Influence on the wear resistance of the particle size used in coatings of Alumina

A Santos¹, R Guzmán¹ and Z Y Ramirez²
¹ Universidad Pontificia Bolivariana, Bucaramanga, Colombia
² Unidades Tecnológicas de Santander, Bucaramanga, Colombia

E-mail: alfonso.santos@upb.edu.co

Abstract. In the literature, it is common to find that the size of the particles used in coatings through thermal spraying processes influences the hardness and wear resistance thereof; this project aimed to quantify the importance of this parameter in the adhesive and abrasive wear resistance when aluminium oxide is deposited on a substrate of AISI 1020 steel, through a thermal spraying by flame process. The methodology consisted of: a) morphological characterization of the powder used in the coatings by scanning electron microscopy, b) deposition of coatings, c) testing of adhesive and abrasive wear (ASTM G99-05 Standard test method for wear testing with a pin-on-disk apparatus and ASTM G65–04 Standard test method for measuring abrasion using dry sand/rubber wheel apparatus), and d) statistical analysis to determine the influence of particle size on wear resistance. The average size of the powder used for coatings was 92, 1690, 8990 and 76790 nm. The obtained results allow to identify an inversely proportional behaviour between particle size and wear resistance, in both types of wear (adhesive and abrasive) is shown a logarithmic trend indicating an increase in loss mass during the test as the particle size is also increased and therefore a decrease in wear resistance of the coating.

1. Introduction

One of the most used techniques in recent years, to improve the wear resistance and hardness of materials consists of the deposition of coatings on its surface [1,2], which can be obtained from ceramic, polymeric or metal materials [3,4] available as wire, rod or powder and deposited through different physical, chemical or thermal procedures [5,6].

Among the ceramic coatings, the coatings made of Al₂O₃ are the most commonly used; one of the processes used to apply them is thermal spraying on metallic surfaces through a spray nozzle which handles an oxyfuel flame, electric arc or plasma arc. The thermal spraying is one of the advanced techniques of hard coatings of engineering for the preparation and surface protection [7]. The technology has been widely used as a remedy to combat wear, corrosion, heat corrosion and other problems that occur across the spectrum of manufacturing and engineering industries [8]. The diversity of thermal spraying processes used for hard coatings is due to the variety of applications and required properties, as well as consideration of economic aspects [9]. The coating material may have the form of wire, rod or powder, and the droplets of particles collide with surfaces at speeds of 100 to 1200 m/s. The surfaces to spray are cleaned and roughed first, to improve the adhesion strength (which depends on the process and the particular technique used). The coating has a layered structure of ceramic deposited and may have porosity caused by air and oxide particles trapped by the high temperatures that are used [10].
In the conventional processing, the ceramic coatings are produced with powders of micron sized particle and their properties have been studied in depth, showing that the wear resistance is related to hardness and toughness of the coating [11-13]. In recent years, the manufacture of ceramic nanostructured coatings using nano-crystalline powder has become more technologically attractive because the mechanical properties of the nanometric coatings exhibit significant improvements over their conventional counterparts, because the properties associated with the nanostructures can improve their performance and durability [14-16].

This paper presents the results of the abrasive and adhesive wear resistance tests of a commercial AISI 1020 steel when is deposited over it an Alumina coating through a thermal spraying by flame process, using as projection material Al₂O₃ powder of different particle size (92, 1690, 8990 y 76790nm); additionally, the influence of the particle size on the amount of removed material during the abrasive and adhesive wear tests performed, is determined.

2. Methodology
For the development of the project, it was started with the morphological characterization of the powders sued to make the coatings, for which the technique of Scanning Electron Microscopy (SEM) was used through the equipment FE Schottky of high resolution equipped with Field Emission technology for electron emission which has integrated a microanalysis system by X-Ray Energy Dispersive Spectroscopy (EDS) that allows to collect the rays generated by the simple and performing semi-quantitative analysis and element distribution on surfaces. In order to quantify the size of the particles with a reliability greater than 95%, it was performed a statistical analysis with a random pre-sample of 10 magnitudes, from the images obtained from MEB and a Digital image processing software.

