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# Effect of the addition of different concentrations of particulate reinforcement on the density, hardness and wear resistance of aluminum composites produced by powder metallurgy

# Efeito da adição de diferentes concentrações de reforço particulado na densidade, dureza e resistência ao desgaste de compósitos de alumínio produzidos via metalurgia do pó

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**Resumo**
O objetivo deste trabalho é avaliar a influência da adição de diferentes concentrações de reforço particulado na produção de compósitos de alumínio comercialmente puro reforçados com escória de alto forno via metalurgia do pó. O processamento desses materiais foi feito peneirando, misturando e compactando pós de alumínio reforçado com 5, 10 e 15% de escória de alto-forno. A compactação uniaxial a frio foi realizada a uma pressão de 430 MPa. Os materiais obtidos foram sinterizados a 610°C por 2h sob atmosfera inerte. Amostras de alumínio não reforçadas também foram produzidas. A caracterização dos materiais foi realizada por meio de medições de densidade e microdureza e ensaios de desgaste. A análise morfológica foi realizada por microscopia eletrônica de varredura. Como resultados, os materiais apresentaram densidade relativa superior a 93,8%, chegando a 98,6% para o alumínio puro. Os compósitos apresentaram distribuição homogênea das partículas de reforço e melhoria progressiva da microdureza com o aumento da concentração de escória. Porém, em relação à resistência ao desgaste, o resultado foi o oposto. Este resultado sugere que as partículas de reforço, por serem feitas de material cerâmico, podem ter funcionado como abrasivo quando liberadas da matriz de alumínio, uma vez que o alumínio comercialmente puro é extremamente maleável e não consegue reter as partículas de escória.
**Palavras-chave:** Compósito particulado de alumínio. Alumínio reforçado com escória de alto forno. Metalurgia do pó.

**Abstract**
The objective of this work is to evaluate the influence of the addition of different concentrations of particulate reinforcement in the production of commercially pure aluminum composites reinforced with blast-furnace slag via powder metallurgy. The processing of these materials was done by sieving, mixing and compacting powders of reinforced aluminum with 5, 10 and 15% of blast-furnace slag. The cold uniaxial compaction was realized at a pressure of 430 MPa. The obtained materials were sintered at 610°C for 2h under inert atmosphere. Unreinforced aluminum samples were also produced. The characterization of the materials was realized by density and microhardness measurements and wear tests. The morphological analysis was realized by scanning electron microscopy. As results, the materials had a relative density greater than 93,8%, reaching 98,6% for pure aluminum. The composites showed a homogeneous distribution of reinforcement particles and progressive improvement in microhardness with increasing slag concentration. However, regarding wear resistance, the result was the opposite. This result suggests that the reinforcing particles, being made of ceramic material, may have worked as an abrasive when released from the aluminum matrix, since commercially pure aluminum is extremely malleable and cannot hold the slag particles.
**Keywords:** Aluminum particulate composites. Aluminum reinforced with blast furnace slag. Powder metallurgy.

## 1. Introduction

The contemporary world is marked by rapid technological evolution and increased conscious consumption. In this context, the development of new technologies seeks to create mechanisms that guarantee efficiency, sustainability and a cyclical economy (Ellen Macarthur Foundation, 2017). Therefore, in a production chain, the introduction of processes that allow the optimization of the use of raw materials as well as the use of so-called “waste” constitutes the core of the circular economy paradigm.

In this way, materials science and engineering seeks solutions to problems regarding the use and development of recyclable and reusable materials, combined with processes that generate less material waste and optimization of properties. This context includes powder metallurgy and composite materials, especially metallic matrix composites, which are normally light and ductile, reinforced with ceramic particles, generally hard and resistant to wear, which have a combination of properties that do not are presented by none of the two or more materials alone (Callister, 2012; Chawla, 1987; Lee *et al*., 2000).

Many studies have been carried out using particulate reinforcements in aluminum alloys produced by powder metallurgy, in order to obtain a metal matrix composite (MMC) with improved properties and technologically viable (Annigeri and Kumar, 2018; Das *et al*, 2014; Singla *et al*, 2009). In these cases, the volumetric fractions used in CMM depend on the type of manufacturing process to which the composite will be subjected, the mechanical properties and the intended behavior of this material (Miliére and Suery, 1988).

In this work, a composite material consisting of commercially pure aluminum reinforced with different concentrations of blast furnace slag particles, waste from pig iron production, was produced via powder metallurgy, with the aim of improving the mechanical properties of aluminum and, as a consequence, giving new applications to this material, in addition to allowing the slag an alternative and sustainable destination, as it will no longer be waste polluting the environment.

