The Size Effect of Silicon Carbide Particles on the Wear of Brake Pad Materials

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ABSTRACT: The research presented in this paper is focused on understanding the influence of the exchange of three different particle size of silicon carbides in brake pads. The average diameter of the commercially used silicon carbide particles was 3 μm, 14 μm and 125 μm respectively, measured by a laser diffraction technique. The morphology was tested through the scanning electron microscopy equipment, the images show similar shapes between the carbides. To simulate a real condition of wear during the use, the brake pad with the 3 types of carbides was tested at an inertia brake dynamometer using a full scale car brake system. The wear effects at the disc rotor and the brake pad materials were tested ranging the temperature from 100 to 400 °C. The results showed that an increment of the silicon carbide particle size increased the total wear of the disc rotor. The test also showed a tendency to stabilize the disc wear by increasing the particle size from the intermediate size to the largest one. However, the brake pad wear showed an opposite correlation, as the particle size of the abrasive increased, the brake pad wear decreased. Temperature plays an important role in the wear phenomenon, as the temperature increases, there is a change in the wear rate between materials with different silicon carbides.

KEY WORDS: particle size, abrasives, silicon carbide, wear, disc rotor, brake pad,

1. Introduction

Companies that produce friction materials for automotive brakes always seek to improve their existing materials in order to conquer new markets and customers around the world. There are three main requirements for friction materials: efficiency improvement, increased life span and low cost. For this, we can choose to improve its manufacturing process or change the composition of the product.

In the case of a composite material, there are several options for innovation and continuous improvement. However, it is important to emphasize that the composition of the friction material is considered an industrial secret, and for this reason it is passed from one person to another for generations. Therefore, there are few publications on the subject and because of that, no knowledge is shared in this field, with each manufacturer being responsible for their own learning and consequently for their own formulations [1]. This paper aims to reduce this subjectivity and increase the knowledge of cause and effect on the exchange of raw materials with different properties, focusing on the influence of particle size on abrasives.

Abrasives, which are usually ceramic powders, have the function of cleaning the disc contact surface from film deposits, so that they ensure a better defined surface. For this, they have a higher hardness than cast iron (between 5 and 9 Mohs), a material that constitutes the brake disc, however this high hardness generates wear and scratches on the surface, and may even cause unwanted noise. [2] [3] In addition, they have the function of keeping the friction level high, given their characteristics, they are able to increase the friction coefficient even in high temperature conditions [4]. Usually 1 to 8% of volume in this class is used in the formulation, abrasives of different types are available. The main abrasives used in brake pads are alumina, silicon carbide, chromite, zirconite, quartz, zirconium oxide, among other high hardness oxides. The selection of the appropriate abrasive is carried out observing properties such as hardness, size and morphology. Since the variation of these characteristics directly influences the performance of brake pads. However, when maintaining the same type of abrasive, the factor of greatest influence becomes the particle size [5].

Tribology divides abrasive wear into two different mechanisms, depending on the movement of the abrasive in relation to the surfaces in contact. Two-body wear is caused by hard protuberances clinging to the surface and three-body wear is the phenomenon where hard particles are free to roll between two surfaces. Wear rates are lower whit three-body wear when compared to two-body wear.

Particulate wear studies show that when the particle size increases, there is an increase in the surface wear rate, but at a certain point the rates remain practically constant for the two wear mechanisms, two-body and three-body abrasion [6]. Therefore, for small sizes, the wear rate grows proportionally to the size, but after reaching a critical point, the behavior changes, stabilizing the wear rate [7] [8], because the larger particles roll out of the friction surface or break generating smaller particles.
The properties of hardness, thermal resistance and corrosion resistance power have made silicon carbide a powerful abrasive [9]. In this study, three silicon carbides with different particle sizes were investigated in a brake pad material of a passenger vehicle, to understand the wear behavior according to the particle size of the abrasive. Product tests were performed on a dynamometer that simulates the use of brake pads in a full-scale vehicle.

