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# Effect of Abrasive Size on Wear

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## 1. Introduction

Due to their high wear resistance, metallic materials are usually used in some mechanical components used for extraction, processing and transportation in mining and agriculture industries. These mechanical components work in contact with hard abrasive particles of different sizes and morphologies, and, in many cases, in highly corrosive environments. As in all other forms of wear, the intensity of abrasive wear depends on the configuration of the wear system, the force applied, and the microstructural properties of materials. Abrasive wear, however, has the peculiarity of being strongly influenced by the characteristics of the abrasive particles, such as hardness, morphology and size.

There are two major groups in which abrasive wear is classified: two body-abrasive wear and three-body abrasive wear (Rabinowicz, 1961; Misra; Finnie, 1980). Two-body abrasive wear occurs when abrasive particles are fixed to one body while the second one slides over it, scratching or removing material, as, for example, in the pin-on-disc test. In three-body abrasive wear particles are free to roll and, as a result, they do not remove material from the body all the time that they are in contact as, for example, in the rubber-wheel equipment.

In abrasive wear, the material is damaged or removed by several mechanisms. In Figure 1 three mechanisms of abrasive wear are shown by scanning electron microscopy (SEM): microploughing, wedge formation, and microcutting (Hokkirigawa; Kato, 1988; Kato, 1990).

The mechanism of microploughing causes displacement of material, resulting in the formation of side edges. In the microcutting the material is removed in the form of microchips, this mechanism operates similarly to a cutting tool. The mechanisms of microploughing and microcutting are related to moderate and severe wear, respectively. Wedge formation is associated with the transition between microploughing and microcutting (Kayaba et al. 1986; Hokkirigawa *et al.,* 1987).

## 2. Abrasive morphology

Literature reports that material can be detached from the surface by microcutting when the attack angle of the abrasive particles is higher than the critical attack angle (Mulhearn; Samuels, 1962; Sedriks; Mulhearn, 1963; Sedriks; Mulhearn, 1964). A gradual transition from microploughing to microcutting occurs when the attack angle increases (Zum Gahr, 1987). This is shown in Figure 2. The attack angle ($\alpha$) is given by the angle formed between the abrasive surface and the material surface.
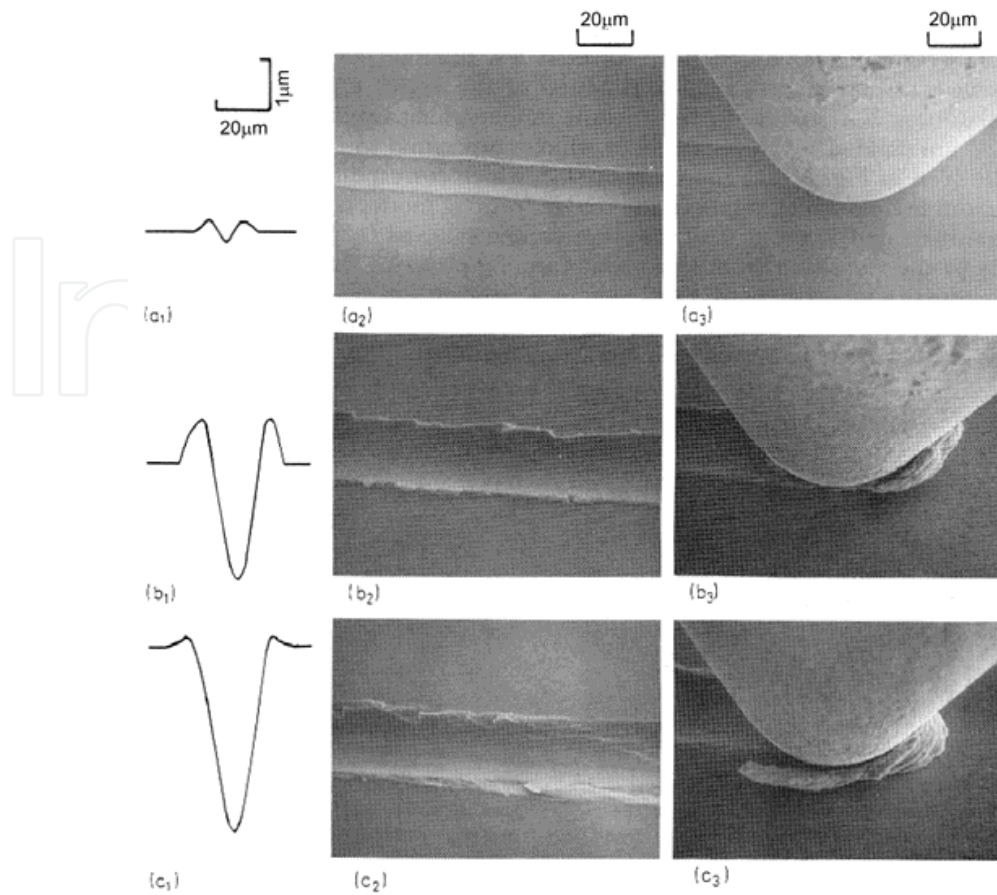
Fig. 1. Wear micromechanisms observed by SEM: (a) microploughing, (b) wedge formation
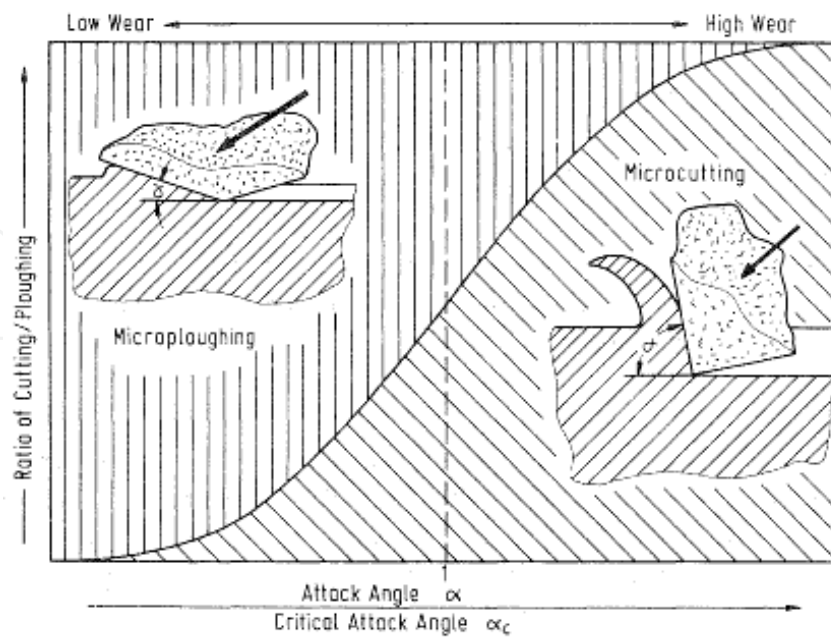(c) microcutting (Hokkirigawa; Kato, 1988)



Fig. 2. Ratio of microcutting to microploughing as a function of the ratio of the attack angle
to the critical attack angle ($\alpha_c$) (Zum Gahr, 1987)

A practical example is the aluminum alloy sheets used in trucks for transporting granular material, which show damage caused by the abrasion of sand and gravel particles. An analysis of granular material show abrasive particles of different sizes and morphologies: large particles tend to have a round shape (figure 3a), while small particles have greater angularity (figure 3b) (Mezlini *et al*. 2005).
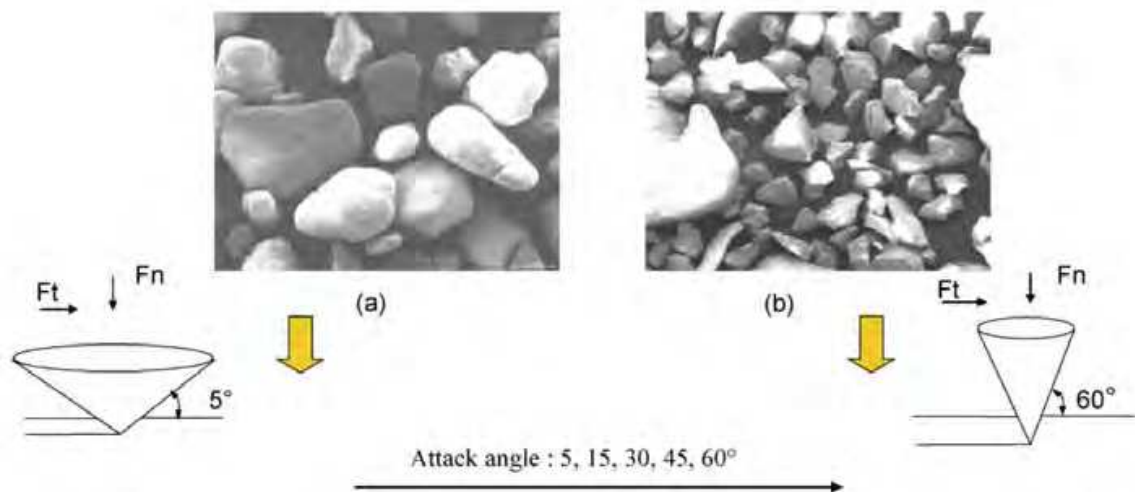


