# Composite Materials of Aluminium/Granulated Slag and Aluminium/Arc-Furnace Dust Prepared by Powder Metallurgy Techniques

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**SUMMARY:** The present document provides preliminary results of aluminium metal matrix composites reinforced with granulated slag and electric arc furnace dust. The composites were synthesized using powder metallurgy techniques. Green density of the compacts was determined as a function compacting pressure and reinforcing particles weight per cent. Sintering experiments suggest good densification in Al/granulated-slag composites and slight densification in Al/electric-arc-furnace dust composites. The hardness and compressive strength of the sintering compacts was determined in order to compare the mechanical properties of the composite material as a function of the granulated slag and electric arc furnace dust content. At present, the best results concern the Al/granulated-slag composites, reaching compressive strengths up to 370 MPa.

**KEYWORDS:** recycling, sintering, Al/Granulated-slag composites, Al/EAF-dust composites, hardness, compressive strength.

## INTRODUCTION

At present metal matrix composites (MMCs) have been developed to a level of commercial production. Potential users of Al-reinforcing particles composites are expected to be the automotive industries. However, the high cost of many of the reinforcing compounds remains as the major barrier in the widespread use of composites in other applications. A possible way to avoid this handicap would be the employment of particles obtained from the recycling of some solid industrial wastes. This idea is becoming popular and several works have been done with fly-ash, glass and other by-products [1].

Thousands of tons of slag and electric arc furnace (EAF) dust are generated in metallurgical plants each year. Tighter environmental regulations have prompted industry to search new methods of treating waste by-products generated by electric arc furnace during the manufacture of steel. Slag and EAF dust (EAFD) are generated during the manufacture of steel via the smelting of scrap metal. EAFD is considered a hazardous solid waste since it contains small amounts of Pb, As and Cr oxides which are formed at high temperatures above the steel bath and in the off-gas systems. Because of the large quantities of slag and dust produced and the present inappropriate manner in which it is discarded, better methods of

treating this waste or new applications are required. Among the possible utilization of granulated slag (GS) and EAFD, we proposed a method based on the recycling and use of these solid wastes as reinforcing particles in metallic, ceramic and polymer matrices [2]. The present article exposes preliminary results concerning on the synthesis and properties of Al/GS and Al/EAFD composites, based on powder metallurgy techniques and having the potential of becoming a low-cost MMC material.

## EXPERIMENTAL PROCEDURE

Commercially pure (99%) aluminum needles supplied by Sigma-Aldrich were used in this research. Slag and EAFD were received from a steelmaking industry. Aluminium needles and slag were mechanically grounded using a ball-milling drum. Aluminium powder, GS and EAFD were mixed using a rotating drum blender. Hexane was incorporated during the aluminium milling process in order to reduce oxidation.