2. Experimental Details

2.1. Silicon Carbide

Several options of different silicon carbides are commercially available, for this study three carbides with different particle sizes were chosen. Characteristics of purity, particle distribution and morphology were evaluated.

The X-ray diffraction technique was used to determine the purity of the materials. It was found that the three samples have silicon carbide as their main crystalline phase, totaling around 97%. The mineral phase is called Moissanite, but it is also known as α-SiC and has a hexagonal crystalline system. In addition, the contaminating phases were quartz, present in all samples, and silicon, present only in sample A.

### Table 1 Silicon carbide descriptions and average particle size

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
<th>Average Particle Size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Small</td>
<td>3</td>
</tr>
<tr>
<td>B</td>
<td>Intermediate</td>
<td>15</td>
</tr>
<tr>
<td>C</td>
<td>Coarse</td>
<td>130</td>
</tr>
</tbody>
</table>

To determine the particle size distribution of each material, the laser diffraction technique was used. Figure 1 shows the distribution of the accumulated particle size and population density. So it is possible to verify that the thinner material A has a bimodal distribution, with the first and smallest peak centered at 3 µm and ranging in size from 0.05 µm to approximately 0.6 µm, these particles represent in volume about 25% of the total. The remaining 75% of the particles form the second and main peak at 4 µm, where particles are found up from 0.6 µm to the maximum size of 12 µm. This results in an average size of 3 µm for silicon carbide A.

The materials B and C present particle distribution with monomodal behavior. For sample B the diameter of the particles are centered at approximately 15 µm, it start with a minimum size of 2.5 µm up to the maximum size of 36 µm. While sample C starts with particles of approximately 30 µm and it has a maximum size of 400 µm, with the average diameter at 130 µm.

There is a significant variation in the average particle size, see Table 1, with carbide C about 8 times greater than particles of carbide B and carbide B about 5 times greater than A.

![Figure 1: Particle size distribution of the silicone carbides A, B and C.](image1.png)

![Figure 2: SEM images of the three silicon carbides used in the study. A) 3 µm, B) 15 µm and C) 130 µm. The images are in different magnifications to facilitate the visualization of the particle shape.](image2.png)
When comparing the morphology of each carbide Figure 2, it is possible to verify that all of them have similar sharper corners, a fact that further increases their aggressiveness in contact with another surface, given that the probability of increasing reaching the angle of critical attack that provides micro-cutting wear. It is observed that carbide A, besides having a smaller particle size, also has a more heterogeneous size distribution than other carbides, which confirms the fact that the particle size distribution has a bimodal population density curve.

2.2. Manufacturing of brake pads
The brake pad used for the study was a semi-metallic formulation, without the presence of asbestos, that is, silicon carbide. For this brake pad formulation, 15 components are used, divided according to their function in Table 2. The same percentage by volume of all components was used and only the carbide used was changed.

Table 2: Brake pad formulation investigated in this study

<table>
<thead>
<tr>
<th>Group</th>
<th>% Volume</th>
<th>% Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binders</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Non-metallic Fibers</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Metallic Fibers</td>
<td>12</td>
<td>27</td>
</tr>
<tr>
<td>Organic Fillers</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Inorganic Fillers</td>
<td>17</td>
<td>13</td>
</tr>
<tr>
<td>Lubricants</td>
<td>51</td>
<td>46</td>
</tr>
<tr>
<td>Abrasives</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

The pads went through the production process divided into 4 main steps. The first step is called mixing, where the material is weighed according to the percentages presented in the formulation Table 2 for a mixer load of 6 kg according to the size of the mixer, for this material a total time of 8 minutes was used for agitation. The next step is called pre-forming, where the material is pressed for 3 minutes without heat in order to acquire the shape of the part for pressing, in this step a specific pressure of 270 kgf/cm² with 2 ventilations is used. The molding step is the third one, where the material is pressed using a specific pressure of 3 kg according to the size of the mixer. For this step a temperature of 148 ºC was used for 5 minutes with a total of 4 ventilations of 2 seconds. Finally, the last step refers to post-curing, a step that ensures that the resin present in the material has been fully cured and will not undergo changes in the application. In post-curing the material is placed in an oven with a temperature of 230 °C for about 5.5 hours, thus ending the process of producing the material to be tested.