Fig. 3. SEM observations of transported granular material: (a) rounded particles, (b) sharp particles. (Mezlini *et al*., 2005)

Mezlini *et al*. (2005) performed scratch tests on 5xxx aluminum alloy to study the effect of the attack angle (geometry of the particle) on abrasive wear micromechanisms. The authors used rigid cones with different attack angles (Figure 3). When an indenter with an attack angle of 30° is used, the material is moved to the edges of the scratch, so the material is accumulated along the edges and in front of the indenter without loss of material (microploughing mechanism), this is show in Figure 4(a). When using an indenter with an attack angle of 60°, a transition in wear micromechanisms from microploughing to microcutting is produced with chip formation in front of the indenter (figure 4(b)).
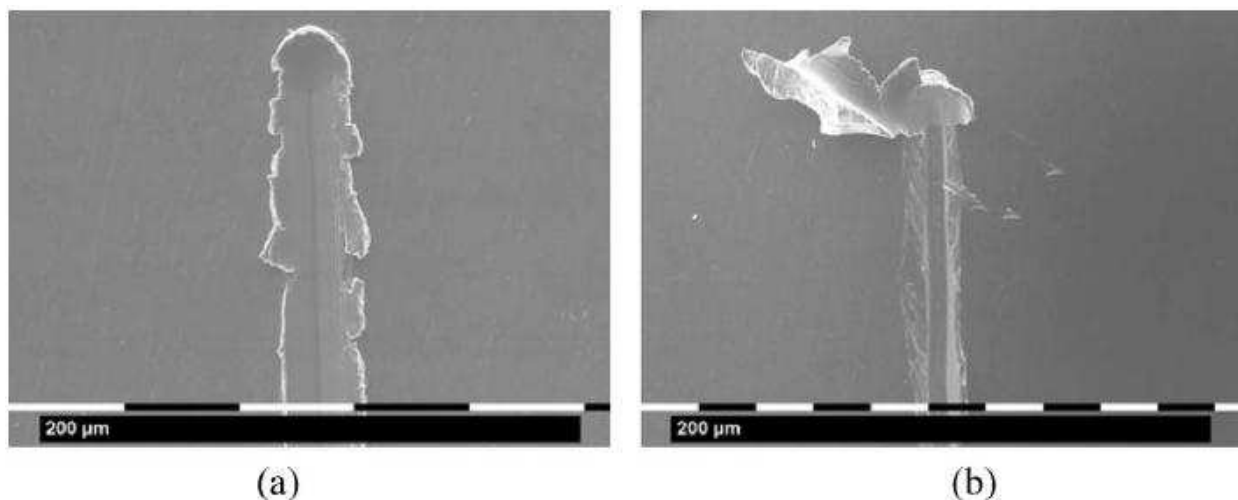


Fig. 4. SEM observations of aluminum alloy scratches for an attack angle: (a) 30° and (b) 60° (Mezlini *et al*., 2005)

## 3. Abrasive size

The literature reports that the abrasive size has a linear relationship with mass loss for small abrasives. The effect of the abrasive size on the wear rate has been studied for homogeneous materials (Anvient, 1960; Rabinowicz; Dunn, 1961; Goddard; Wilman, 1962; Rabinowicz; Mutis, 1965; Nathan; Jones, 1966; Larsen-Badse, 1968a; Larsen-Badse, 1968b; Samuels, 1971; Date; Malkin, 1976; Sin *et al.*, 1979; Misra; Finnie, 1981a; Misra; Finnie, 1981b; Sasada *et al.*, 1984; Jacobson *et al.*, 1988; Costa et. al., 1997; Gahlin; Jacobson, 1999; Sevim; Eryurek, 2006). For small abrasives, the wear rate increases proportionally with the increase in the abrasive particle size until it reaches the critical particle size (CPS). After reaching the critical particle size, the wear rate changes. Figure 5 summarizes the three behaviors described in the literature.
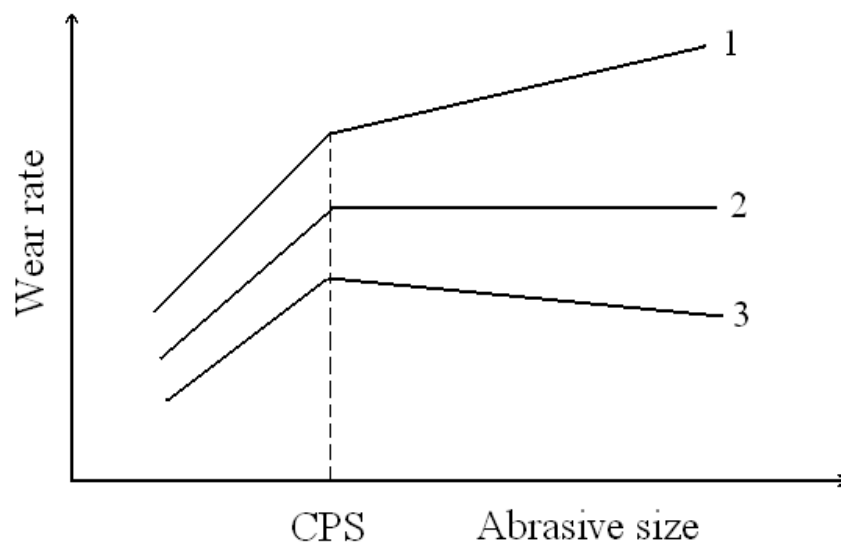


Fig. 5. Schematic representation showing the typical curves of wear vs. abrasive grain size (Coronado; Sinatora, 2011a)

After the CPS, three phenomena can occur: the wear rate can increase at a lower rate (curve 1), it can become constant, independent of further abrasive size increases (curve 2), or it can exhibit a decreasing rate (curve 3). There are many hypotheses to explain this phenomenon; however, there is still no explanation generally accepted by the entire scientific community. The phenomenon of CPS occurs in two-body abrasive wear, three-body abrasive wear, erosion and machining processes. Because of the importance of the effect of abrasive size, both in tribology and in manufacturing processes, a detailed discussion of the literature is presented chronologically in this chapter.

Anvient *et al.* (1960) conducted tests of abrasive wear in pure metals: Ag, Cu, Pt, Fe, Mo and W. The results are shown in Figure 6. The authors reported that the wear rate increased with the increase in the abrasive size in the range of 5 to 70 μm and was independent of the wear rate within the abrasive size ranges of 70 to 140 μm.
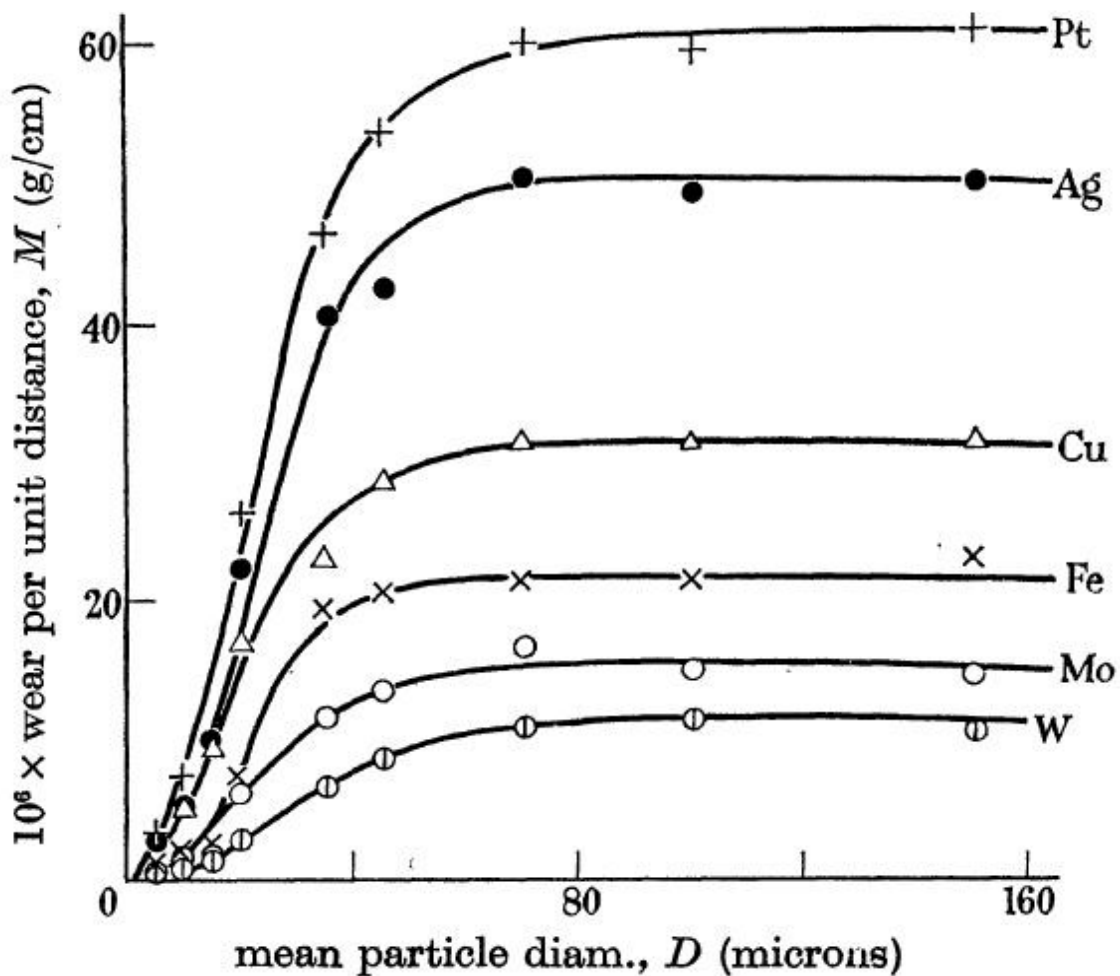
Fig. 6. Relationship between the wear rate and mean abrasive size (Anvient *et al.*, 1960)