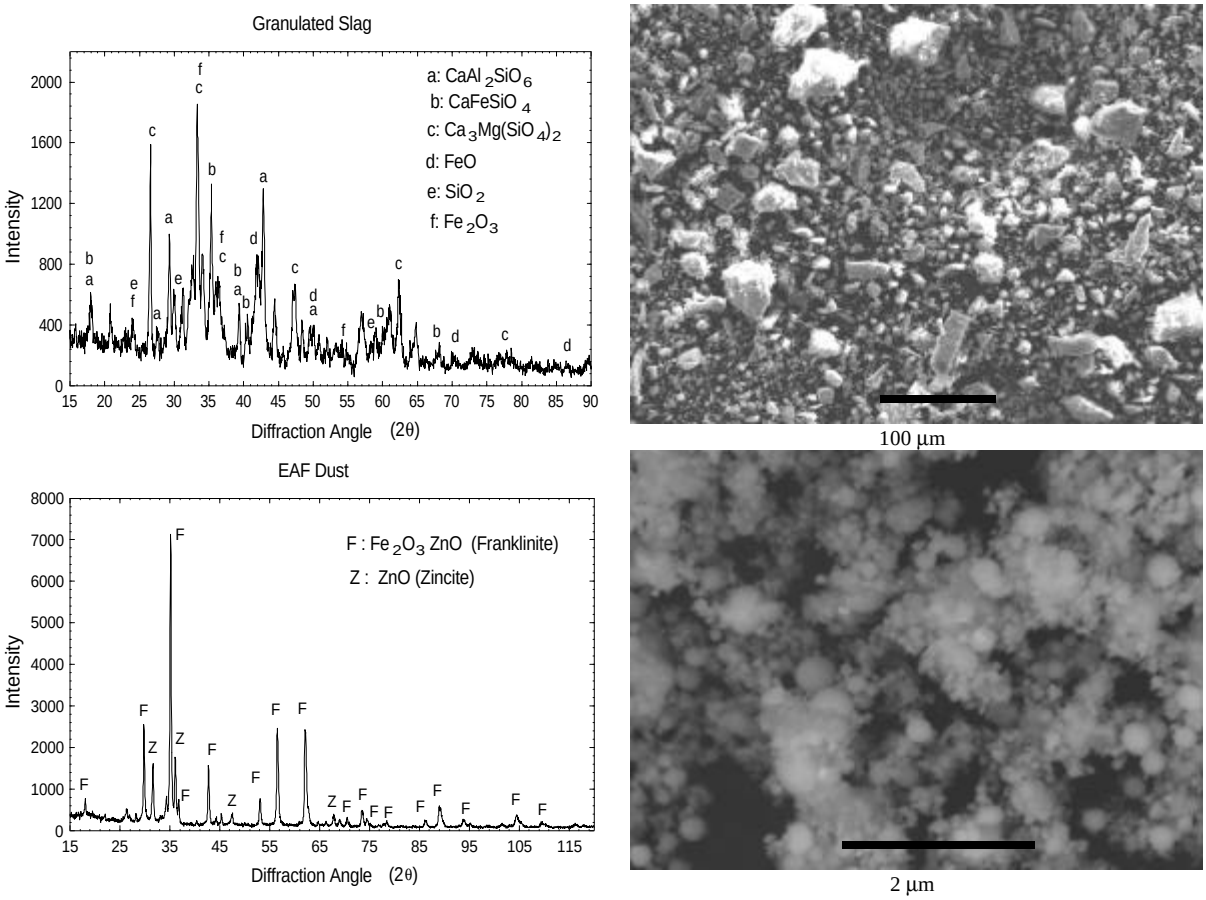


FIGURE 1. XRD and SEM images obtained from the powders; (a) granulated slag powder; (b) electric arc furnace dust.

The oxide composition of the slag and the mineralogical composition of the EAFD was determined by X-ray diffraction (XRD) and by Energy Dispersive X-ray Spectroscopy (EDX). Figure 1 shows that the EAFD was determined as franklinite ($ZnO{\cdot}Fe_2O_3$) and zincite (ZnO), with some small amount of hematite ($Fe_2O_3$), while the major components in the slag were FeO, CaO and $Si_2O$ and variable amounts of MgO, $Al_2O_3$ and MnO. The size, distribution and shape of the powder particles were evaluated using scanning electron microscopy (SEM). The EAFD was mainly composed of nanometric particles presenting spherical shape, generally its size ranging below 500 nm (figure 2). The final mean size of Al particles was about 55 μm having a flake-like morphology. On the other hand, slag particles

were irregular with a mean particle size of 35 μm. The GS presented a mean apparent density of 3.2 g/cm$^3$ and the EAFD of 4.1 g/cm$^3$.

Al/GS and Al/EAFD composites were manufactured by conventional uniaxial compaction and sintering route. Table 1 shows the Al/GS and Al/EAFD mixtures containing different weight percentage of GS and EAFD that were prepared. The powder mixtures were compacted at pressures ranging from 150-600 MPa. The compacts prepared were sintered in He atmospheres up to 620 °C, using in all cases a heating rate of 10°C/min. The soaking time at the final temperature ranged from 0 to 1 hour. The green density of compacts was determined by pycnometry as a function of the compacting pressure and slag/dust weight percent. Densification during sintering of green compacts was also evaluated as a function of increasing slag and dust content using dilatometry. Hardness and compressive strength of the sintering compacts were determined in order to compare the mechanical properties of the composite material as a function of the EAFD and GS content. Compressive testing was performed under displacement control using an Instrom 20 kN machine. Cylindric shaped specimens were used with a length of 8 mm and approximate cross-sectional area of 50 mm$^2$. A cross head speed of 0.76 mm/min was used, giving a strain rate of 1.6 x 10$^{-3}$ 1/s.