## 2. Materials and methods

The powders of commercially pure aluminum and coke blast furnace slag were supplied, respectively, by Alcoa Alumínio S.A. and ArcelorMittal S.A. The chemical compositions of the powders were determined by x-ray fluorescence and EDS. The materials were subjected to a sequential sieving process to determine particle size distribution using 100, 200, 300 and 400 mesh sieves. Materials that passed through a 400 mesh sieve were selected, i.e., with particle sizes less than 37μm.

Samples were prepared with different concentrations of slag: 5, 10 and 15% by weight. Individually, each concentration was subjected to mechanical agitation for 5 min to ensure greater homogeneity. The homogenized materials were uniaxially cold pressed in a metal matrix at a pressure of approximately 430 MPa. For comparison purposes, commercially pure aluminum samples (without reinforcement) were prepared by the same process.

The sintering process was carried out in an inert atmosphere (nitrogen) at 610°C for 2h. Geometric density measurements before and after sintering were carried out. Next, for microstructural characterization of the materials obtained, samples were subjected to traditional metallographic preparation and analyzed using scanning electron microscopy (SEM). The mechanical characterization was carried out using Vickers microhardness measurements (Standard NBR ISO 6507-1 of 06/2019) and pin-on-disc wear resistance tests (Standard ASTM G99). For microhardness, 10 measurements were carried out per sample and for wear resistance, two tests were carried out for each condition.

The results obtained were correlated to evaluate the efficiency of the composites in relation to commercially pure aluminum obtained by the same process.

## 3. Results and discussion

The chemical compositions of commercially pure aluminum and blast furnace slag, determined by x-ray fluorescence (XRF), are presented in Table I.

**Table 1 - Chemical composition of aluminum and slag [% by weight].**

| Commercially Pure Aluminium | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Al | | | O | | | Others | | |
| 97.98 | | | 2.01 | | | 0.01 | | |
| Coke Blast Furnace Slag | | | | | | | | |
| $Al_2O_3$ | CaO | FeO | MgO | MnO | S | $SiO_2$ | $TiO_2$ | Others |
| 10.60 | 41.60 | 0.74 | 7.86 | 0.52 | 0.84 | 36.20 | 0.64 | 1.00 |

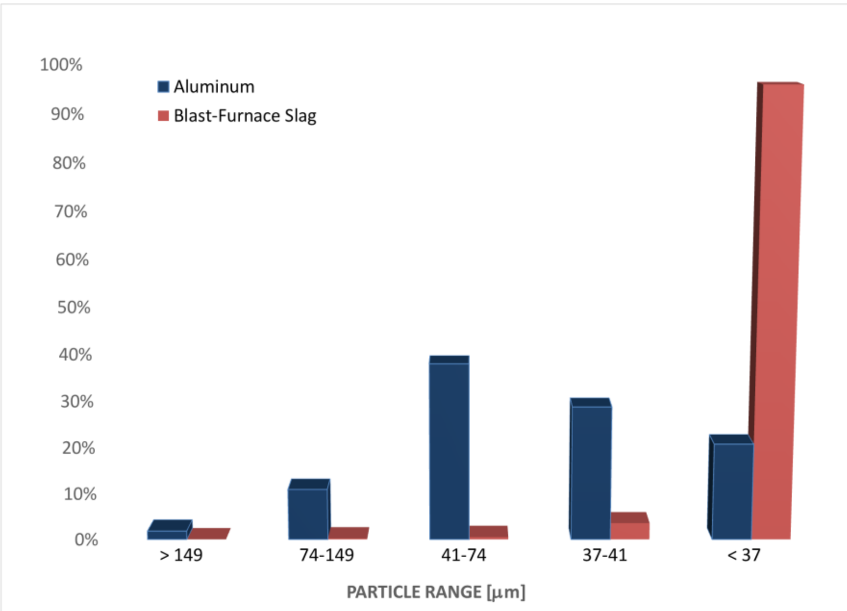


**Figure 1 - Graph of particle size distributions of commercially pure aluminum powders and blast furnace slag determined by sequential sieving.**

The results of sequential sieving to determine the particle size distribution of commercially pure aluminum and blast furnace slag can be seen in the graph in Figure 1. It is possible to observe that the particle size distribution for aluminum indicates that the majority of them are smaller than 74µm (more than 87%) and around 20% are smaller than 37µm. For slag, more than 95% of the particles are smaller than 37µm, that is, almost all of the slag passed the 400 mesh sieve. For sample preparation, the powders selected were those that passed the last sieve, therefore with sizes smaller than 37µm. Aluminum powder was produced by atomizing water and slag powder through high-energy grinding.

