The influence of crystalline structure of alumina abrasive grains on wear flat generation

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Abstract. Despite the development of new abrasives, vitrified alumina grinding wheels are still the most competitive, so, abrasive wheel manufacturers are continuously developing a new generation of alumina abrasive grains. The latest developments are related to microcrystalline alumina abrasive grains. Concurrently, wheel wear is a critical issue for grinding process, leading to a great economic loss. Therefore, to know how the new abrasives behave during a grinding operation is the key to improve grinding process efficiency. Wear flat is one of the most difficult type of wear to characterize and at the same time generate the greatest damage in the workpiece, mainly thermal damage. In order to improve the knowledge of wear mechanisms involved in the loss of cutting ability of abrasive grains, the characterization of wear flat on alumina abrasive grains with different crystalline structure is carried out. The results show the higher *%A* reached on microcrystalline abrasive grains and the variation of contact condition between abrasive grains and workpiece due to the third body generation.

Introduction

Grinding process is a finishing process commonly used if low tolerances and high surface quality is required, being the most critical issue of this process is wheel wear. To minimize wheel wear, wheel configuration is as important as grinding parameters chosen. Worn design of both elements has an influence on process efficiency and workpiece quality leading to a dynamic problems and even surface burn [1].

Grain fracture, bond fracture and wear flat are the most significant types of wear [1], [2]. Wear flat leads to a power increase and thermal damage on the final surface. If workpiece surface is burned, the workpiece have to be refused, with the economic losses that it implies. For this reason, from a scientific point of view, to know the appearance of wear flat and its quantification is one of the key to improve grinding process.

Commonly, wear flat is characterized as a tribochemical wear. The combination of wear mechanisms as chemical reactions, plastic deformation and mechanical friction leads to a flat surface on the abrasive grain. Wear flat is quantified as a percentage of flat area in total of apparent area of grinding wheel, *%A* [3]. The randomness of the surface difficult the detection and quantification of wear flat. There is not exist a predominant methodology to detect and quantify it. In case of non-contact methods, the quantification of wear flat is done processing the images, using automatic methods based on binary segmentation techniques [4], [5]. These techniques are capable to distinguish between flat surface and brightness of abrasive crystals, leading to a real quantification of *%A*.

Wear flat generation has been addressed from two field of study, grinding process and tribological contact. Some authors [3], [6] studied generated wear during grinding process directly, achieved pressures are around 1-2GPa and cutting speed of 30m/s [2]. Under these conditions, chemical reactions together with adhesion and abrasion take place. This combination leads to a third body generation, changing tribological behavior, and contact conditions between abrasive grains and workpiece material. Third body always is generated when 2 bodies are in contact and the previous wear mechanisms take place.

The third body is directly related to wear flat generation and the composition depends on both materials in contact. Malkin show the third body adhered being spinel ($FeAl_2O_4$) the predominant component. Also results shown that the normal forces increases with the *%A*, decreasing friction coefficient promoted to third body adhered to flat grain [3].

Furthermore, Nadolny carried out more recent study on internal cylindrical grinding using SG alumina wheels [6]. In this case wear flat had not been isolated. The work concluded that SG abrasive grains suffer micro chipping, thermo-fatigue wear and also plastic flow during grinding.

The study of tribological contact is the previous step to well understanding of abrasive grain wear during grinding. Ravikiran [7] carried out only tribological studies, and its results are useful to understand the behavior of abrasive grains during grinding. 50MPa is the maximum pressure and 12m/s the maximum sliding speed, values that are not close to grinding contact conditions. However, Ravikiran confirm the third body generation due to the contact of alumina and steel and the changes promoted on the contact. Therefore, the effect of third body in the contact has to be studied to ensure a deep analysis of wear between two bodies.

Following this trend, pin on disk tests are carried out by Klocke [8] to characterize SG alumina wear. Contact conditions implemented are sliding speed of 2m/s and contact pressure of 1.5GPa. The order of magnitude of pressure is the same that achieved during grinding, however, sliding speed is smaller, making more complex the extrapolation of result to grinding process. Regarding to wear of SG, third body is adhered to worn alumina. In this case, the main component is FeO and spinel could be found adhered to plastically deformed SG.

The main objective of this work is to understand the influence of crystalline structure on wheel wear, particularly on wear flat. Grinding tests are carried out using very hard grinding wheel with the aim of isolate wear flat. This study is a complement to a previous study [9] in which only WFA and SG alumina were studied. In this case, also monocrystal alumina is included to better understanding of the influence of wear flat generation.