Table 1. Chemical Composition (wt%) of the Prepared Composites

| Designation | Aluminium | Granulated Slag | Electric Arc Furnace Dust |
|---|---|---|---|
| 95Al5EAFD | 95 | | 5 |
| 90Al 10EAFD | 90 | | 10 |
| 85Al15EAFD | 85 | | 15 |
| 80Al20EAFD | 80 | | 20 |
| 95Al5GS | 95 | 5 | |
| 85Al15GS | 85 | 15 | |
| 75Al25GS | 75 | 25 | |
| 65Al35GS | 65 | 35 | |

## RESULTS AND DISCUSSION

The predominant goal in powder compaction is to achieve good compact properties with minimal applied force. Particle packing is important in most powder forming processes, due to the fact that the packing density dictates the die fill, binder content, and shrinkage in sintering. Increasing pressure during compaction provides better packing and leads to decreasing porosity with the formation of new particle contacts [3]. Figure 2 shows the effect of compaction pressure on Al powders, indicating that the sample densification increases easily with increasing pressure, approaching relative densities of 0.95 % at 500 MPa. The same procedure was carried out with a mixture of Al and each of the industrial ceramic particles. In Al/GS case, the presence of the slag particles did not permit to obtain a similar densification rate (Figure 2), obtaining relative densities of almost 90% at the same compaction pressure, the bulk density of the composite being calculated according to the rule-of-mixture [4]. Powder metallurgy manufacturing experience has shown that green density depends on the method of producing a powder and its particle size distribution. Green density usually decreases with decreasing particle size [5] and compaction of powders become quite difficult when particles belong to the nanometric domain [6]. As shown in figure 1, the EAFD is made of particles in this range. Figure 2 shows the effect of pressure on Al/EAFD powders, indicating that the small particles of the EAFD reduce densification. Once again, the presence of the ceramic particles did not permit to obtain a high densification rate (Figure 2), obtaining relative densities of 86% at 500 MPa. Other experimental studies have found that densification of metallic powders is always easier than the densification of the powder mixtures [7]. The above results indicated that above 400 MPa the gain in densification in

Al/GS and Al/EAFD compacts was quite small, hence all the compacts subjected to sintering were compacted at this pressure.