Anvient *et al.* (1960) and Goddard and Wilman (1962) proposed that the CPS is controlled by clogging of the smaller sized abrasives. Due to the clogging is not possible in three-body abrasive and erosion, this explanation cannot explain de CPS effect (Misra; Finnie, 1981a).

Nathan and Jones (1966) conducted wear tests in copper, aluminum, brass and steel using a two-body abrasive wear equipment. The authors studied the correlation between variation of volume of wear, variation of diameter of abrasive particles of SiC (35 to 710 µm), load (0.5 - 6 kg), speed of abrasion (0.032 - 2.5 m/sec), and distance traveled (1.5 - 6 m). The results presented in Figure 7 indicate that the volume of material removed increases linearly with the size of the abrasive particles up to 70 µm. Between 70 µm and 150 µm, the gradient continuously decreases, and above 150 µm, it presents a linear relationship at a lower rate.
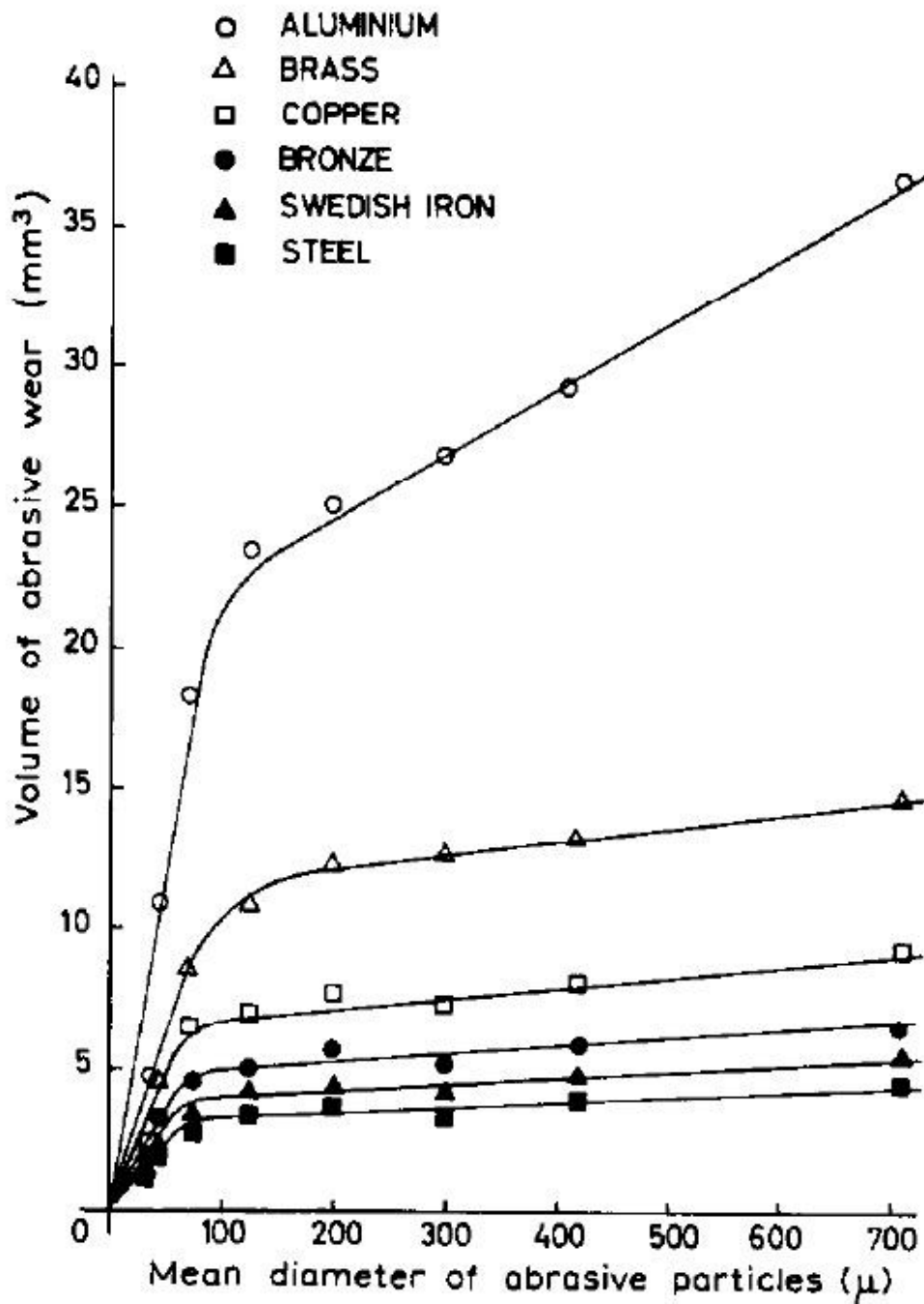
Fig. 7. Relationship between the volume of abrasive wear and the mean diameter of abrasive particles (Nathan; Jones, 1966)

Larsen-Badse (1968a) carried out two-body abrasive wear tests on copper using SiC as abrasive. The author found that the wear rate increases rapidly until it reaches the CPS. The value of CPS was in the range of 40 μm to 80 μm. Above the CPS, two things happened: the wear rate was constant for low loads and the wear rate decreased for high values of load. The results are shown in Figure 8.
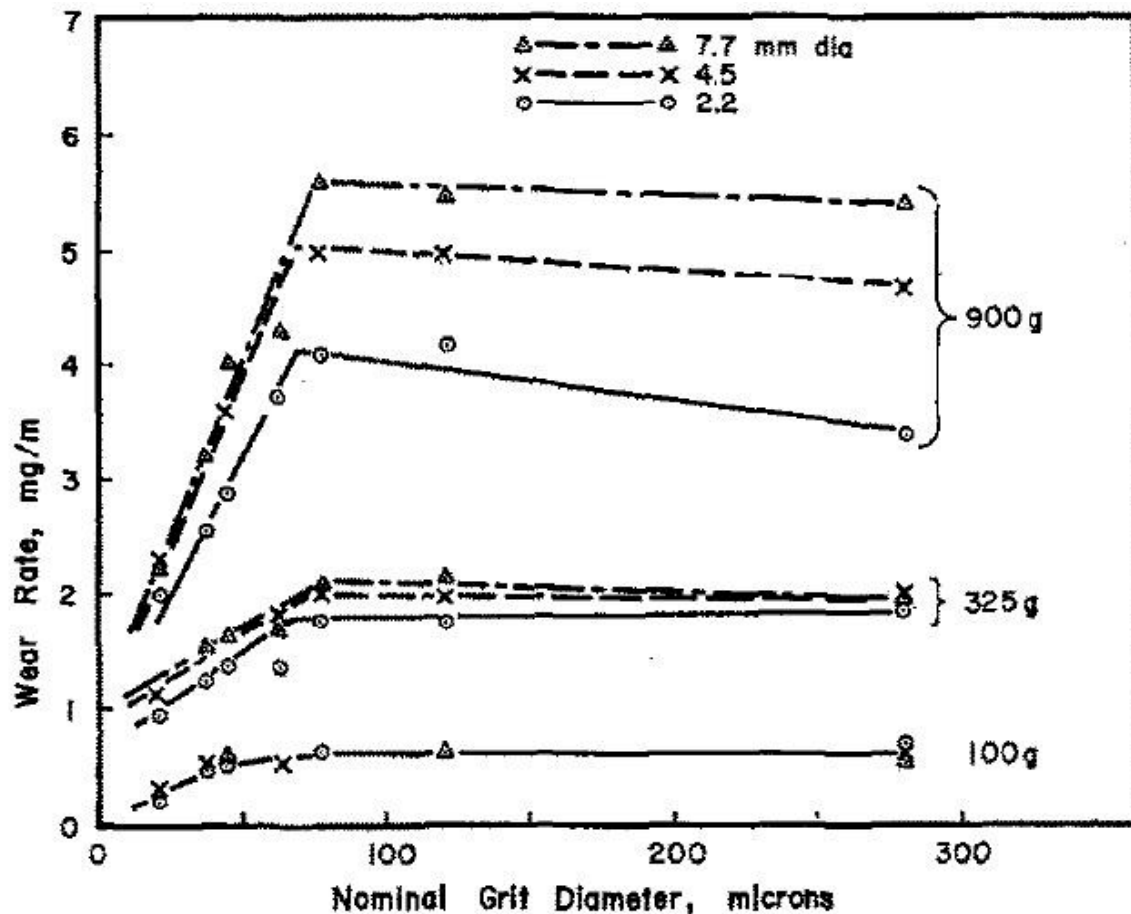
Fig. 8. Effect of grit size on wear rates (Larsen-Badse, 1968a)