2.3. Test procedure for wear
The durability of a friction pad is assessed for wear, structural integrity and other behaviors derived from use. Besides that, the behavior of the disc is also evaluated, since it is a contact between two surfaces, it is expected for the disc to also have high durability. The brake pad tests were performed in an inertial dynamometer as shown in Figure 3. In the equipment an electric motor (1) drives a set of floating discs (2) that provide the required inertia for the test. At the end of the shaft is the disc (3) together with the clamp (4) that is connected to the torque measurement system (5).

For the carbide test, the Agile vehicle brake with an inertia of 50 kg.m² was used. This test was carried out in 5 cycles of 500 braking at a speed of 60 km/h to 0 km/h. The braking were performed with a constant deceleration of 2 m/s². Each cycle has a constant braking start temperature, with the first at 100 ºC, the second at 200 ºC, the third at 300 ºC, the fourth at 400 ºC and the fifth again at 100 ºC. The purpose of repeating the cycle at 100 ºC is to check whether the wear repeats its behavior even after being exposed to high temperatures.

3. Results and discussion

3.1. Brake disc wear
Brake discs, also called rotors, are items that must be replaced over time. However, due to their high cost, brake pad manufacturers must also assess their wear. As a disc and a tablet are a tribological pair, a joint analysis of these results is unavoidable. The wear of the disc is necessary for the cleaning of the films formed on its surface, such a film, if not removed, may affect the brake performance. However, high wear will generate some disc failures, such as grooves, ripples and scratches, in addition to the need to change the disc in a short period of time.

Figure 4: Disc wear as a function of silicon carbide particle size
Given the importance of this characteristic for the customer, this article seeks to investigate the effect of the particle size of the abrasive silicon carbide on the disc wear behavior. In the results of the brake system wear test, there is an increasing total disc wear as the particle size increases. The wear increases significantly, about 107%, from the smaller carbide A to the intermediate carbide B, with the particles of A 6 times smaller than the particles of B. However, the wear increases 18% when comparing the result of the carbide B for the carbide C, the B particles being about 9 times smaller than C. This phenomenon indicates a stabilization of wear by increasing the average particle size. As a result, a non-linear logarithmic regression was used, see Figure 4 to describe the visualized behavior.

When analyzing the bibliography, the expected behavior when increasing the particle size is a significant increase in the wear rate, however, as it continues to increase, the tendency is that the wear stabilizes, which confirms the behavior observed in the wear test. Several hypotheses are explained in the bibliography for increased wear with increased particle size, it is understood that it is not a specific reason, but a set of factors that lead to increased wear. However, the only theory that is attributed to the two types of wear mechanisms (two bodies and three bodies) concerns the increase in surface hardness due to plastic deformation in a layer of approximately 10 µm. In Figure 5, the results of the experiments with the two mechanisms are shown.

As a result, the smaller particles only wear out this layer, due to its low penetration. However, the larger particles have greater penetration and wear out both the harder layer and the softer layer underneath. This phenomenon also explains why the wear rate stabilizes after approximately 100 µm, since the penetration depth has already exceeded the thickness of the plastically deformed layer.

The Figure 6 shows the accumulated wear when increasing the test temperature in each cycle. It is observed that there is an increase in disc wear with increasing temperature. It is possible to suppose that this behavior is due to the reduction in the hardness of the cast iron that makes up the disc with the increase in temperature (8). It is also verified that carbide C has low wear, similar to thin carbide A, in the first stages with temperatures of 100 ºC and 200 ºC. However, its wear skyrockets when passing through higher temperatures such as 300 ºC and 400 ºC. While the wear rate of carbides A and B remains constant with the increase in temperature, sometimes the wear rate decreases, carbide C increases its wear significantly, from 3 g in the lowest temperature stage to almost 15 g in the 400 ºC stage.

