Enhanced tensile, hardness and wear behaviors of pure aluminum matrix reinforced with steel chips via powder metallurgy technique

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Abstract. The mechanical properties and wear behavior of aluminum matrix reinforced with steel machining chips was investigated. Pure aluminum was reinforced with 5, 7.5, and 10 wt% steel chips with an average size of 100 μm using powder metallurgy technique. Aluminum reinforced with 5 and 10 Wt.% SiC particles were manufactured for comparison. The investigation showed clear evidence that the addition of steel machining chips resulted in significantly low porosity levels in the aluminum matrix composites compared with the use of SiC as reinforcement. The mechanical properties (tensile and hardness) as well as the wear resistance were also observed to improve with the use of the steel machining chips as reinforcement. The results demonstrate the capability of steel machining chips to act as efficient reinforcing material and a reliable cost effective candidate in the development of aluminum matrix composites.

1. Introduction
Although aluminum reinforced with ceramic particulates enhances the tensile strength, still suffer from inadequate ductility [1, 2]. In order to achieve a higher strength and retain ductility of the composite, nano-sized ceramic particles are often used resulting in a metal matrix nano-composite [3, 4]. Many applications require components to be made with materials possessing light weight, high tensile and wear resistance as well as maintaining microstructure stability and high temperature resistance. For such applications requiring these highlighted complicated blend of properties, aluminum matrix composites have been found to be the most promising engineering material for selection. The development of aluminum matrix composites has relied on the use of ceramic reinforcements with silicon carbide and alumina the most commonly utilized due to their high hardness and wear resistances, refractory nature, relative availability and adequate cost [5-7].

The choice of steel machining chips as reinforcement in the current research was based on economic, environmental and metallurgical considerations. Steel machining chips is an industrial machine shops waste with very low cost implications. From a Mechanics point of view, the high deformation strains underlying chip formation causes chip microstructures to form an ultrafine grained microstructure which imparts significantly high strength to the chips with several higher magnitude than that of the bulk material [8-10]. Thus, it has the potential of improving the strength of a relatively softer matrix through load transfer from the matrix to the dispersed chips. At present, the use of steel machining chips as reinforcements in metal matrix composites has attracted very little
interest. The present work evaluates the mechanical properties and wear behavior of aluminum matrix composites reinforced with steel machining chips via powder metallurgy technique.

2. Materials processing

The composite powders were fabricated from pure aluminum 99.7% with particle size average of 75µm. The steel chips used were discontinuous chippings from milling of medium carbon steel. Sieving of the chips was performed and chip size range of 100µm was obtained to manufacture the composites. SiC powder with an average particle size of 30 µm was used to manufacture the control composites for good dispersion and mixing with the matrix material.

The powders were fabricated through mixing under argon atmosphere using a TURBULA Shaker for 1 hour at 96 rpm. This was followed by ball milling of the mixed powders under argon atmosphere in stainless steel jars containing 5 mm and 10 mm stainless steel hardened balls using the RETSCH 400MA high energy ball mill. The milling speed was maintained at 300 RPM. The ball-to-powder ratio (BPR) was 15:1, while the milling time was 3 hours. Consolidation of the milled powders were green compacted in a die under pressure of 475MPa for 1 hr at room temperature followed by sintering at 500°C for 1hr and hot extrusion at 4:1 extrusion ratio as shown in figure 1. The produced rods were air-cooled down to room temperature. The extruded rods were 10mm in diameter and approximately 100 mm long, as shown in figure 2.

Density was measured using Mettler Toledo densitometer. The hardness of the composites produced was evaluated on a Vickers hardness testing machine using 50 Kgf over dwell time of 15 seconds. Hardness of the pure aluminum and composites was measured on sections cut perpendicular to the extrusion direction. Hardness value measurements were carried out at room temperature. Five hardness indents were made on each specimen. The tensile properties of the composites were evaluated at room temperature using an Instron universal testing machine. The test was conducted at a strain rate of 0.1 mm/min. The testing procedure and basis for determination of the tensile properties were in accordance with the specifications of ASTM E8M-04 standard [11], as shown in ‘figure 2’.

![Figure 1. Manufacturing Setup.](image1)

![Figure 2. Billet, Extrudate and Tensile Test Specimen.](image2)

3. Density measurements

Table I, shows the theoretical and experimental densities for the manufactured composites as well as the percent porosity. It is observed that the composite densities are generally higher than that of the
unreinforced aluminum, and that density increases with increase in the weight percent of the steel machining chips. This is expected as the density of steel (7.81 g/cm³) is higher than that of aluminum (2.71 g/cm³). It is also clear that the addition of steel machining chips in aluminum minimizes the porosity level in the aluminum matrix composites compared with the use of SiC as reinforcement. This can be attributed to the ductile behavior of the steel chips compared to SiC (brittle ceramic material) that incorporates high levels of deformation during the powder compaction, consolidation and hot extrusion which increases the grain refinement levels for both the aluminum and steel particulates and consequently reducing the porosity percentage.