Methodology and experimental set up

Conventional, monocrystalline and microcrystalline structures of alumina are studied. Furthermore, to isolate wear flat from bond and grain breakage, very hard grinding wheel is chosen 60R6V89, grade R. Wheel hardness difficult the grain pull out. The force needed to this kind of wear occurs have to be higher than if softer grinding wheel is used. The dimension of abrasive grinding wheel is 220x40x127mm, being the size of abrasive grain of 250µm and with vitreous bond. Workpiece material employed to study wear flat generation is tempered AISI D2, with a hardness of 60 ± 2 HRC. This material present high wear resistance and low machinability and it is widely used as tool steel. The dimensions of workpiece are 30x20x100mm. The combination of hard grinding wheel and hard steel promotes wear flat generation, which is the objective of this experimental study.

Grinding tests are carried out on a surface grinder Blohm Orbit CN 36. Grinding forces are measured using KISTLER 9257B dynamometric device during the tests. Also wheel surface images are taken both in the grinder machine during the tests, using Optical PCE MM200 Fig. 1 (c), with magnification of 200.

Wear flat characterization is carried out analyzing the evolution of wheel wear during accumulative grinding tests. Grinding wheel is only dressed at the beginning of the tests in order to ensure the same initial contact conditions in all the tests. During a complete test the wheel is not dressed to achieve an accumulative wear in the surface. Dressing parameters are shown on Table 1. The influence of cutting parameters on wear flat appearance is studied varying depth of cut and workpiece speed. Sliding speed is constant for all the tests, on Table 1 test parameters are shown. Each grinding tests is carried out with grinding width of b_w=10mm, and on each test the specific material removal is 100 mm^3/mm. The complete test is divided in 10 parts and after each part wheel surface is measured. In order to control real depth of cut, after each grinding pass real a_e is measured and spark out is done.

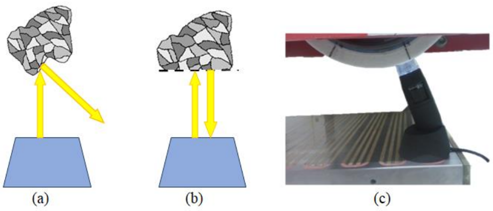

Fig. 1 (a) Light reflexion on non flat surface, (b) light reflexion on flat surface and (c) surface measurement set up.

Regarding to wear flat characterization, firstly surface images are taken using a coaxial light, allowing wear flat identification. To determine wear flat areas, light reflection is employed. If the light shines on no flat surface the light reflects on any direction as show Fig. 1(a). These flat parts correspond to wear flat area. On the contrary, if the light shines on flat surface Fig. 1(b), it reflects perpendicularly to flat, and the microscope receives the light rays, being wear flat easily identifiable as brightest area of the images. The images are processed using Leica commercial software based on binary segmentation. Furthermore image filters are used to delete brightness that not corresponds to wear flat areas. This software also allows the quantification of wear flat as *%A*. All images are measured in different wear states in order to evaluate the evolution of wear flat appearance.

Table 1 Grinding and dressing parameters

TEST	**v_s [m/s]**	**v_w [mm/min]**	**a_e [µm]**
1	30	15000	10
2	30	15000	15
3	30	25000	10
4	30	25000	15

Dressing Parameters		
v_s [m/s]	**v_d [mm/min]**	**a_d [µm]**
30	250	10

Results and discussion

Before starting with the discussion of the results, it is convenient to clarify the differences found between programmed and real depth of cut. While programmed depth of cut is of 10-15µm, real depth of cut is of 3-5 µm. Therefore, the results are based on real measured parameters. The reason of these dissimilarities is the elastic deformation of grinding machine increased by the hardness of employed grinding wheel. Tests are designed to promote wear flat, therefore obtained values of *%A* are going to be higher and are achieved more quickly than on industrial grinding process.

With respect to the influence of crystalline structure of abrasive grains Fig. 2(a) represent *%A* evolution for test 2.This graph shows a similar linear increasing tendency for all studied structures. The first time that worn surface is measured is at 10 mm^3/mm and the value is about 6.5% in all cases. However, microcrystalline structure present higher slope and a maximum value reached of 14%. Conventional and monocrystalline wear flat is 12% approximately. Therefore, microcrystalline present higher tendency to get flat under finishing grinding conditions. Monocrystalline and conventional abrasive are more adequate to finishing.

