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Metal adhesion issues in dry grinding: The role of active fillers

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ABSTRACT

The dry grinding of metals is a common machining operation. The main issue with such techniques is metal adhesion on the abrasive tool, which decreases the material removal rate. In this work, the effect of active filler metal loading with materials such as cryolite and KBF_4, which are present in the resin of commercial abrasive belts, was studied. Grinding belt experiments and friction tests were performed with carbon and stainless steel and with belts containing zirconia-reinforced-alumina grains, as well as active fillers. The tests were followed by SEM-EDX, TEM or XPS characterizations of the belts and ceramic pieces. Different behaviors were observed for different types of metal, as stainless steel is more sensitive to loading than carbon steel, and because active fillers have a stronger positive effect against metal adhesion, such as in the case of stainless steel. Then, a fluorine based layer, derived from the active fillers, was found at the interface between the grain and the metallic transfer. This layer likely limits the adhesion of metal on the grain and decreases the contact friction, as well as the specific grinding energy (SGE). The corrosion of alumina in the abrasive grains by active fillers was also observed near contact temperatures. Finally, the results are discussed to gain a better understanding of different active filler action mechanisms taking place during the steel grinding process.

1. Introduction

For dry grinding metals, the cutting efficiency of an abrasive tool is related to the mechanical properties of the abrasive grains. The grains need to be well adhered to the support and need to be much harder than the material being ground to easily remove the metal through abrasive wear (plastic deformation) [1]. The cutting efficiency can decrease because of the blunting of grain edges or metal adhesion. When these processes occur, grain fracture is required to yield new sharp cutting edges. Finally, hard materials with optimized fracture toughnesses are often used as abrasive grains [2]. Ceramic grains such as alumina, alumina–zirconia composite, diamond, SiC, etc. are commonly used in such applications [2].

One of the main issues in grinding processes is metallic transfer on the abrasive tool. This metal may come directly from the machined steel or from metal chips emitted during the cutting operation. Adhesion of the metal to the ceramic then occurs. Because the plastic flow stress of the metal is much lower than for the ceramic, metal transfer is formed on the ceramic grain [3]. This fouling of the tool results in a significant decrease in cutting efficiency, which is associated with an increase in the required energy to machine. According to the nature of the steel being ground, this phenomenon varies in importance. Metal adhesion must be limited on abrasive tools to ensure that the tool retains its grinding capacity.

In this work, a belt grinding tool is considered. This abrasive tool consists of a backing, a coating and ceramic grains. The coating is usually made of a polymeric resin with fillers such as cryolite, KBF_4 or $CaCO_3$. Different patents are mentioning for the types of fillers [4–6]. $CaCO_3$ is known to reinforce the mechanical behavior of the resin as the temperature increases. Cryolite (Na_3AlF_6) and KBF_4 are employed for the role they play in the frictional behavior of the metal/grain interface [7,8].

In this work, it is proposed to investigate in detail the roles of active fillers during grinding operations. Several questions that we will address include: Are they lubricating the contact? Are they corroding the metal? Are they corroding the grains? Are they limiting the temperature at the contact (by endothermic reactions for example) [9]? Are their actions the same for different metals?

To answer such questions, the effect of active fillers is studied on the grinding efficiency in two ways:

(1) First, performing an “industrial” test to mimic real conditions and referred to here as a belt grinding test. Mechanical measurements are performed during the experiments and *post-mortem* analyses of the worn belts are also performed.
(2) Second, tests on a specific tribotest are developed and performed to investigate the role active fillers have on the tribological properties of the grain/steel contact.

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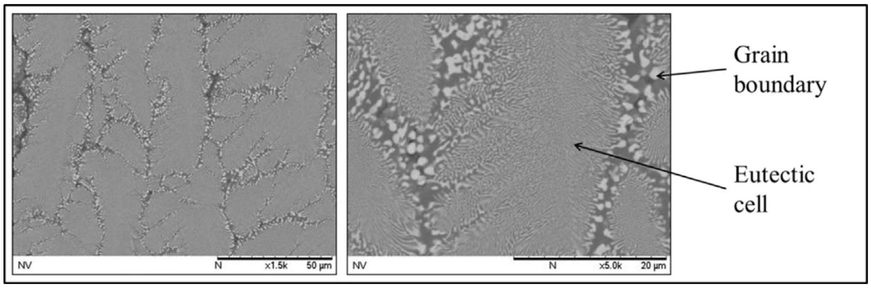

Fig. 1. Structure of the abrasive grain composed of eutectic zirconia reinforced alumina (ZRA) as observed by SEM after polishing (white area=zirconia and black area=alumina).