The specimens for testing were made from a traditional machining process, the geometric shape and dimensions are adapted to the requirements of ASTM G65-04 (Standard Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus) and ASTM G99-05 (Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus), and the equipment used in the different tests. The coatings were made through the thermal spraying by flame process using an Eutalloy 85 BX gun, which is adapted to a conventional equipment of oxyacetylene combustion, the distance used between the torch and the base material was 30cm with an inclination of 60° relative to horizontal, the oxygen pressure was 170kPa and the acetylene pressure was 34kPa which defines a pressure ratio of 1:5; To anchor the coating to the base material is used a fusible nickel-based alloy.

The tests were conducted on specimens of AISI 1020 steel with Alumina coating, obtained from particles of 92, 1690, 8990 and 76790nm in size; The abrasive and adhesive wear resistance tests are made following the ASTM G65 – 04 and ASTM G99-05 standards respectively, which are listed in Table 1 for abrasive wear and in Table 2 for adhesive wear. The wear measurements are reported as the volume loss in cubic millimetres for each of the specimens used in the tests.

| Table 1. Testing parameters of abrasive wear. |
|---------------------------------------------|
| Specified Procedure | Force Against Specimen (N) | Wheel Revolutions (rpm) | Linear abrasion (m) |
| A | 130 | 6000 | 4309 |
| B | 130 | 2000 | 1436 |
| C | 130 | 100 | 71.8 |
| E | 130 | 1000 | 718 |

Source: ASTM G65 – 04 standard (REAPPROBED IN 2010) [17]
Table 2. Testing parameters of adhesive wear.

| Specified Procedure | Force Against Specimen (N) | Wheel Revolutions (rpm) | Contact diameter (m) | Linear distance covered (m) |
|---------------------|----------------------------|------------------------|----------------------|---------------------------|
| A                   | 10.2                       | 3980                   | 0.02                 | 250                       |
| B                   | 10.2                       | 5971                   | 0.04                 | 750                       |
| C                   | 10.2                       | 5307                   | 0.06                 | 1000                      |

Source: ASTM G99-05 standard [18].

3. Results

The tests performed in the scanning electron microscope result in images as the seen in Figure 1(a) which allow determining the morphology and size of the particles used for the realization of coatings.

![Figure 1](image1.png)

**Figure 1.** (a) Image of alumina particles of micrometric size obtained by SEM, (b) Size distribution of the alumina particles of nanometric dimensions.

Based on the images, a pre-sample of dimensions of smaller side of 10 different particles is analysed, and with them a sample size of 45 measurements is defined in order to obtain a reliability of 95% and a maximum error of 5%. The distribution of measurements for the nanometric powder is shown in Figure 1 (b), the average value of the particles size was 92.88nm and the higher frequency are in the range of sizes of 90 to 100nm corresponding to 37.8% of the total, besides the 73.3% of the particles has a size less than 100nm. Other powders used are in the range of micrometric size and showed average values of 1690, 8990 and 76790nm under the same considerations used for nanometric size powder.

The process and the final result of the coating obtained through thermal spraying by flame process is related in Figure 2(a) and 2(b) respectively, it can be observed how the particles are projected onto the base material and the alumina deposits adhered on the anchor material used to attach them to the substrate. It can be concluded that the coating is not uniform on the surface which is characteristic of this deposition process.
Figure 2. (a) Image of thermal spraying by flame process used to perform the coatings, (b) Image obtained by SEM of the coating made by thermal spraying by flame process.

The results of the tests of abrasive and adhesive wear made to alumina coatings are related in Figure 3 and 4 respectively; in both a linear behaviour of the volume of lost material during the test with regard to the linear distance covered, is observed. Additionally, it is displayed that in so far as the size of the particles used to make the coatings increases, the volume of material lost during the test also increases, which describes a directly proportional behaviour between these two parameters.

Figure 3. Lost material during abrasive wear tests conducted on alumina coatings obtained from particles sizes of 92, 1690, 8990 and 76790nm.
Figure 4. Lost material during adhesive wear tests conducted on alumina coatings from particles sizes of 92, 1690, 8990 y 76790nm.

In Figures 5 and 6 is related the influence of particle size used in conducting the alumina coatings in the volume of material lost during the abrasive and adhesive wear resistance tests. It can be seen in both figures that the greater the size of the particles used, the volume of material lost during the tests is also increased which allows to conclude that there is an inverse proportional ratio between the particles dimension and the wear resistance, that is among smaller the particle size, the abrasive and adhesive wear resistance of the coating are greater.