Damage of smaller abrasives has been proposed by Larsen-Badse (1968a) to explain the effect of abrasive size. The explanation of the damage of smaller abrasive, however, was not corroborated, for when the abrasive size increases, the probability of finding more defects increases.

Date and Malking (1976) realized abrasion tests on AISI 1090 steel using alumina as abrasive (# 320, # 240, # 150, # 80 and # 36). The results are shown in Figure 9.

These authors performed an extensive study on the abrasives after wear using SEM and found that the largest abrasive had more damage. Date and Malking (1976) also found a deposit of material covering the surface of the abrasive below the CPS. A similar but less intense effect was present in bigger abrasives. Microchips resulting from abrasion and debris resulting from adhesion in the interstices of the smaller abrasives were also responsible for the decrease in wear rate with the decrease of abrasive size (Date; Malking, 1976). The tests were not performed on unused abrasives. Some complications observed in some of the previous work, such as clogging, could be avoided if the tests were conducted on unused abrasive.
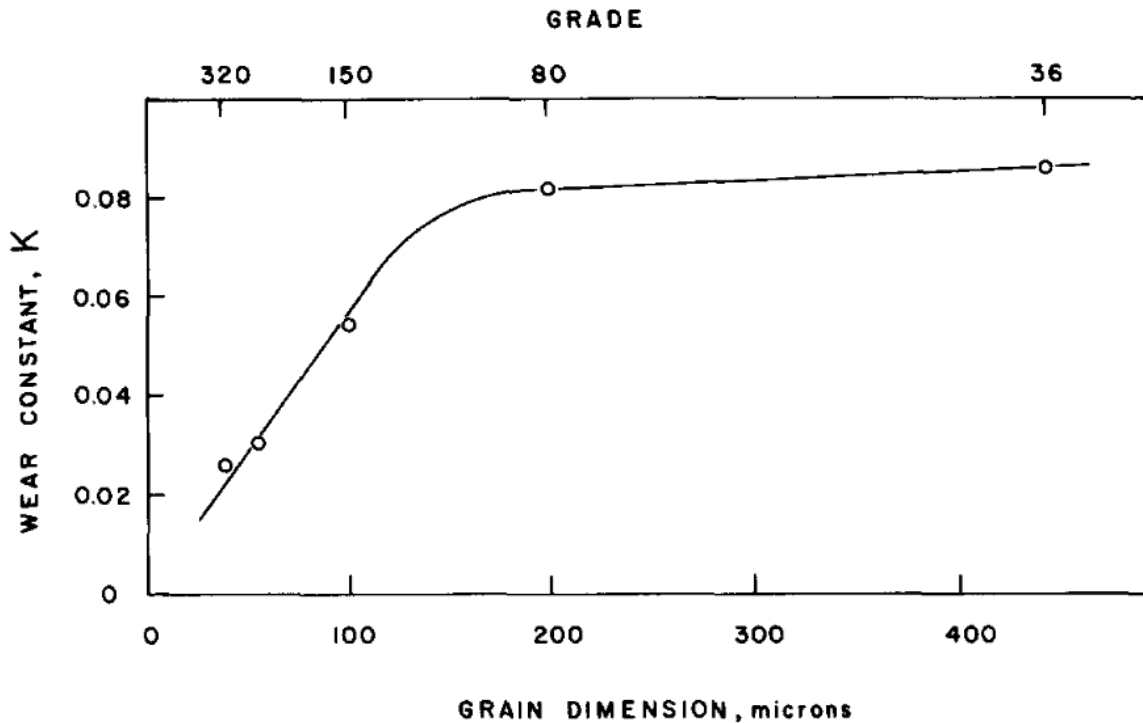
Fig. 9. Relationship between wear coefficient and abrasive size (Date; Malking, 1976)

Sin et al. (1979) conducted tests using pin-on-disc equipment in spiral trajectory using SiC abrasive. The materials tested were PMMA (polymethylmethacrylate), pure nickel and AISI 1095 steel. The results shown in Figure 10 indicate that as the abrasive size increases, the wear coefficient increases rapidly until it reaches the CPS. Above the CPS, the wear coefficient is independent of the size of the abrasive. The CPS was approximately 80 μm for the materials tested.

Sin *et al*. (1979) proposed that the effect of size of the abrasive is due to the round edges of smaller abrasive grains. Misra and Finnie (1981a) demonstrated, however, that abrasive grains of reduced sizes are more pointed. Sin *et al*. (1979) also reported that smaller abrasives with rounded ends produce more microcutting than microploughing. However, Misra and Finnie (1981a) observed the wear surfaces with SEM and found little increase in microploughing with the decrease in the abrasive size.

