Mechanical and Tribological Characteristics of the AMC, Prepared by P/M Route along with Thermo-Mechanical Treatment

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Abstract. Thermo mechanical treatments have the ameliorated impacts on the mechanical and tribological properties of powder metallurgy components. In this investigation an aluminium matrix composite (AMC) {Al (92) + Mg (5) + Gr (1) + Ti (2)} has been prepared by following powder metallurgy technique, with double axial compaction and ulterior sintering. Secondary thermo-mechanical treatment i.e. hot extrusion through mathematical contoured cosine profiled die was considered. The die causes minimum velocity relative differences across the extrusion exit cross-section, which provides smooth material flow. Comparative result analysis for the mechanical and tribological characteristics of the specimen before and after extrusion was concentrated. Extrusion engenders significant amount of improvements of the properties those are attributed to excellent bond strength and uniform density distribution due to high compressive stress. Oxidative and delaminated wear mechanisms were found predominating type. To furnish the suitable explanation scanning electron microscopies have been performed for the wear surfaces.

Keywords: AMC, Extrusion, Powder Metallurgy, Wear.

1. Introduction

Light weight high performance materials have the substantial implications in the automotive, aerospace, hand hold tools and sports sectors. Aluminium matrix composites (AMCs) in the above segment of materials was been severely commercialized to fulfill the advanced needs [1]. Among different methods of manufacturing, powder metallurgy (P/M) route suits good for its own advantages like apparently infinite compositional possibilities and uniform distribution of the proportions [2, 3].

A significant amount of investigations have been acquitted to investigate the results of different ceramic reinforcements in different aluminium series of powder matrix [4, 5]. Aluminium possesses poor wettability with ceramic reinforcements so as to improve bond strength as well as distribution, the P/M component is provided a secondary thermo-mechanical treatment. These secondary treatments like forging, extrusion [6] etc. helps to improve its mechanical as well as tribological properties [5, 7]. Addition of graphite improves the tribological property by minimizing interface friction with compromising hardness, flexural strength [8-10].
This research area has influenced the investigators to tailor different properties of the composite by altering the compositions with their proportions and types of manufacturing process [11]. During preparation of the specimen particles get oxidise around its surface. This oxide layer breaks due to the higher shear stress, induced by the implementation of secondary treatments which leads to the formation of strong microstructural bond [12]. For extrusion of P/M specimen, shear faced dies does not perform well in concern to flow characteristics and surface properties. Hence a mathematical contoured die is used for the extrusion operation.

Here in this research one composition has been selected for manufacturing the component by P/M route and subsequent secondary thermo-mechanical treatment: extrusion. The improvement of properties after extrusion has been investigated.

2. Methodology followed

2.1. Specimen preparation

The composition selected for the specimen preparation is in weight percentages of Al (92) + Mg (5) + Gr (1) + Ti (2). The composition was blended uniformly in a centrifugal blender. At 200 RPM, the stainless balls and powder (in a weight ratio of 10:1) were revolved for 10 hours. Apparent density and tap density were checked before the cold compaction, conducted by double axial compaction method. The blend was compressed at 275 MPa in a cylindrical die with low rate of pressure rise and accorded for ten minutes of dwelling period. Green specimens were sintered in an argon atmospheric tubular furnace. Dwell periods of 20, 30, 90 minutes at 110°C to evaporate water vapour, 450°C to gasify zinc stearate lubricant, 590°C to form the metallic bond were maintained respectively.

2.2. Secondary processing

Sintered specimens of 10 mm diameter were extruded through a mathematical contoured die profile. The contour plot is shown in Figure 1. The cylindrical specimens were extruded at an operating temperature range of 400-450°C, to square cross-section. For composite extrusion shear faced die are not suitable, therefore a specially designed cosine profiled die was implemented to minimize the surface defects. Figure 1 shows the cross sectional change of the die as cosine profile, presented in one quarter-circle. By considering the generated coordinates of the die profile, three dimensional die has been manufactured indigenously.