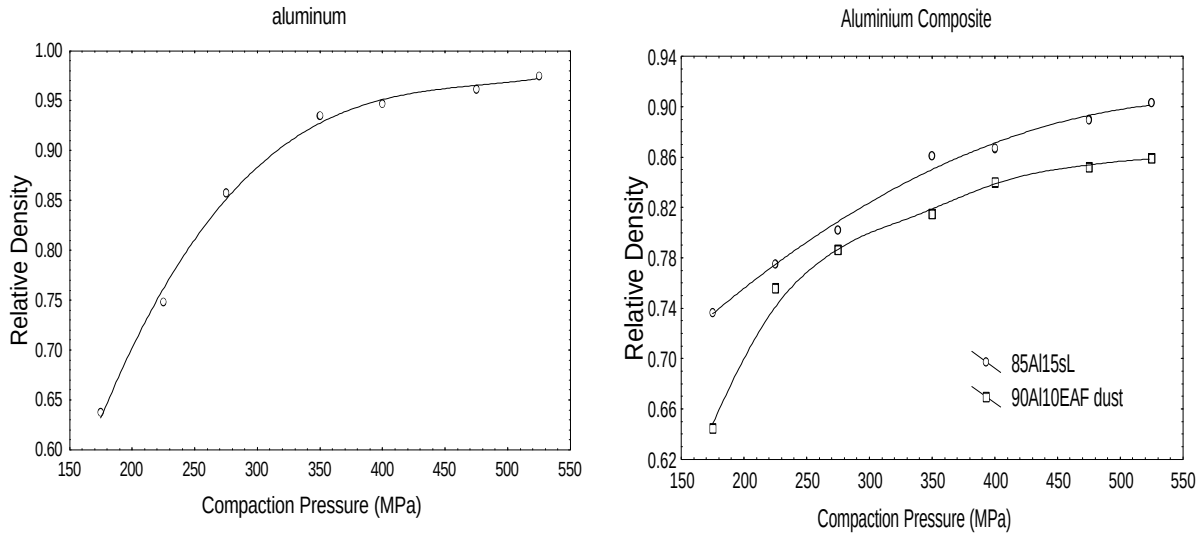


FIGURE 2. Samples density versus compaction pressure during Al, Al/GS and Al/EAFD powder compaction, showing declining compressibility as the Al is reinforced with ceramic particles.

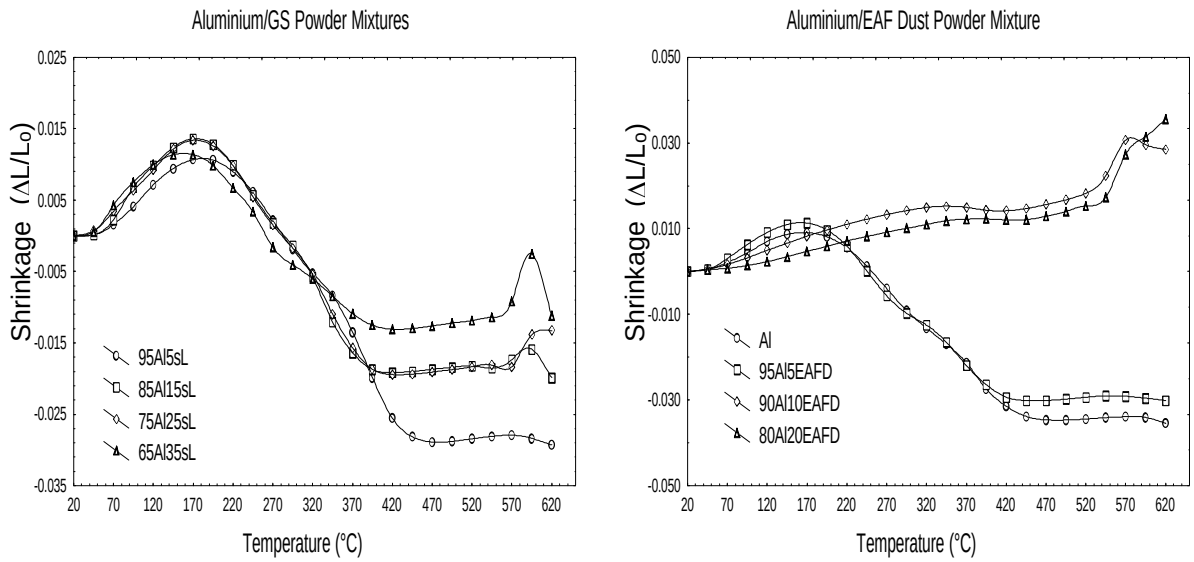


FIGURE 3. Sintering curves of the Al/GS and Al/EAFD composites having different ceramic particle content.

During dilatometry, all experiments were carried out at a constant heating rate of 10°C/min. Relative shrinkage ($\Delta L/L_o$) was calculated as the change in sample length divided by its initial length. Figure 3 shows results obtained by dilatometry from samples having different GS content. From these experiments, it was observed that shrinkage in Al/GS composites starts at 200 °C. The presence of porosity is a characteristic of powder metallurgy processing. Nevertheless, the slag content slightly affects the final density of the samples. After heating the samples to 620 °C, the compact density changes from 92 to 99 % for those with no GS and from 90 to 95 % for those having 15 weight pct of GS. The presence of peaks on the dilatometric curves indicates that composite compact expands and the porosity increases on sintering (figure 3). This figure indicates that the sintered density decreases with