Misra and Finnie (1981a) carried out tests on copper using two-body abrasive wear, three-body abrasive wear and erosion. The results showed that when the abrasive SiC size is over 100 μm, the wear rate is little affected by the increase in abrasive size. Figure 11 shows that for abrasive sizes lower than 100 μm, the wear rate decreases. The wear process becomes less efficient as the particle size decreases below 100 μm. An analysis of the curves, however, shows that only two abrasive sizes larger than 100 μm were used. The authors propose that a shallow layer near the worn surface shows more flow stress than that of the bulk material. The explanation of a shallow layer was first proposed by Kramer and Demer (1961).
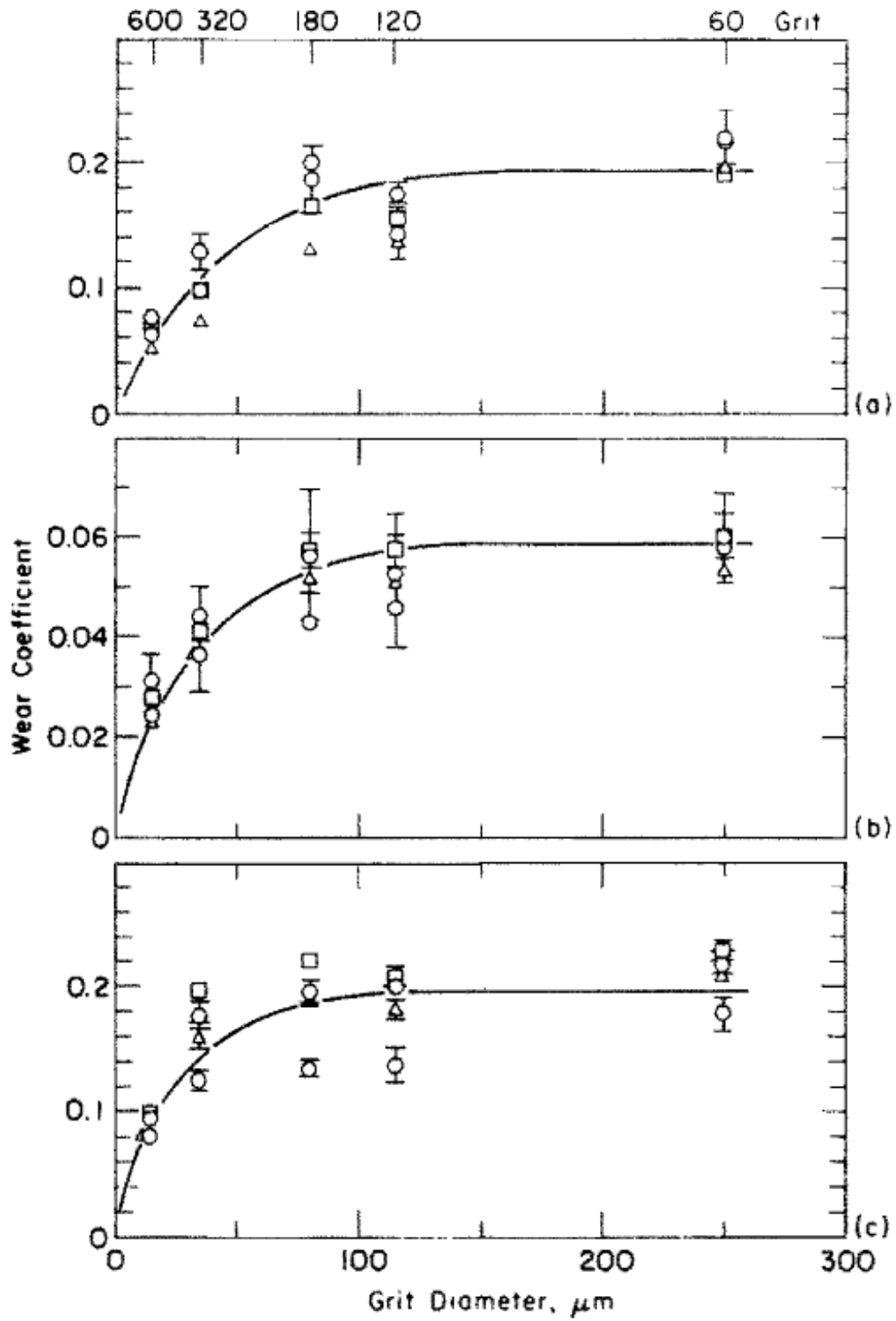
Fig. 10. Wear coefficient vs. abrasive grit diameter for different normal loads: (a) PMMA, (b) nickel and (c) AISI 1095 steel (Sin *et al.*; 1979)
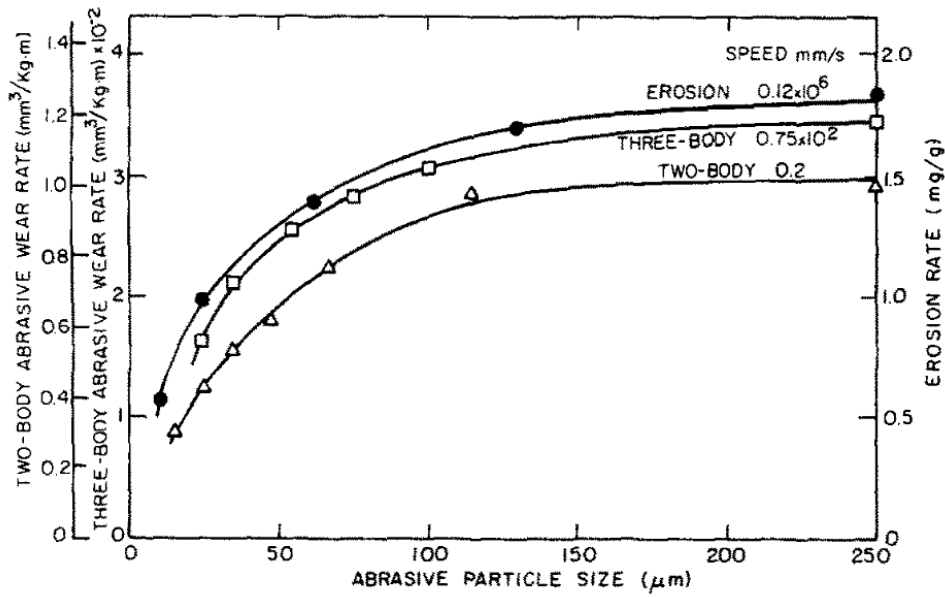
Fig. 11. Wear rate as a function of particle size for copper samples under erosion, two-body abrasion and three-body abrasion (Misra; Finnie, 1981a)

Previous research, however, was made by Goodwin *et al.* (1969). They studied the effect of abrasive size on erosion in steel using different speeds and impact angles. The authors found that above the CPS the erosion was not influenced by the size of the abrasive and this value (CPS) increased with the increase of impact velocity.
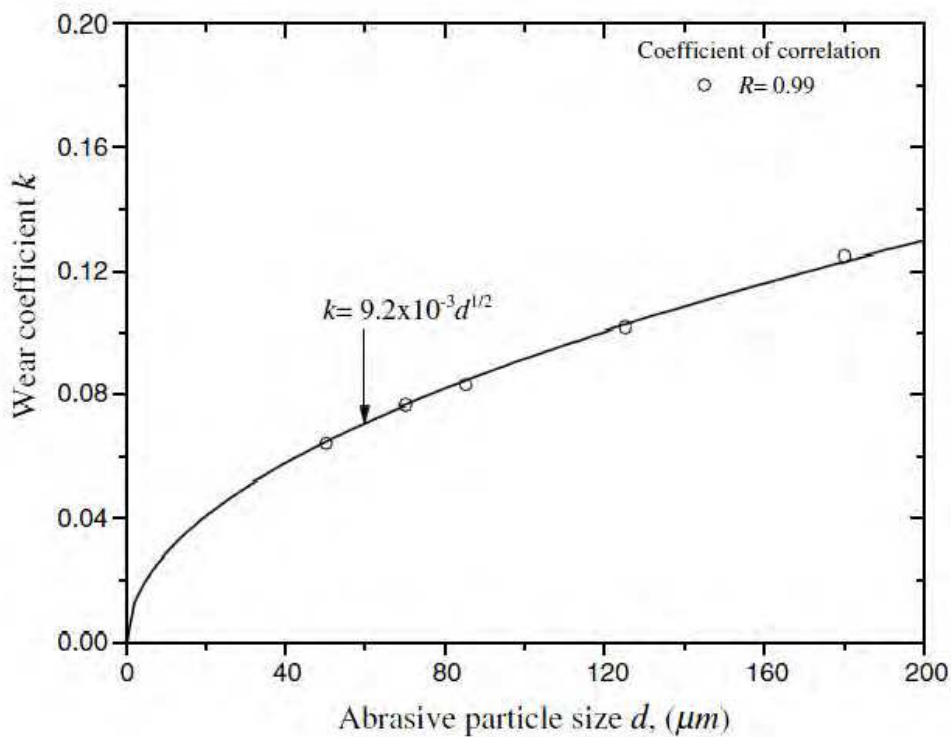


Fig. 12. Variations of wear coefficient *k* of non-heat-treated steels versus abrasive particle size *d* (Sevim; Eryurek; 2006)

In a more recent work, Sevim and Eryurek (2006) conducted tests on steels using alumina abrasives with sizes between 50 and 180 µm. Figure 12 shows that there is a parabolic relationship between the wear coefficient (*k*) and the size of the abrasive (*d*). The coefficient *k* is not constant with the increase of *d*. The slope, however, decreases with the increase of *d*. A more detailed analysis of the curve, however, indicates that a linear relationship can be used between *k* and *d* with a high correlation coefficient. The authors show that the effect of reducing the size of the abrasive grain in the severe regimen results in decreases in mass loss of about 20% to 40%.

In hard second phase materials the effect of the abrasive size on wear rate has been focused on the white cast irons with high chromium and alloy development (Santana; De Mello, 1993; Pintaúde et al., 2001; Dogan et al., 2001; Bernardes, 2005; Dogan *et al.*, 2006).