The originality of this experimental approach is first to combine both industrial and tribological tests and then to perform characterization (SEM-EDX, XPS and FIB-TEM) of friction parts.

2. Materials and method

2.1. Materials

2.1.1. Ceramics

Various ceramics were used as abrasive grains for grinding metals. In this paper, an eutectic composition of zirconia reinforced alumina (called ZRA, 60% alumina–40% zirconia) is studied. The zirconia is partially stabilized in the tetragonal and cubic phase by adding small quantities of yttria. This ceramic combines the high hardness of alumina and the “high” toughness of the partially stabilized zirconia. The structure of the ceramic (eutectic composition of alumina and zirconia) is shown in Fig. 1.

2.1.2. Commercial and specific belts

Different abrasives belts are made with this ZRA grain (with grain diameters between 500 and 600 μm). However, they all exhibit the same structure shown in Fig. 2.

For all of the belts, the backing is a finished fabric containing the first coating layer, which is composed of phenolic resin and $CaCO_3$ is deposited. In the second layer, some “active fillers” may be added to the phenolic resin to improve the belt efficiency. These active fillers are fluorinated compounds as cryolite (Na_3AlF_6) or KBF_4. Table 1 presents the composition of the different belts, both commercial and specific (with either no active fillers or cryolite).

2.1.3. Metals

Two metals are studied in this paper: 304 stainless steel (304 SS) and 4140 carbon steel (4140 CS). Their compositions are given in Table 2. Both metals have a Vickers hardness of 200 HV at ambient temperature.

2.2. Belt grinding test

The belt grinding test allows the abrasive tool to be worn under conditions close to industrial ones. The belt linear speed is 30 m/s and a metal bar is ground at a constant feed rate. A complete grinding test is composed of a succession of 6 cycles lasting 10 s separated by 60 s, as schematically shown in Fig. 3a. A new belt is used for each test.

During the test, two parameters are measured and recorded: the applied normal load necessary to maintain a constant material removal rate; and the power supplied to the machine, which permits the calculation of the specific grinding energy

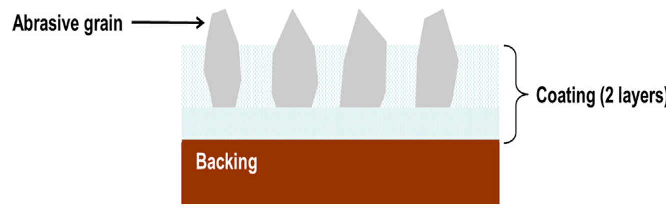

Fig. 2. Structure of the abrasive belts.

Table 1
Belt compositions.

Belt designation	Backing	Abrasive grain	Coating composition (second layer)
Commercial belts	Finished fabric	Zirconia reinforced alumina	Phenolic resin and mixture of cryolite and KBF_4
Only cryolite belt	Finished fabric	Zirconia reinforced alumina	Phenolic resin and cryolite
Belt without active filler	Finished fabric	Zirconia reinforced alumina	Phenolic resin and $CaCO_3$

Table 2
Metal (304 stainless steel and 4140 carbon steel) compositions.

	Fe (%)	C (%)	Cr (%)	Ni (%)	Mn (%)	Si (%)	Mo (%)
304 SS	69.94	0.06	18	9	2	1	–
4140 CS	97.26	0.40	1.00	–	0.87	0.27	0.20

(SGE). This represents the belt efficiency and is defined by

$$SGE\left(\frac{J}{mm\hat{3}}\right) = \frac{Power * Time}{Volume\ of\ metal\ grinded}$$

A low SGE is representative of an efficient belt, which is able to remove a large volume of material for a low power.

Fig. 3b shows the typical evolution of the mean SGE value for each cycle during the tests. The evolutions obtained are similar for identical conditions, indicating good reproducibility between tests.

2.3. Belt characterization

After the grinding test, the worn belts are characterized using

(1) Scanning Electron Microscopy (SEM) coupled with Energy Dispersive X-ray spectroscopy (EDX) to quantify the metal transfer on the grains. The apparatus used was a TESCAN microscope.
(2) Then, X-ray Photoelectron Spectroscopy (XPS) was performed on the worn grains, after any transferred metal was removed. This technique permits determination of the elements present by analyzing the first ten nanometers of the selected surface. The apparatus used is an ULVAC-PHI Versaprobe II with a