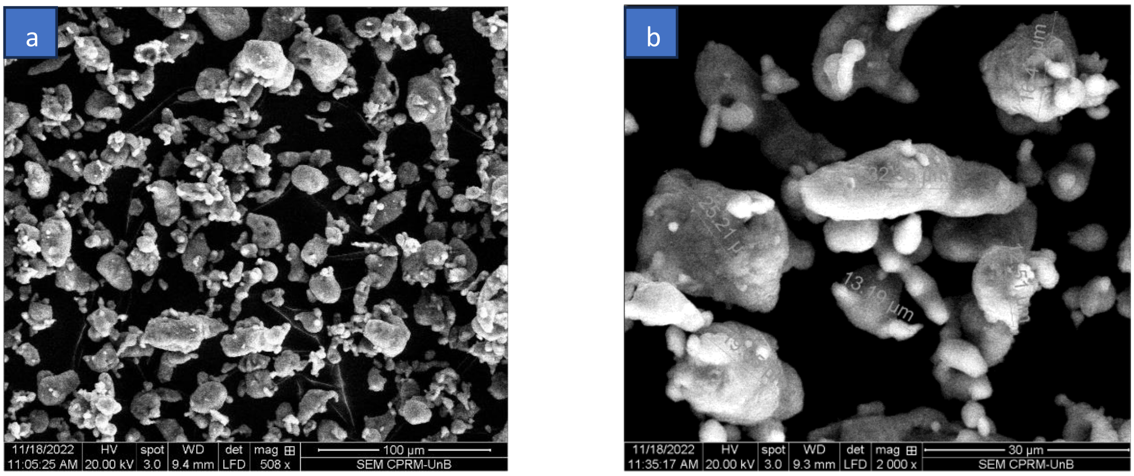


**Figure 2 - SEM images of commercially pure aluminum powder particles. In figure (a), there is an increase of 500x; in (b), 2000x.**

Figure 2 shows the results of the morphological characterization in scanning electron microscopy (SEM) of aluminum powder. The morphology of the aluminum powder reveals a rounded particle shape (Figure 2a), with sizes less than 50µm, as shown in Figure 2(b). This refined and rounded particle size is a function of the rapid cooling produced by the water atomization process.

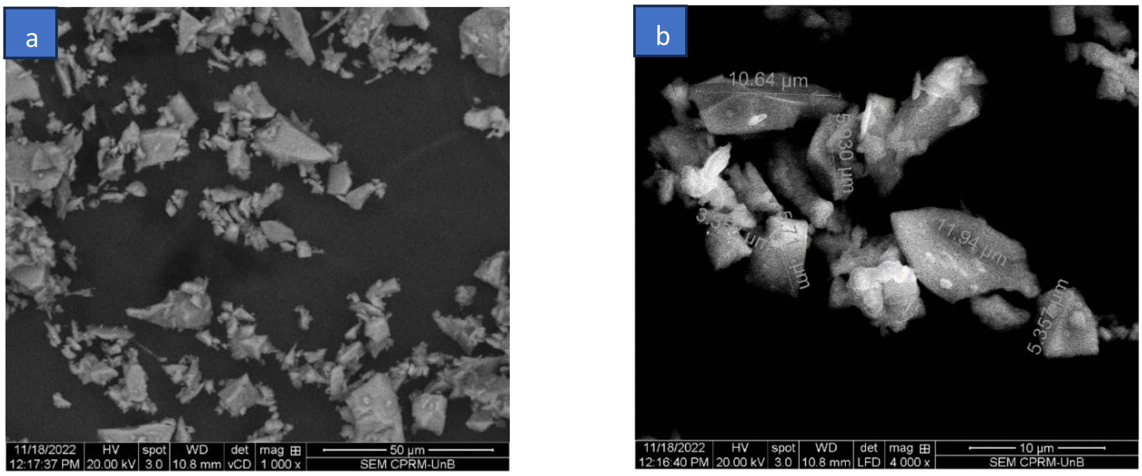


**Figure 3 - SEM images of blast furnace slag dust particles. In figure (a), there is an increase of 1000x; in (b), 2000x.**

Figure 3 shows the morphology of coking coal blast furnace slag powder particles. It is possible to note that this material has a very irregular grain size (Figures 3a and 3b), especially when compared to aluminum alloy, as, in addition to being a fragile material, it was produced by high-energy milling.