2.3. Mechanical and tribological characterization

Different densities like apparent and tap density, green and sintered density, theoretical and extruded densities were measured. By the relation mentioned in Equation 1, theoretical densities were checked.

\[ \rho_{\text{Theoretical}} = \sum (\rho_i \times m_i) \]  

(1)

Where \( \rho_i \) and \( m_i \) are the density of each constituent and the mass fraction of each constituent respectively.

The solid body’s densities were measured by adopting Archimedes’ principle mentioned in Equation 2.

\[ \rho_{\text{Sample}} = \frac{W_A \times \rho_f}{W_A - W_f} \]  

(2)

Where \( W_A \) represents the mass of the solid specimen measured at atmospheric condition, \( W_f \) and \( \rho_f \) are the mass and density of the fluid chosen respectively.

Vicker’s hardness number in micro scale was determined the both sintered as well as extruded specimen. To determine the number, 50 grams of load through a pyramidal diamond with 136° of face angle was applied on the polished surface for a dwell period of 15 seconds.

Transverse rupture strength (TRS) of both the specimen were determined by 3-point bend test. Ram rate of 2 mm/min for the span of 30 mm specimen was maintained during the test in the universal testing machine Instron -5979.
The prepared specimens were subjected to two-body pin-on-disc type wear testing setup for the investigation of dry sliding wear characteristics. The cylindrical pins of diameter $\Phi 10$ mm and height 25 mm with two parallel surface were prepared. Specimen holder carries the stationary pin vertical to the horizontal counter disc surface. The EN-31 counter disc (60 HRC) has a surface roughness in average of 2 $\mu m$. The schematic of the wear testing setup is presented in Figure 2. Each experiment was conducted for a time duration of ten minutes. The pin (specimen) was weighed with an average accuracy of 0.1 mg for determining the weight loss due to wear.

3. Results and discussion

3.1. Physical characterisation

Physical attributes of the powder particles has the influence on flowability, hence strength and tribological performance get affected. Among different popular techniques like sieve analysis, LASER diffraction and microscopy along with image analysis the latter one is used to determine Particle size. Scanning electron microscopy (SEM) images shown in figure 3 depict the shape. The selective informations of different powders are detailed in Table 1.

| Powder type | Supplier     | Average size | Particle shape            | Purity / Assay (%) |
|-------------|--------------|--------------|---------------------------|--------------------|
| Al          | Loba Chemie  | 45 $\mu m$   | Spherical or sub-rounded  | 98.0               |
| Mg          |              | 140 $\mu m$  | Flakey                    | 99.0               |
| Graphite    |              | 20 $\mu m$   | Rounded and Flakey        | 98.0               |
| Ti          |              | 85 $\mu m$   | Extreme angular           | 98.0               |

Different densities like bulk density or apparent density and tap density were directly recorded. Nearly 30-35% enhancement of density occurs due to tapping, depicted in the Figure 4, and indicates good flow ability of the blend. Good consolidations of blended particles in green specimens were observed at 275 MPa of compaction pressure. Effect of sintering in terms of shrinkage or growth was ascertained by the non-dimensional densification parameter presented in Equation 3.

\[
\text{Densification parameter} = \frac{(\text{sintered density} - \text{green density})}{(\text{theoretical density} - \text{green density})}
\]  

Equation 3

Shrinkage and swelling or growth were affirmed by Positive and negative densification parameter respectively. The specimens here possess swelling behavior. Thermo-mechanical treatment (extrusion) causes improved density which can be calculated by the relation illustrated in Equation 4.

\[
\text{Density improvement due to extrusion} = \frac{\text{extruded density} - \text{sintered density}}{\text{sintered density}}
\]  

Equation 4
50% dimensional reduction causes 15-20% of density improvement here, still lesser than the theoretical density, discernible in Figure 4. Densification factor, improved density, and porosity are tabulated in Table 2.