## 4. Recent works

In recent researches the effect of abrasive size on metallic materials using two-body configuration was investigated and the most relevant results are discussed in this chapter. In a first series of experiments the samples of mottle cast iron were quenched and tempered in temperatures ranging from 300°C to 600°C, forming different percentages of retained austenite (RA). For small abrasive particles, the wear mass loss increased linearly with the increase of particle size. However, for higher abrasive sizes the mass loss increased much more slowly (Figure 13). For lower abrasive sizes the main wear mechanism was microcutting. For higher abrasive sizes, the main wear mechanism was microploughing (Coronado; Sinatora, 2009).
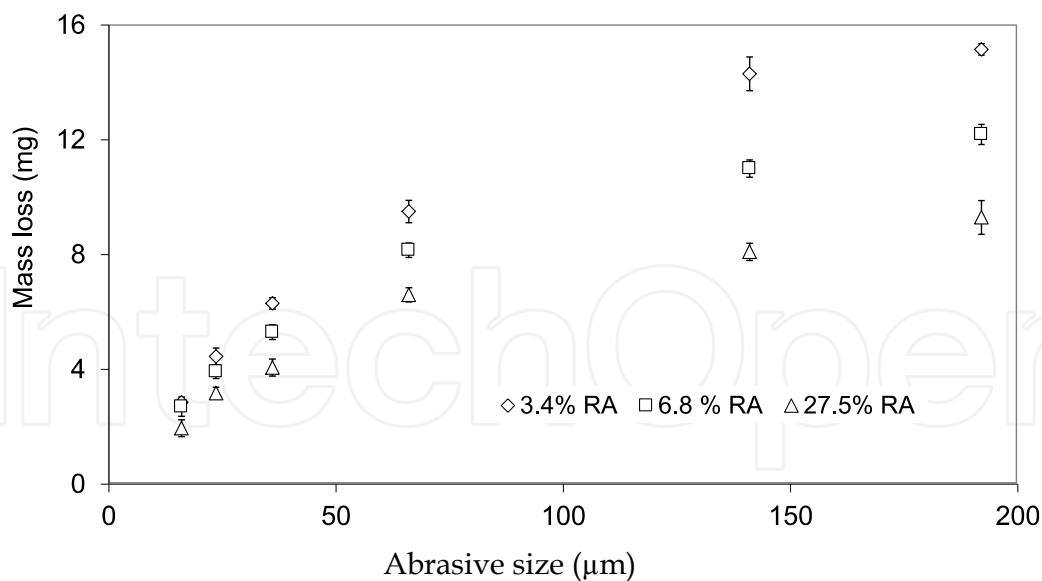


Fig. 13. Relationship between mass loss and abrasive sizes (Coronado; Sinatora, 2009)

In a second series of experiments, white cast iron with $M_3C$ carbide with austenitic and martensitic matrix were tested (Coronado; Sinatora, 2011a). The alumina abrasives of lower size are characterized by sharp tips and the alumina abrasives of greater size are characterized by rounded edges and polyhedral shapes. The results show that the mass loss for cast irons

with austenitic and martensitic matrices increases linearly with the increase of particle size, until reaching the critical particle size. After that, the rate of mass loss of the cast iron with austenitic matrix diminishes to a lower linear rate, and for cast irons with martensitic matrix the curve of mass loss is non-linear and flattens at the critical particle size. It becomes, then, constant, independent of additional size increases (figure 14). The abrasive paper in contact with the iron of both austenitic and martensitic matrices presents fine continuous microchips produced by microcutting before reaching critical particle size, and after that it presents deformed discontinuous microchips produced by microploughing (figures 15 and 16).
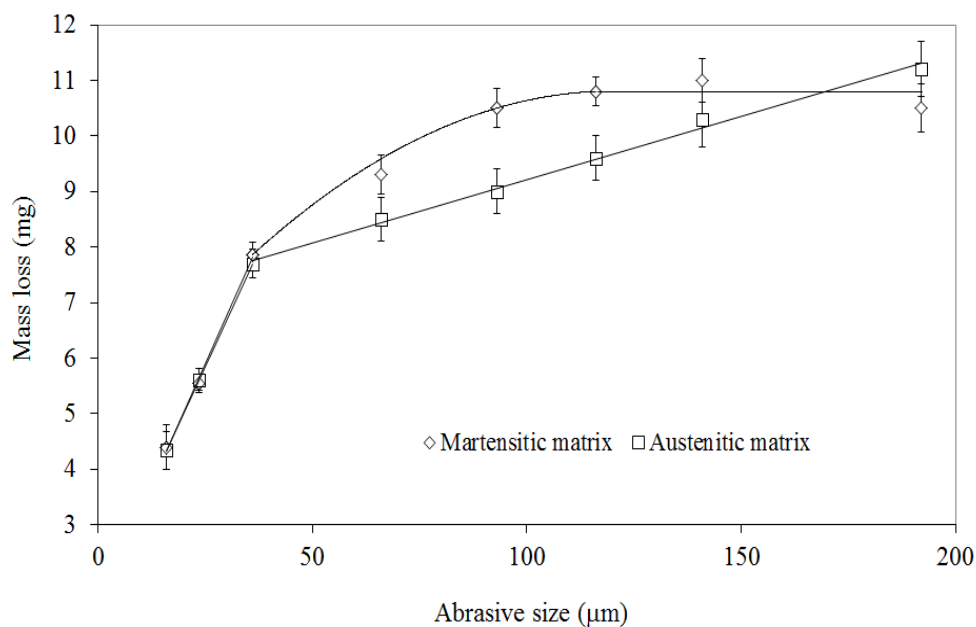


Fig. 14. Comparison between the cast iron with austenitic and martensitic matrix (Coronado; Sinatora, 2011a)
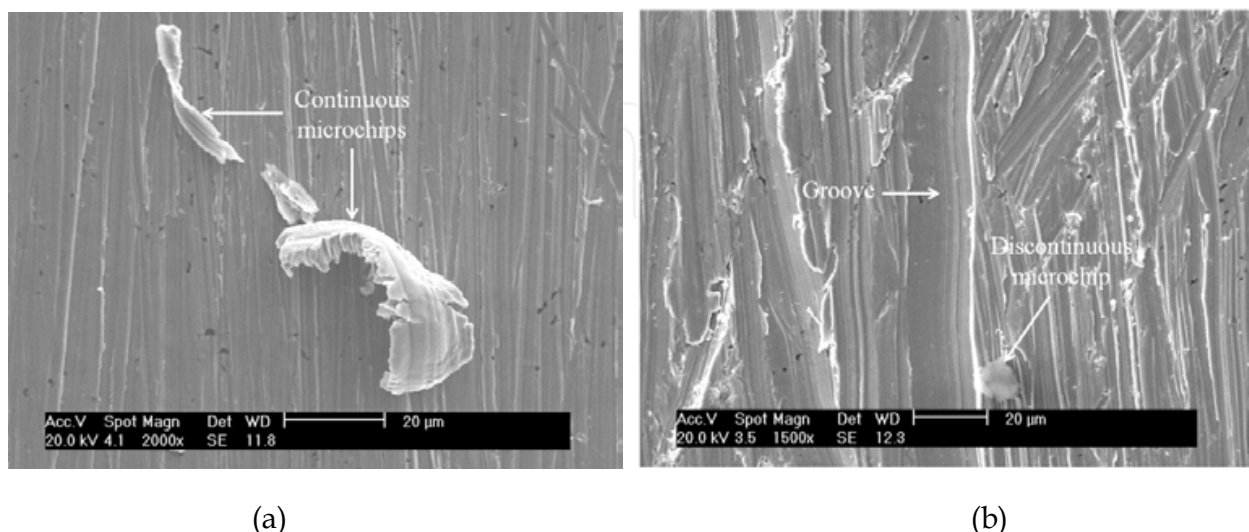


(a)                                                                    (b)

Fig. 15. SEM of the wear surface for WCI with austenitic matrix (a) 23.6 μm and (b) 141 μm (Coronado; Sinatora, 2011a)

(a)                                                                                           (b)
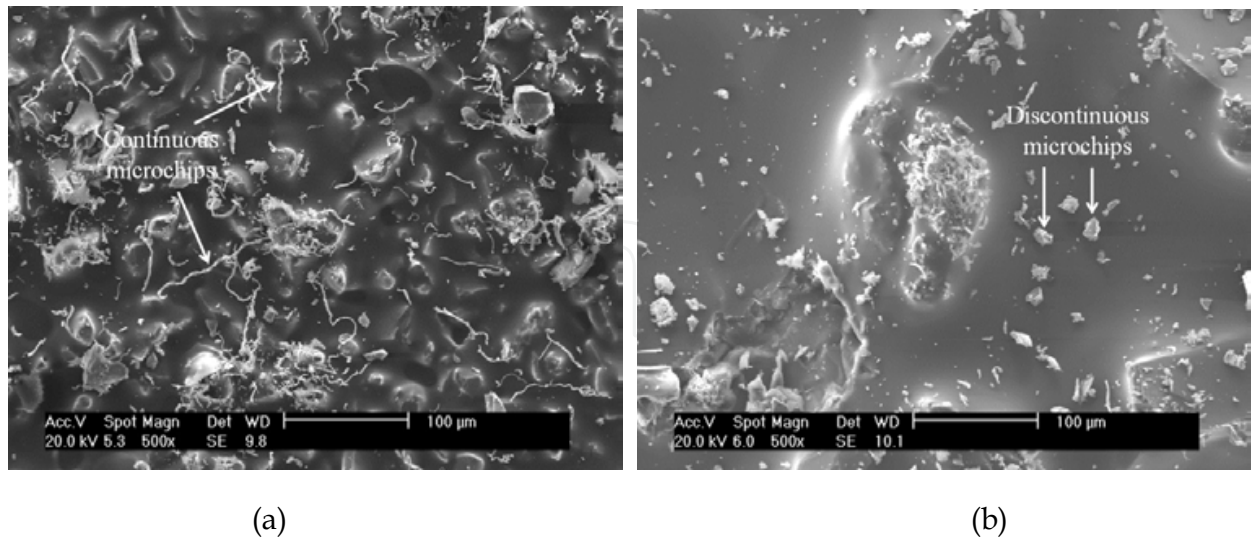
Fig. 16. SEM of the abrasive paper against cast iron with austenitic matrix and abrasive size of: (a) 23.6 μm and (b) 116 μm (Coronado; Sinatora, 2011a)