Table 2 presents the densities of the compacted samples, before and after the sintering process, for pure aluminum (without reinforcement) and for composites reinforced with different concentrations of slag. For each condition analyzed, four samples were prepared and the average of their geometric densities and standard deviations were calculated. Considering the theoretical densities of pure aluminum and blast furnace slag, calculated from their chemical composition (Furtado, 2016), it was possible to determine the relative densities of the sintered materials.

**Table 2 - Densities of commercially pure aluminum and composites reinforced with different concentrations of blast furnace slag before and after sintering.**

| Densities | Aluminium | Composite 5% | Composite 10% | Composite 15% |
|---|---|---|---|---|
| Theorical [g/cm$^3$] | 2.700 | 2.730 | 2.752 | 2.775 |
| Pressed [g/cm$^3$] | 2.644 ± 0.014 | 2.618 ± 0.019 | 2.610 ± 0.020 | 2.594 ± 0.018 |
| Sintered [g/cm$^3$] | 2.663 ± 0.006 | 2.634 ± 0.010 | 2.630 ± 0.021 | 2.604 ± 0.008 |
| Relative [%] | 98.63 ± 0.10 | 96.48 ± 0.24 | 95.56 ± 0.18 | 93.84 ± 0.21 |

It is possible to observe a progressive reduction in green and sintered densities from the addition of slag in relation to the material without reinforcement. This behavior, combined with the scanning electron microscopy results shown in Figures 4 and 5, suggest that, in some way, the slag makes the compaction and sintering of the material difficult, since it is a particle that does not deform plastically and It has low diffusivity (insulating material) when compared to aluminum, therefore reducing its densification and causing the appearance of porosity. Similar behavior was also observed for the AA6061 aluminum alloy composite reinforced with blast furnace slag (Lima *et al* 2019).

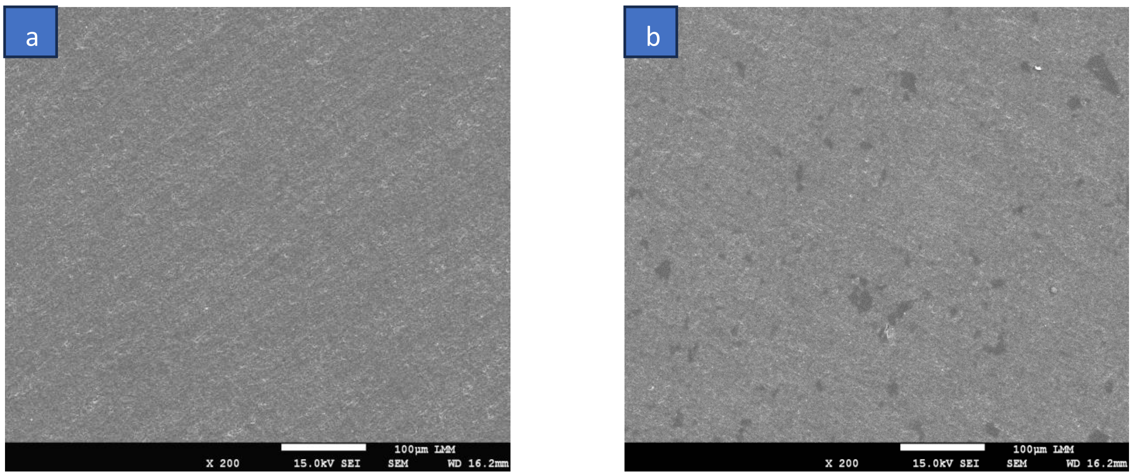


**Figure 4 - SEM images of sintered samples of commercially pure aluminum (a) and the composite reinforced with 5% blast furnace slag (b).**

It is possible to observe in Figure 4(a) that the sintering of pure aluminum (without reinforcement) proved to be effective as it did not indicate apparent porosity. The same can be observed for the composite with the addition of 5% slag, Figure 4(b), in which it is also possible to notice a relatively uniform dispersion of the reinforcement particles.