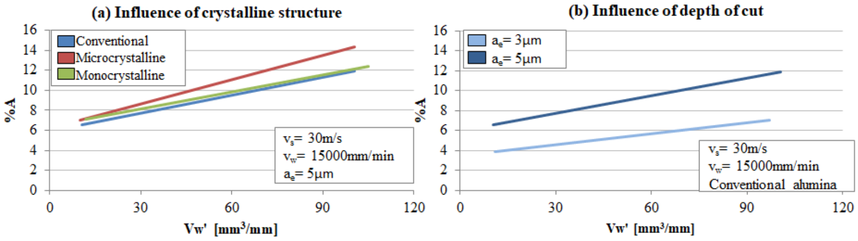

Fig. 2 Wear flat evolution with specific removal rate. **(a)** Influence of crystalline structre, **(b)** Influence of a_e.

Regarding to depth of cut, Fig. 2(b) shows that higher a_e lead to higher *%A* reached at 100 mm^3/mm, 4% in case of a_e=3 µm and 6.5% for a_e=5 µm. All studied structures behave in the same way. Contrary, workpiece speed influence does not present a clear tendency. depending on compared crystalline structure, tendencies are different.

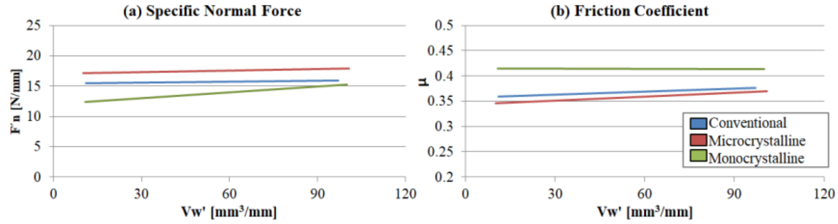

Fig. 3 Test 1, (a) specific normal force and (b) friction coefficient evolution with specific removal rate.

Concerning to grinding forces, on Fig. 3(a) specific normal force evolution with specific removal rate achieved on test 1 for all crystalline structure is plotted. F_n' presents so slightly increase with specific removal rate and hence with *%A* independently of grain structure. From monocrystalline to microcrystalline structure, the increase of F_n' mean value is of 18%. On the contrary between conventional and microcrystalline structure the difference is less than 7%. In general, the increase of F_n' is negligible comparing with results obtained by Malkin, in which a clear increasing tendency of forces is shown with wear flat evolution. The reason of these dissimilarities is the range of studied parameters.

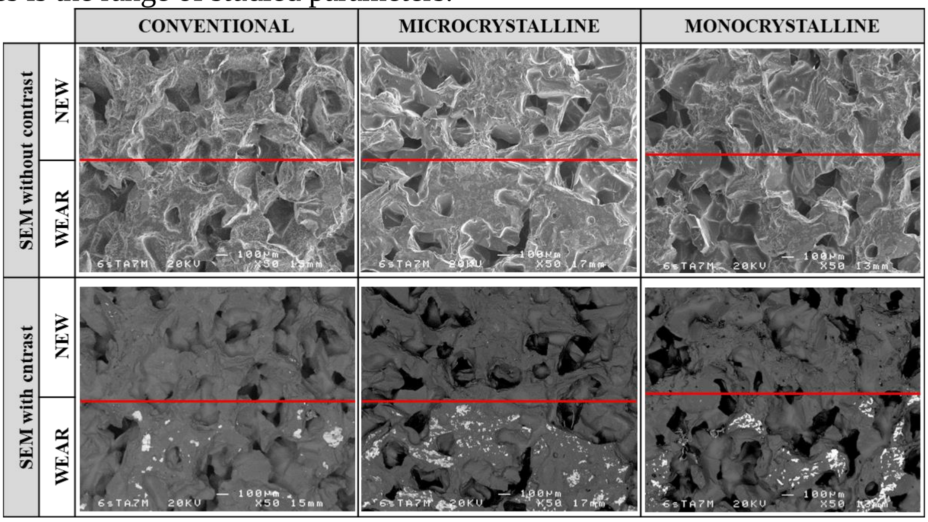

Fig. 4 SEM images of crystalline structures and the comparison of worn and new surface. Magnification of 50x.

Finally, the friction coefficient evolution with specific removal rate is analyzed on Fig. 3(b). As F_n', friction coefficient presents a quasiconstant evolution. In case of conventional and microcrystalline structure, values vary from 0.33 to 0.37. However, higher values about 0.41 are achieved for monocrystalline abrasive grains. Taking into account that finishing parameters are used during the tests, in this case friction coefficient show a more effective cut for monocrystalline grinding wheels comparing with the others.

To summarized, the increase of %A with specific removal rate and on the contrary the slightly increase of specific normal forces and friction coefficient need a microscopic study of grinding wheel surface to better understanding of the tribochemical wear that take place in the contact between abrasive grains and steel. Firstly, wheel topography is analyzed. SEM images are taken at magnification of 50x and 500x.