an increase in the slag content. Scanning electron images of Al/GS revealed that the typical microstructure of the Al/GS composites shows low porosity levels and uniform distribution of the GS, nevertheless, clustering of the particles was observed at high slag contents. On the other hand the results obtained from samples having different EAFD were totally different. In this case, EAF particles largely affect the sintering behavior, consequently the final density of the samples. After sintering the samples to 620 °C, the compact density changes from 86 to 80 % for those presenting 20 weight pct of EAFD. Scanning electron images of Al/EAFD have revealed agglomeration of the nanometric particles in the aluminium matrix. Agglomeration pose special problems making compaction and sintering more difficult. As the EAFD content increase, the composite compact expands drastically, increasing rapidly the porosity (figure 3). Probably, the agglomeration comes from the poor surface active agent employed during the blending process of Al and EAF powders.

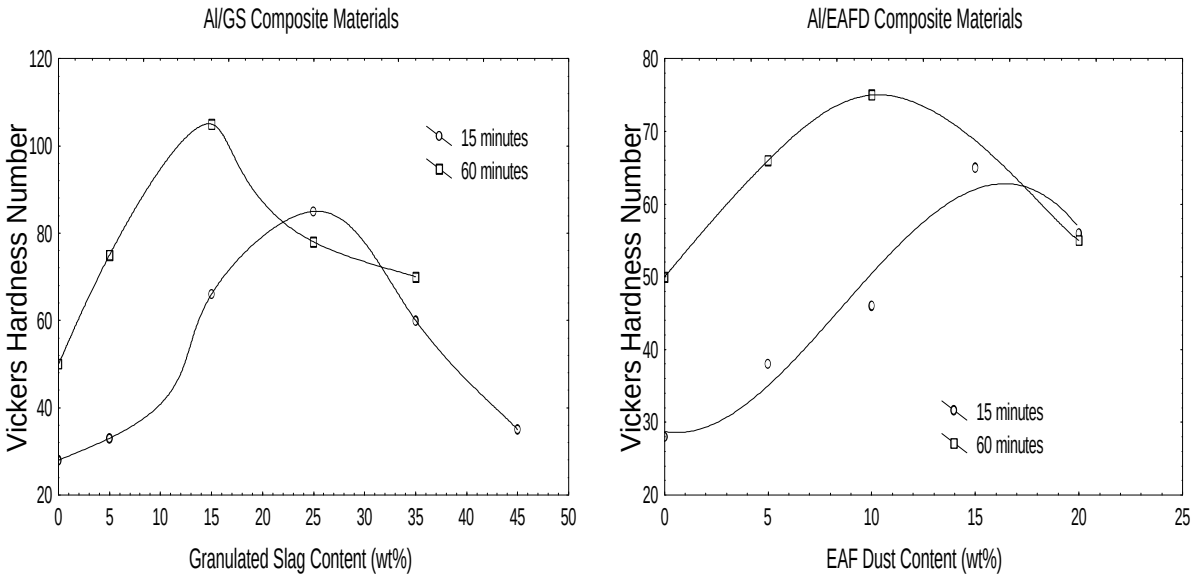


FIGURE 4. Effect of the ceramic particle content on the sintered hardness. Samples were sintered at 620° C during 15 and 60 minutes in Ar.

In powder metallurgy is widely accepted the fact that all the mechanical properties, including strength, elastic modulus, fatigue life and fracture toughness, depend on the sintered density [5]. Also, it is well established that the mechanical properties of particulate MMCs are sensitive to the distribution of reinforcing particles [8]. In general, inhomogeneities, particularly concentrated clusters of particles, are expected to have an adverse effect on the ductility and fracture toughness. Figure 4 shows Vickers hardness as a function of the ceramic particle weight percent for two different sintering times. This figure shows that under the present experimental conditions, increasing weight percent of GS or EAF particles result in an increase of hardness. The maximum hardness corresponds to 25 and 15 wt % using GS and 15 and 10 wt % using EAF dust, both for sintering times of 15 and 60 minutes respectively. Beyond these values, increasing the reinforcing particle content produces an appreciable decrease in hardness. Concerning figure 4, an important aspect is the hardness peak displacement as the sintering time increases. In both cases, as the sintering time increases the maximum hardness of the composite shift to the low ceramic particle content composition.