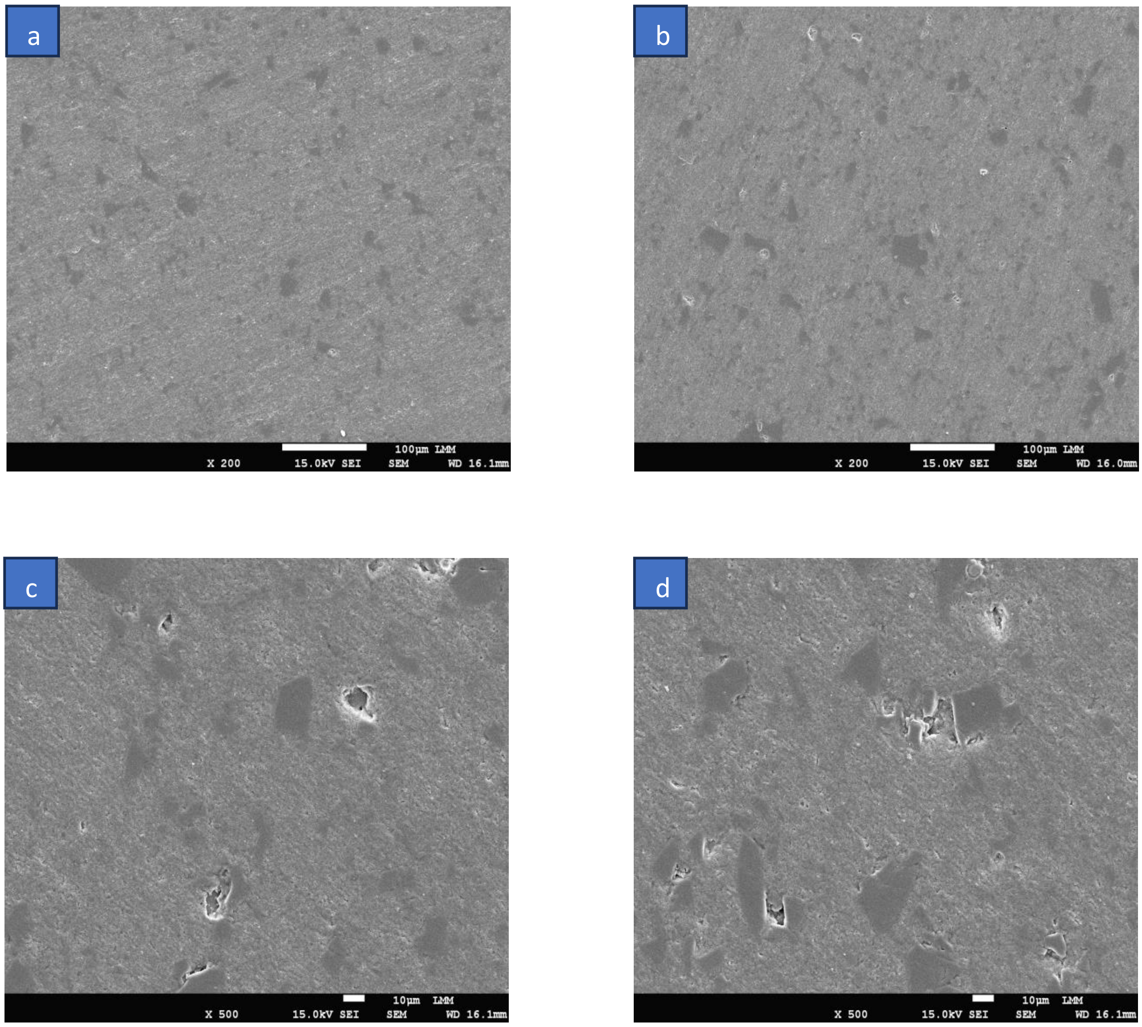


**Figure 5 - SEM images of the composites reinforced with 10% (a) and 15% (b). In (c) and (d) porosities and voids are shown in detail for the composites with 10 and 15% blast furnace slag, respectively.**

For composites with 10 and 15% slag, it is possible to see in Figure 5 (a and b) a significant increase in the concentration of slag particles, which remain uniformly distributed in the aluminum matrix. However, it is also possible to observe in Figure 5 (c and d) the appearance of porosities and voids, mainly in areas close to the reinforcement particles, corroborating the density results.

Figure 6 shows a graph with Vickers microhardness results for pure aluminum (without reinforcement) and for composites with different slag concentrations. It can be observed that the incorporation of slag and the increase in its quantity produces an increase in the microhardness of the material when compared to commercially pure aluminum produced by the same process and under the same conditions. The increase produced by the addition of slag was greater than 35% for samples with 15% reinforcement.