![Figure 3. SEM of (a) Al (b) Mg (c) Graphite and (d) Ti powder.](image)

### Table 2 Porosity analysis.

| Parameters                                | Data     |
|-------------------------------------------|----------|
| Calculated densification factor           | -0.742   |
| Improvement of density after extrusion (in %) | 17.35    |
| Porosity of the sintered specimen (in %)  | 22       |
| Porosity after extrusion (in %)           | 8.53     |

3.2. Mechanical characterisation

Considering the ram rate of 3 mm/min compression test of the specimen was carried out at room temperature condition in the Instron-setec series UTM. The average ultimate stress found is 381MPa depicted from the stress versus strain plot conducted for three different tests shown in Figure 5.

![Figure 5. Stress versus strain.](image)

![Figure 6. Transverse rupture strength.](image)
The average hardness found from ten readings taken at different locations of both sintered as well as extruded specimen were 80 HRV and 110 HRV respectively. The hot working causes the storage of large thermal and internal stresses that establish improved properties. In loosely packed sintered specimen the TRS is very low as shown in Figure 6, which could be attributed to the stress concentration around the large titanium particles as well as presence of porosity.

3. 3. Microstructural analysis
Scanning electron micrographs of the thermo-mechanical treated specimen at different magnifications are presented in Figure 7. Secondary operation causes the improved density by minimizing porosity and creates a well dispersion in the matrix phase. The irregular and angular shape of Ti is very suitable for the improved bond during plastic deformation. Distribution of Ti and graphite powders in the matrix is very fine and appears to be homogeneous.

![Figure 7. Microstructure of the specimen after thermo mechanical treatment.](image)

3. 4. Wear analysis
Two-body dry sliding wear test was conducted for the specimen before as well as after extrusion. By considering three variables such as normal load, track diameter and revolution per minute of the disc in three levels as in Table 3, wear rate in terms of mass loss was analysed through L₉ orthogonal array. The mass loss in a run is converted to volume loss per sliding distance and the same is plotted in Figure 8 for two types of specimen comparatively. It was observed the wear rate is reduced by the implication of secondary treatments to the P/M specimens. The improved bond strength avoids the erosion of the pin material and consequent three body wear [10].

![Figure 8. Wear rate for L₉ array.](image)

Table 3 L₉ orthogonal array adopted for wear characterization.

| Run   | Normal Load (N) | Track Diameter (mm) | RPM of the counter disc |
|-------|-----------------|---------------------|-------------------------|
| 1     | 20              | 50                  | 200                     |
| 2     | 20              | 70                  | 400                     |
| 3     | 20              | 90                  | 600                     |
| 4     | 40              | 50                  | 400                     |
| 5     | 40              | 70                  | 600                     |
| 6     | 40              | 90                  | 200                     |
| 7     | 60              | 50                  | 600                     |
| 8     | 60              | 70                  | 200                     |
| 9     | 60              | 90                  | 400                     |

FESEM images of arbitrarily chosen weared surfaces were captured. Figure 9 (a) run-2 (b) run-7 (c) run-2 for extruded sample and (d) run-7 for extruded sample is presented below. It was observed delamination as well as combination of three such as abrasion, delamination and adhesion is the
predominating mechanism of wear for high velocity and heavy loading conditions. Shear deformation of the surface occurs by the continuous sliding over the crack. Presence of graphite as a solid lubricant at the tribo-interface minimizes friction and wear. Presence of porosity causes severe erosion, crack formation and fracture of the specimen.

![Wear morphology](image)

**Figure 9.** Wear morphology.

4. Conclusion
Effect of thermo-mechanical treatment on the P/M specimen was analysed successfully. There observed a significant enhancement of mechanical as well as tribological properties due to the thermo-mechanical treatment considered as secondary operation. Very less amount of surface defects due to smooth flow characteristics caused by cosine die extrusion made the specimen stronger. Presence of fine graphite particles ameliorates the tribological properties by compromising with strength marginally. A motley type of wear i.e. oxidative, adhesive, delamination as well as abrasion is predominant in the AMC surfaces.

5. References
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