Table 1. Density values and porosity percentage for the unreinforced aluminum and composites.

| Sample composition | Theoretical density (g/cm³) | Experimental density (g/cm³) | Porosity (%) |
|--------------------|-----------------------------|------------------------------|--------------|
| Al-0wt.% steel chips | 2.71                        | 2.67                         | 1.47          |
| Al-7.5wt% steel chips | 2.74                        | 2.71                         | 1.09          |
| Al-10wt% steel chips | 2.74                        | 2.72                         | 0.73          |
| Al-10wt% SiC      | 2.66                        | 2.63                         | 1.12          |
| Al-5wt% SiC      | 2.64                        | 2.61                         | 1.13          |

4. Mechanical properties

Table 2, represents the tensile properties of the composites derived from the stress–strain curves. It is observed that the 10 wt.% steel machining chips reinforced aluminum composite has the highest yield tensile strength with adequate percent elongation compared to the control samples. The increase in tensile properties accounts for the good bond between the aluminum matrix and the steel machining chips, which allows for the transfer and distribution of load from the matrix to the stronger (higher yield and ultimate strength than aluminum) reinforcement. The improved ductility is due to the higher plastic strain capacity which is significantly enhanced by the good matrix/reinforcement interface bonding and the retained ductility of the steel chips reinforcements is also a clear phenomenon accompanying powder metallurgy technique.

Table 2. Tensile properties of the unreinforced aluminum and composites.

| Sample composition         | Yield Strength (MPa) | Elongation (%) |
|---------------------------|----------------------|----------------|
| Al-0wt.% Steel Chips      | 110                  | 28             |
| Al-7.5wt% Steel Chips      | 176                  | 25             |
| Al-10wt% SiC              | 220                  | 20             |
| Al-10wt% Steel Chips      | 260                  | 17             |
| Al-5wt% SiC               | 161                  | 10             |
| Al-5wt% SiC               | 134                  | 13             |

Figure 3 shows the hardness of the different composites produced. The hardness of the pure aluminum matrix composites is observed to increase with increasing the weight percent of steel machining chips. The hardness of the pure aluminum reinforced with 5 and 10 wt.% SiC particles serving as the control sample had hardness records slightly lower than that of the steel chips reinforced
composite. This can be due to the relatively low percent porosity of the steel machining chips composites compared with the SiC reinforced aluminum composites.

![Composite Hardness Graph](image)

**Figure 3.** Vickers hardness results of the unreinforced aluminum and composites.

5. **Wear behavior**

The wear behavior of the composites was evaluated using a rotary platform Taber abrasion machine. The samples were placed on the abrasion machine rotary platform and gripped with a constant pressure. The rubbing action between the sample and the abrasive wheel during the rotating motion of the machine, results in the generation of loose composite debris from the sample surface. The wear index is calculated by measuring the loss in weight in milligrams per thousands cycles of abrasion. The lower the wear index, the better the abrasion resistance [12].

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\text{Wear Index} = \frac{(\text{Initial sample weight} - \text{Final sample weight}) \times 1000}{\text{Test cycle time}}
\]

![Wear Index Graph](image)

**Figure 4.** Wear index of the unreinforced pure aluminum and composites produced.

Figure 4 shows that the wear index increases with the increase in the weight percent of the steel machining chips but highest with the SiC reinforced aluminum matrix composite. Iglesias et al. [10] reported similar wear pattern in zinc aluminum based alloys reinforced with steel machining chips; where a high integrity interface observed between the metallic matrix and the steel chips serving as barriers to chip pullout and damage during wear. The high wear rate observed with the SiC reinforced
aluminum matrix composites can be attributed to the relatively poor matrix/SiC particulate interface bonding which may facilitate the abrasive wear of the composite. Also SiC is a very brittle (ceramic) material that may suffer from fragmentation due to the rotational abrasive force applied.

6. Conclusions
1) The current work can underline the feasibility of incorporating steel machining chips as reinforcement in aluminum matrix composites as well as holding promises to improved mechanical properties.
2) The tensile, hardness and wear behavior of pure aluminum matrix composites reinforced with steel machining chips have been investigated in comparison with that reinforced with 5 and 10 wt.% SiC particulates.
3) The addition of steel machining chips in aluminum was found to minimize the porosity level in the aluminum matrix composites compared with the use of SiC as reinforcement.
4) The pure aluminum matrix strength was observed to improve with increasing the steel machining chips wt.% as reinforcement with a retained ductility levels compared to that with the SiC reinforcements.
5) The hardness values were also observed to improve with the use of the steel machining chips as reinforcement.
6) The wear rate increases with the increase in the weight percent of the steel machining chips but highest with the SiC reinforced aluminum matrix composite.

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