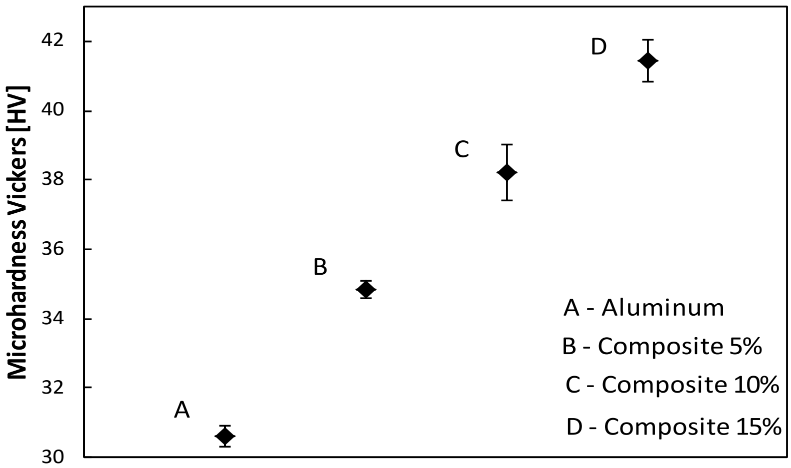


**Figure 6 - Vickers microhardness measurements for sintered aluminum samples and composites reinforced with different concentrations of slag.**

Although it is considered a specific property and, therefore, subject to variations due to the heterogeneities inherent to composite materials, it was quite uniform (low dispersion), indicating that the material, for all concentrations produced, presented good homogeneity.

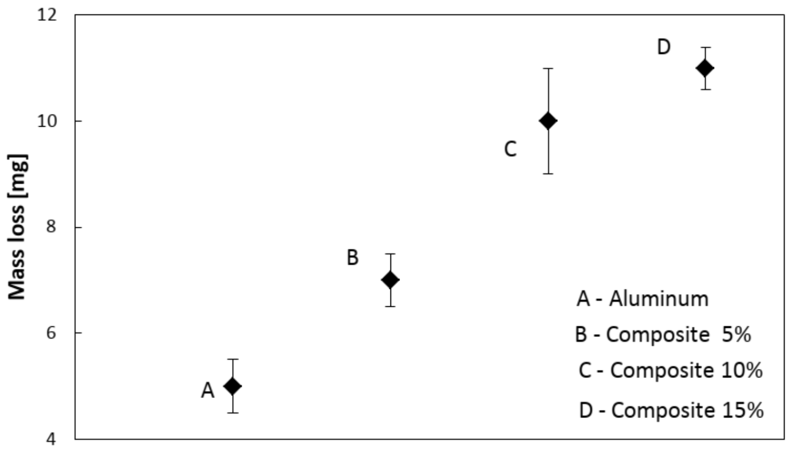


**Figure 7 – Results of wear tests (pin on disc) for sintered aluminum samples and composites reinforced with different concentrations of slag.**

With regard to wear resistance, evaluated by the loss of mass during the pin-on-disc test, we can observe from the graph in Figure 7 that the loss of mass increases as there is an increase in the slag concentration (the loss of mass was directly proportional to the increase in slag concentration in the composite), with the pure aluminum sample (without reinforcement) being the one that presented the lowest mass loss among all the materials tested. This behavior, contrary to what was expected, suggests that the commercially pure aluminum matrix, which surrounds the slag particles, does not have sufficient mechanical resistance to prevent the slag particles from being removed from the surfaces by the tangential friction forces developed during the tests. of wear. In this way, some slag particles removed could remain stuck to the disc surface or loose between the sliding surfaces, acting as abrasive particles that would accelerate mass loss.

## 4. Conclusions

The significant decrease in relative density and the appearance of small porosity with the increase in reinforcement concentration suggest that the presence of slag particles may have hindered the compaction of the material and the diffusional process in aluminum, thus affecting sintering and, consequently, the densification of the material.

The addition of blast furnace slag particles to aluminum caused an increase in the material's microhardness of more than 35% despite the appearance of a small residual porosity, especially for slag concentrations of 10% and 15%. However, the wear resistance decreased with increasing reinforcement concentration. Such behavior suggests that the commercially pure aluminum matrix, which surrounds the slag particles, does not have sufficient mechanical resistance to prevent the slag particles from being removed from the surfaces and starting to act as an abrasive, accelerating the loss of dough.

Although it is considered a residue from the reduction of iron ore, blast furnace slag coke, in particulate form, is an efficient reinforcement for commercially pure aluminum, giving this residue a new possibility of use in the metal-mechanical industry, in addition to contribute to environmental issues.

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