On Fig. 4 new and worn surface of three type of alumina is shown. The images are taken with a magnification of 50x, showing in the upper part a new surface, just dressed, and on the down part worn surface, after 100mm^3/mm. Furthermore, on the down part of Fig. 4 are differentiate grinding wheel from adhered material.

Comparing new and worn surfaces of any crystalline structure, the differences are evidence, grains get flat and surface appearance change. On worn monocrystalline and conventional surfaces, flat grains are easily identifiable. However, microcrystalline alumina presents larger flat areas than the other two, being flat surface more homogeneous and abrasive grains and bond are difficult to distinguish.

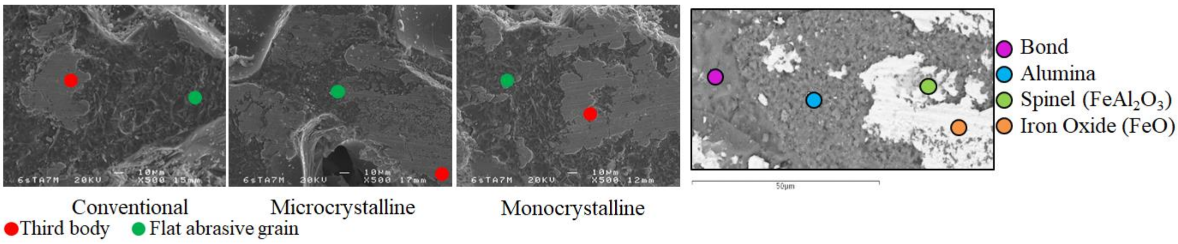

Fig. 5 Flat abrasive grains detail at magnification of 500x and EDAX analysis of microcrystalline abrasive grain.

In additions, the amount of third body adhered to flat grains is higher for microcrystalline and monocrystalline wheels. On Fig. 5 flat grains with third body adhered for all studied structures are shown. Flat abrasive is pointed with green dot and third body with red ones. Also less quantity of third body adhesion to conventional grains than to the others is shown. The crystalline structure has influence on the conductivity. Klocke [8] shows lower conductivity for microcrystalline structure than for conventional. During grinding, contact temperature is about 1300ºC [2] and melting point of Si is approximately 1200ºC. Therefore, bond could be melted, and in the case of microcrystalline structure is observed.

Finally, to complete the study, the EDAX analysis, Fig. 5, of worn surface allows the identification of different elements that affect to the contact. Purple dot pointed deformed bond, being Si the main element, which is on worn abrasive grain. Blue dot refer to abrasive grain, Al and O are the main elements. On this zone the microcrystals characterize the alumina. On third body two parts are distinguish. In green is pointed the grey zone of third body, which correspond to spinel, being Cr, Fe, Al and O the elements found. The other zone is indicated in orange, Fe and O are found elements, leading to iron oxide. Spinel layer is thinner than iron oxide layer, furthermore, spinel appears attached to abrasive grain and iron oxide generally is found on the spinel and also on the abrasive grain [8].

Microcrystalline wheels *%A* is higher than in the other cases, and the appearance of surface is flatter with greater quantity of third body adhered. The differences found between conventional and monocrystal abrasive grain is not so significant in terms of *%A* reached and worn surface appearance. On the contrary, reached friction coefficient is the highest on monocrystalline abrasive grains, and the relation with worn surface is not found, however, with finishing grinding conditions the highest friction coefficient confirms that works better monocrystalline alumina.

Conclusions

From discussion of results the following conclusion are obtained:

1. Linear increase of *%A* with specific removal material is shown for all crystalline structures. Microcrystalline grains present higher increase of wear flat on studied range.
2. For all crystalline structures wear flat increase with depth of cut. However, there is not possible to take a clear tendency of wear flat with workpiece speed variation.
3. The forces reached during the tests present a quasi-constant value. The specific normal force reached on microcrystalline structure is about 18% higher than reached with monocrystalline abrasive grains. Therefore, *%A* for specific removal rate of 100 mm^3/mm on microcrystalline wheels is about 25% higher than on monocrystalline wheel.
4. Friction coefficient remains approximately constant. However reached value of monocrystalline grains is about 0.41 and in case of other crystalline structure of 0.34. On the contrary, these differences are not evidenced on surface analysis.
5. Comparing the worn surface of three crystalline structures, a flatter appearance of microcrystalline grains is shown and the quantity of third body adhered is higher than on conventional grains.
6. EDAX analysis shows two components on the third body. Attached to abrasive grain spinel is found and in the most external layers, both attached to grain or to spinel, iron oxide is the third body component. The contact conditions changed.

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