and discussions

4.1. Effect of SiCp addition with Al 6061 on hardness

Figure 8 shows the effect of the compaction pressure and the addition of SiCp content on Rockwell hardness value. The result shows that hardness increases with the increase in amount of silicon carbide added to the aluminium. The given compaction pressure 50 tons developed the closely packed and high densification material during pressing. This resulted in high diffusion bonding and higher vacancy emission from the pore due to dislocation climb during the controlled sintering. The addition of SiC content with base aluminium also contributed to the improvement in hardness to some extent. The grain refinement effect on hardness value can be observed from the Figure 8. The finer grain size builds up the higher hardness material composition. The same effect was revealed in the P/M processed Al-SiCp spur gear blanks. 3% SiC with Al has shown less hardness, 6% SiC with Al has shown improved hardness values whereas 9% SiC has shown better hardness values than other compositions. It is clearly visible from the results that adding hard ceramic particles with aluminium highly influences the hardness values.

| Samples          | Surface roughness (Ra) µm |
|------------------|---------------------------|
|                  | Trial 1   | Trial 2   | Trial 3   |
| 3% sic composition | 2.432    | 2.7      | 1.391     |
| 6% sic composition | 1.89     | 0.168    | 0.498     |
| 9% sic composition | 1.327    | 1.94     | 0.941     |

**Table 5. Surface Roughness measurement**

**Figure 8. Hardness measurement**
4.2. Surface roughness measurement

Figure 9 shows the effect of the compaction pressure and sintering behaviour with the addition of SiCp content on Surface roughness value. The result shows that the surface roughness decreases with the increase in amount of silicon carbide added to the aluminium. The addition of SiC content with base aluminium also contributed to the improvement in roughness to some extent. The grain refinement effect on surface roughness value can be observed from the Figure 9. It also depicted the surface nature of sintered parts and the need of further surface treatment to obtain good surface properties. There was a drop of surface roughness values with addition of SiC ceramic particles with aluminium.

5. Conclusions

The Al/SiCp MMC net shaped spur gear blank produced using the P/M technique had been produced successfully with minimum material loss. Initially, the die was designed and produced using EN24T material. SiCp was added with Al 6061 in different weight percentages such as 3%, 6% and 9% and particle size was considered as 50 μm. Then, the sequence of P/M processes had been performed with specified process parameters. The load of 50 tons was given during compaction process and sintering has been done at a temperature of 500°C using muffle furnace. The effect of SiCp with aluminium was measured with mechanical properties of gear blanks. Hardness test and surface roughness measurement was carried out as per ASTM standards. The result obtained from the P/M process indicates the influences on the improvement in physical and mechanical properties of Al/SiCp spur gear blanks from the addition and grain refinement of SiCp. The increase in SiCp content showed a tendency to enhance hardness of gear blanks. It was seen that Al + 9% SiCp 50 μm compacted at 50 tons has higher properties than other compositions. The gear blank will be further processed for gear hobbing in future. The effectiveness of SiC reinforcement in Al 6061 matrix with respect to properties are as follows:

- The Al/SiCp of 9 wt. % and 50 μm size SiCp compacted had showed the highest the hardness of 114HRc, which was higher than that other compositions.
- The Al/SiCp of 9wt. % and 50 μm size SiCp compacted had showed good surface finish with the lowest surface roughness compared with other compositions.

6. References

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