In a third series of experiments, aluminum and AISI 1045 steel were tested (Coronado; Sinatora, 2011b). The first (FCC structure) showed a behavior similar to that observed in the white cast iron with austenitic matrix, and the latter showed a behavior similar to that observed in white cast iron with martensitic matrix (Figure 17). Both aluminum and AISI 1045 steel show similar changes in microchip morphology and in wear micromechanisms, something that had been observed before in materials with a hard second phase (Figures 18 and 19).



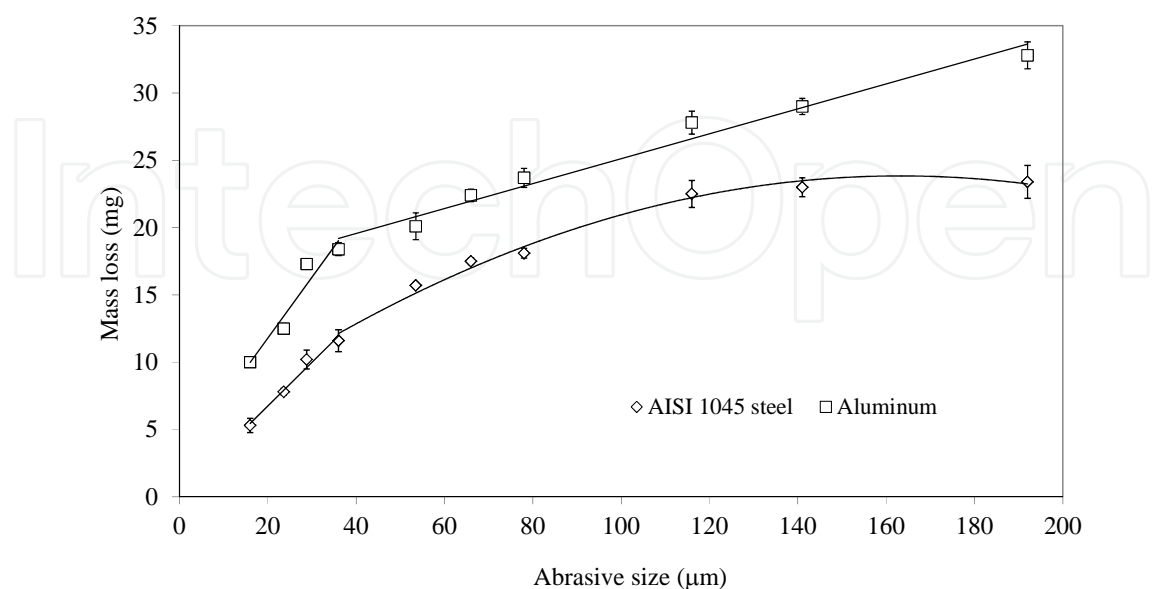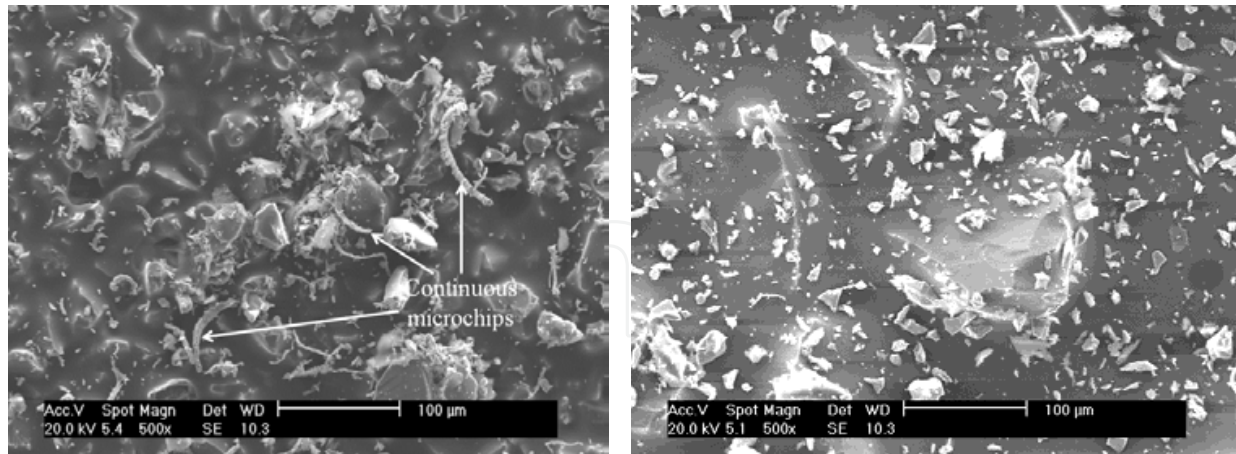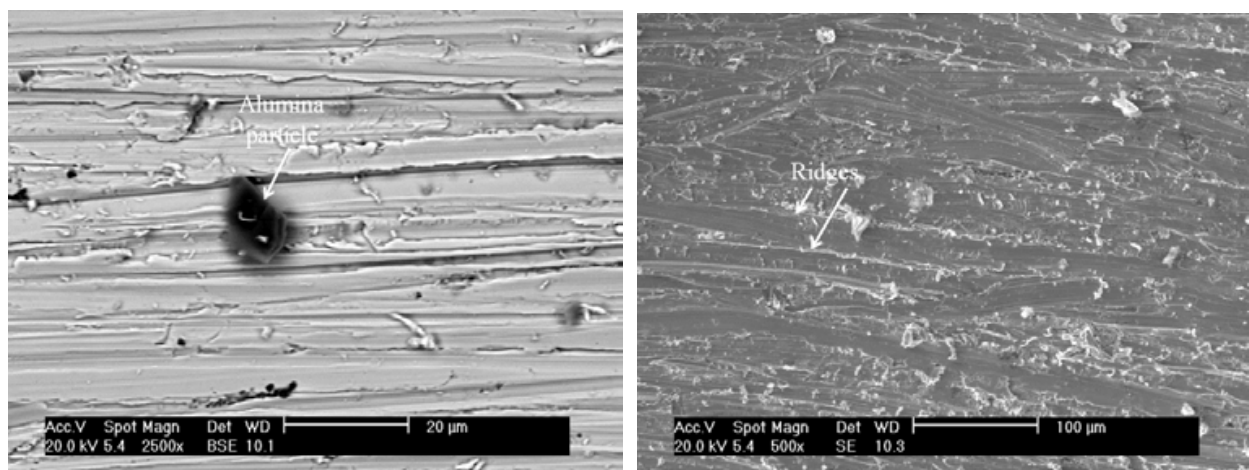Fig. 17. Comparison between the AISI 1045 steel and the aluminum alloy (Coronado; Sinatora, 2011b)

(a)                                                                                    (b)

Fig. 18. SEM of the abrasive paper against AISI 1045 steel and abrasive size of: (a) 23.6 μm and (b) 141 μm (Coronado; Sinatora, 2011b)



(a)                                                                                    (b)

Fig. 19. SEM of the wear surface of AISI 1045 steel using alumina of: (a) 23.5 μm and (b) 141 μm (Coronado; Sinatora, 2011b)