Since the iron's hardness decreases with temperature, it is supposed that the carbide of greater size will have an even deeper penetration depth than the other carbides. Therefore, the influence of the particle size of the abrasive on the wear behavior of the brake disc becomes even more evident.

It is understood that another factor that influences wear is how tightly this particle is in the brake pad matrix. According to (9), it is assumed that the abrasive particles with a larger diameter serve as anchors for the wear debris of the other components of the pad. Similar to Eriksson's primary and secondary plateau theory, where the metallic fiber forms the primary plateau because it is more attached to the matrix, and the wear particles form the secondary plateaus around the fiber with the rotating movement of the disc. In this case, the larger silicon carbide particle will act as the fiber. As a result, material with this type of particle will wear the disc more severely.

3.2. Brake pad wear

When dealing with the requirements of the brake system, it is essential to think about a balance between performance, wear, noise and cost, whenever one of these parameters increases or decreases, inevitably the others will change behavior. Brake pads are categorized in a vehicle as consumable items, this is because they are worn out with use and need to be replaced. Given this, an important parameter for the customer is the useful life of his pads set, to reduce costs over time.

By observing the results of pad wear in this study, it is possible to notice an also logarithmic correlation of the pad wear in weight with the particle size. Figure 7. The results of total wear in weight loss indicate a reduction of pad wear with the increase in the average particle diameter.
The material with the greatest wear is material A with the smallest particle size. Followed by material B, with wear about 15% lower and with intermediate particle size, about 5 times greater than A. The wear of the pads from material B to material C falls significantly, around 43%, since the C particles are 9 times larger than B particles. Therefore, for wear of the pads it is not possible to observe a wear stability with the studied intermediate particle sizes, only an indication of the behavior of the trend curve.

One hypothesis studied to justify the phenomenon of decreased pad wear with increasing particle size was linked to the pressure parameter required for braking. Since, the wear test was set up to establish a constant deceleration of 2 m/s² with the vehicle at a constant initial speed of 60 km/h and a temperature that will be constant in each cycle. However, to achieve this condition, the pressure necessary for braking until the total stop is variable and does not depend on the test. Table 3 presents the average pressure applied for the entire test and also an average of the pressure applied in the 500 brakes in each of the temperature cycles.

Table 3: Average pressure (bar) of 500 stops for each temperature step and average test pressure per silicon carbide.

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>22</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>200</td>
<td>20</td>
<td>24</td>
<td>21</td>
</tr>
<tr>
<td>300</td>
<td>24</td>
<td>25</td>
<td>22</td>
</tr>
<tr>
<td>400</td>
<td>31</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Average Pressure</td>
<td>24</td>
<td>21</td>
<td>24</td>
</tr>
</tbody>
</table>

Pressure variations were observed throughout the test, mainly when changing the temperature of the cycles. However, there is no direct correlation between operating pressures and the particle size of the abrasives under study. Another assumption, also indicated by MATĚJKA [4], is regarding the stability of the friction surface of the insert. Friction materials with finer particles tend to have a more heterogeneous surface due to the formation of smaller contact plateaus, as explained in item 3.1 Brake disc wear.

4. Conclusion

Considering the tests carried out, the following conclusions are drawn for the variation of wear with the increase in the particle size of silicon carbide.

- By increasing the particle size of the abrasive, the disc wear is also increased. This phenomenon was attributed to the depth of penetration of silicon carbide.
- Disc wear tends to stabilize with the significant increase in the particle size of the carbide. It is understood that this phenomenon may be related to the hardening effect of the surface layer of the disc.
- The test that used the pad with the thickest carbide showed a significant increase in the wear of the disk when increasing the temperature. It is assumed that this fact is related to the reduction of the hardness of the cast iron with the temperature and with this an even greater depth of penetration of this carbide.
- Pressure variations were observed throughout the test, mainly when changing the temperature of the cycles. However, there is no direct correlation between operating pressures and the particle size of the abrasives under study.
- At lower temperatures, pads with thin and intermediate carbides show similar wear, distancing only in cycles of higher temperature. Regardless of the temperature, the least wear is on the pad containing particles of the thicker carbide.
References


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