Concerning mechanical response of the MMCs produced, figure 5 shows the typical compression stress-strain curves of the Al/GS and Al/EAFD composites. According to these results, the attained compressive strength of the present composites are relatively high compared to the compressive strength obtained for pure Al (183 MPa). Nevertheless, the maximum compressive strength was obtained with a GS content of only 15 wt %. The good

strength could be a sign of good interfacial bonding between the slag particles and the aluminium matrix in Al/GS composites. On the other hand, figure 5 indicates for Al/EAFD that under the present experimental conditions, the compressive strength decreases with increasing weight per cent of EAFD. This behavior could be associated to the presence of particle agglomeration. The present results suggest that optimization of the sintering process could give MMCs having good low-temperature tensile and compressive strengths. Nevertheless, more testing and improvement in the mechanical properties is required to make them a real low-cost composite material.

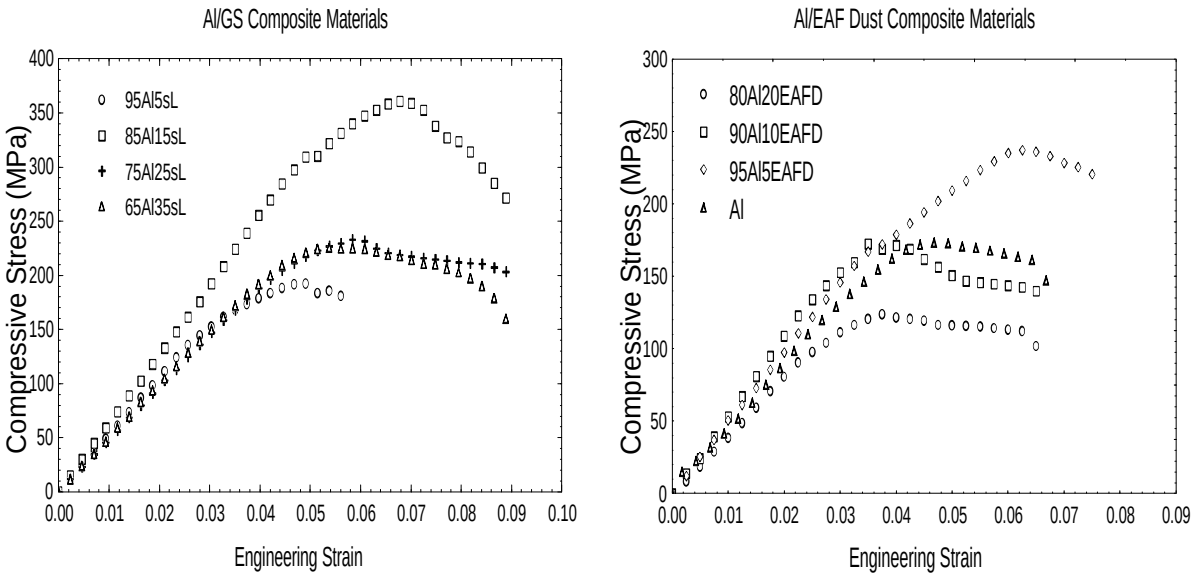


FIGURE 5. Effect of the ceramic particle content on the compressive strength. Samples were sintered at 620° C during 15 and 60 minutes in Ar.

## CONCLUSIONS

Al/GS and Al/EAFD composites can be prepared by pressing and sintering techniques involving conventional powder metallurgy processing. The green and sintered densities of the MMCs here obtained range from 2.8 to about 3 g/cm$^3$. The mechanical response of the Al/GS and Al/EAFD composites was determined in compression. The compressive strength of the MMCs made with GS vary between 225 and 370 MPa and for those made with EAFD between 125 and 250 MPa. The results suggest that optimization of the sintering process could give MMCs having good mechanical properties, rebounding in this way to a new possible application of these industrial solid wastes.

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