Finally, in a fourth series of experiments, gray cast iron was tested in order to demonstrate the relationship between the abrasive wear micromechanisms and the type of microchips, before and after achieving critical abrasive size (Coronado; Sinatora, 2011b). The gray cast iron did not show a transition in the curve of abrasive size against mass loss (figure 20). The morphology of the microchips was similar (discontinuous) for the different sizes of abrasive. However, smaller abrasive sizes – some thin continuous microchips – were formed (figure 21). The main abrasive wear micromechanism was microcutting for the different abrasives sizes tested (Figure 22). This, therefore, shows that the critical abrasive size is related to the wear micromechanisms and the microchip morphology.
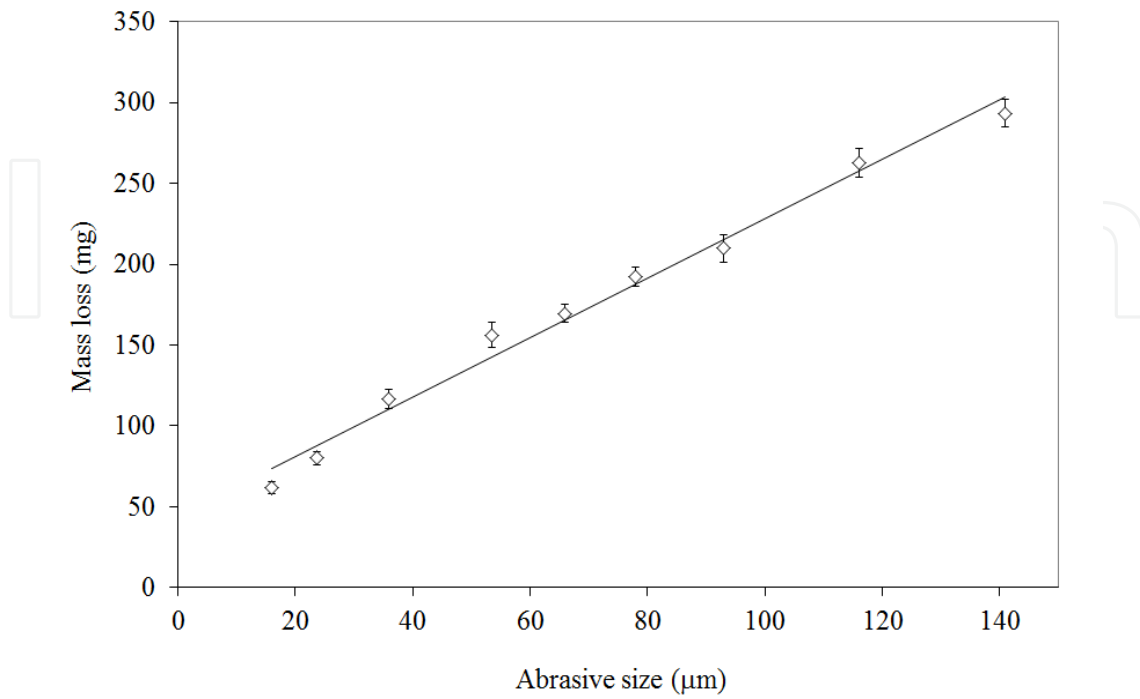
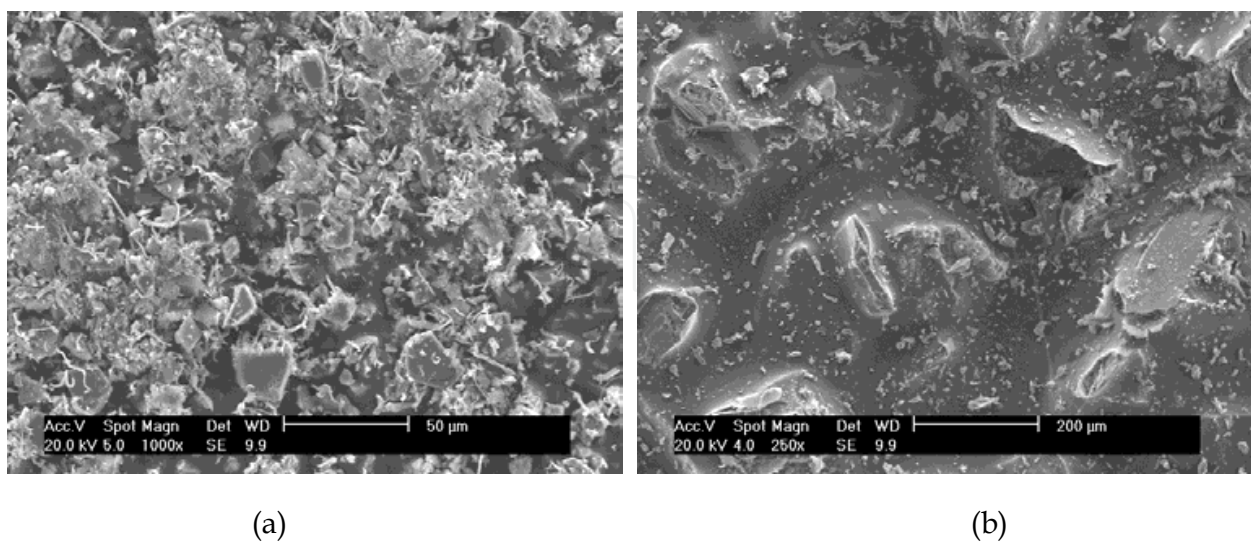Fig. 20. Relationship between mass loss and abrasive size for gray cast iron (Coronado; Sinatora, 2011b)



(a)                                         (b)

Fig. 21. SEM of the abrasive paper against gray cast iron and abrasive size of (a) 16 μm and (b) 116 μm (Coronado; Sinatora, 2011b)

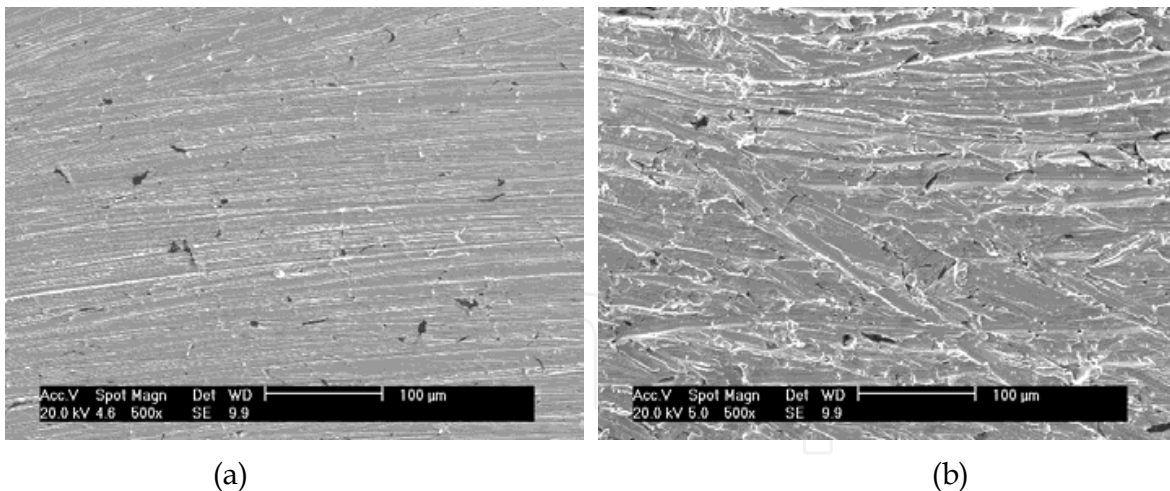(a)                                                                                                    (b)

Fig. 22. SEM of the wear surface of gray cast iron using alumina of: (a) 16 μm and (b) 116 μm (Coronado; Sinatora, 2011b)

## 5. Conclusions and future trends

For metallic materials and using two-body abrasive configuration, the following general conclusion can be obtained: at lower abrasive sizes the sharp tips cut the material with lower penetration producing continuous undeformed microchips. However, at some critical abrasive sizes, the prevalent wear mechanism changes from microcutting to microploughing, producing discontinuous deformed microchips. With abrasives of bigger sizes with round edges and polyhedral shapes, the microploughing component decreases the wear rate because the plastic deformation becomes more important than the microcutting action (Coronado; Sinatora, 2011a,b).

Although recent researches show an adequate explanation to the phenomenon of critical abrasive size, there can be no assurance that these results can be generalized for all abrasive wear settings. In the future, the effect of grain size in three-body abrasive wear and erosion should be studied, in order to know whether the results found in the two-body abrasive wear in metals are also valid for three-body abrasive wear and erosion.

Nowadays, there is a significant potential growth in the use of ceramics and polymers with the purpose of protection of components subjected to wear, but studies in the literature do not mention abrasive size effect in these materials, with some exceptions. The study of this phenomenon in ceramic materials and polymers in two-body abrasive tests is an area of research and practical interest yet to be developed.

One thing the development of research in this area has demonstrated is that in the analysis of any engineering materials, a good approach to follow is to observe the effect of abrasive size in composite materials using two-body abrasive wear configuration in correlation with the wear micromechanisms and microchips formed, comparing results with those from the materials previously researched.

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