Figure 5. Influence of the particles size used on making the alumina coatings in the volume of material lost during abrasive wear resistance tests.
Figure 6. Influence of the particles size used on making the alumina coatings in the volume of material lost during adhesive wear resistance tests.

It can also be seen in Figures 5 and 6 that the influence is much more accentuated when the particle size passes from the nanoscale (<100 nm) to the micrometric scale as much so that for particles larger than 10 µm practically the volume of lost material during the test is not affected by this parameter.

4. Conclusions
The particle size used for making alumina coatings through thermal spraying by flame process influences inversely proportional in the abrasive and adhesive wear resistance of the coating.

The influence of the size of the particles used for making the alumina coatings is much more accentuated when this parameter passes from the nanoscale (<100 nm) to micrometric scale, as much so that for particles larger than 10 µm practically the volume of lost material during the test is not affected by this parameter.

References
[1] He J, Schoenung J M 2002 Nanostructured coatings Materials Science and Engineering A336(1-2) 274-319
[2] Tjong S, Chen H 2004 Nanocrystalline materials and coatings Materials Science and Engineering R45(1-2) 1-88.
[3] Rainforth W M 2004 The wear behaviour of oxide ceramics-A Review Journal of Materials Science 39 6705-6721
[4] Konyashin I Y 1995 Wear-resistant coatings for cermet cutting tools Surface & Coatings Technology 71 284-291
[5] Thankur A, Gangopadhyay S 2016 Influence of tribological properties on the performance of uncoated, CVD and PVD coated tools in machining of incoloy 825 Tribology International 102 198-212
[6] Nilsson M, Olsson M 2011 Tribological testing of some potential PVD and CVD coatings for steel wire drawing dies Wear 273 55-59
[7] Knotek O 2001 Thermal spraying and detonation gun process Hand Book of Hard Coating ed. R F Bunshah (New Jersey: Noyes Publications) pp 77-107
[8] Harrisson K A-Metco Ltd. 1996 Thermal spraying: An overview *Surface Engineering Casebook: Solutions to corrosion and wear-related failures* ed. Burnell J S, Datta P K (England: Woodhead Publishing Limited, Cambridge) pp 73-92

[9] Grainger S, Blunt J 1998 *Engineering Coatings: Design and Application* 2nd ed. Grainger S, Blunt J (UK: William Andrew Publishing) pp 1-7

[10] Kalpakjian S, Schmid S R 2002 *Manufactura, ingeniería y tecnología* 4ta (México: Editorial Pearson Educación.) pp 906-911

[11] Shipway P H, McCartney D G, Sudaprasert T 2005 Sliding wear behavior of conventional and nanostructures HVOF sprayed WC-Co coatings *Wear* 259 820-827

[12] Yang Q, Senda T, Kotani N, Hirose A 2004 Sliding wear behavior and tribofilm formation of ceramics at high temperatures *Surface & Coatings Technology* 184 270-277

[13] Stewart D A, Shipway P H, Mccartney D G 1999 Abrasive wear behaviour of conventional and nanocomposite HVOF-sprayed WC-Co coatings *Wear* 225-229(4) 789-798

[14] Gell M, Jordan E H, Sohn Y H, Goberman D, Shaw L and Xiao T D 2001 Development and Implementation of plasma sprayed nanostructured ceramics coatings *Surface & Coatings Technology* 146-147 48-54

[15] Jordan E H, Gell M, Sohn Y H, Goberman D, Shaw L, Jiang S, Wang M, Xiao T D, Wang Y and Strutt P 2001 Fabrication and evaluation of plasma sprayed nanostructured alumina-titania coatings with superior properties *Materials Science & Engineering A* 301 80-89

[16] Taimin G, Pingping Y, Xiaoting Z, Zhongyi Z, Yelong X, Lin Z, Haibin Z, Minwen D, Qi W, Aiwen Z 2016 Influence of WC carbide particle size on the microstructure and abrasive wear behavior of WC-10Co-4Cr coatings for aircraft landing gear *Wear* 362-363 135-145

[17] Standard ASTM G65-04 2010 *Standard Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus* (Philadelphia: American Society for Testing and Materials) pp 1-14

[18] Standard ASTM G99-05 2010 *Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus* (Philadelphia: American Society for Testing and Materials) pp 1-5