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Analysis of the Performance of Superabrasive and Alumina Grinding Wheels with Different Bonds and Machining Conditions

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This paper presents a review of researches on CBN (cubic boron nitride) grinding wheels with the purpose of identifying the state of art in abrasive machining and serving as the basis for future researches and laboratory tests. The scientific studies investigated here report on interesting results involving grinding, published by Brazilian and foreign authors. The methods and the results are presented and discussed. In addition, a grinding setup is presented which provides more reliable experimental results about the surface integrity of fragile materials. This setup was obtained for grinding tests in several grinding conditions during the wheel service life, using alumina and vitrified and resin bond CBN grinding wheels. Results of cutting force, surface roughness and G ratio are also presented and discussed. They confirm the excellent machining capacity of the CBN wheel, with stable behavior in cutting force and roughness results during the tests. The G ratio values are in agreement with the results found by other researchers.

Keywords: *machining, grinding wheels, tangential cutting force, bonds*

1. Introduction

The requisites of quality and functionality of industrially manufactured components, which have become increasingly stringent in recent years, have led to the manufacture of better quality components produced more rapidly, offsetting material and machining process costs. The production cost of machined parts is substantially higher for parts with a complex geometry[13].

Foreign competition is forcing the national industry to meet international standards of product quality and performance. This, in turn, implies detailed knowledge of basic aspects ranging from the design to the manufacture of machines and equipment.

The manufacture of precision machines and equipment involves the use of parts with controlled tolerances (dimension and shape) and extremely slight surface roughness. Such parts are usually produced in a precision machining operation, which must combine minimum cost with maximum production output[1,2]. The performance of the machining operation is strongly dependent on the operator's skill and sensitivity, as well as on the machining and dressing conditions of the grinding wheel (sharpness). This machining operation cannot be optimized simply by changing a process input parameter. The operator is usually responsible for deciding, based on trial and error, about the procedures to which the parts are to be subjected. Knowing the behavior of the machining process enables him to make a better interpretation of the operation that is carried out on a part and to make any modifications of the process that will allow him to reach the desired results.

Successful scientific research is often evidenced by the

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means through which it enables manufacturers of mass production and of medium-sized and flexible production lots to make significant advances in productivity. Today, the superabrasive grains of Cubic Boron Nitride (CBN) are used in a broad range of industrial applications and, although their use in machining processes doesn't have yet the impact of integrated and computer-aided processes such as CAD, CAM and CNC, among others, this impact lies in the very near future. Currently, while most technical schools and even manufacturing companies possess CAD laboratories and offer computer and CNC programming courses as well as many other facilities, very few teach their students about uses and applications of superabrasives in machining. There is a clear gap between the real capacity of superabrasives and the industrial skills in their practical use.

New tooling machines and materials for cutting tools have been developed as the result of continuous efforts to improve the quality of products and manufacturing methods[4,10]. Some types of composite materials are provenly very difficult or even impossible to subject to the machining process using superabrasive grinding wheels, even though the cutting capacity of this type of grinding wheel is superior to that of the alumina ones, depending on the applicability of each tool. However, superabrasives have proved to be exceptional in the machining of hard ferrous metals, cast iron and nickel and cobalt super-alloys. It is also a fact that superabrasive grinding wheels have high efficiency, cutting capacity and can produce a larger variety of high precision parts using the same physical effort expended on alumina grinding wheels at lower cost and, hence, with higher productivity.

In typical manufacturing operations, the grinding wheel is the interface between the machine and the part. For the grinding wheel to transfer the energy available in the machine to the machining operation it must, among other things, be harder than the part and, therefore, more resistant to wear. The abrasive crystal grains of CBN are appropriate and even exceed this requirement and, for that reason, they are used in the manufacture of grinding wheels for high efficiency machining of difficult to grind (DTG) materials.

Alumina and silicon carbide grinding wheels quickly lose their cutting capacity when machining DTG materials, resulting in high cutting forces and temperature (generated by friction), and low material removal rates, which affect the geometrical and dimensional precision of machined parts. In contrast, CBN grinding wheels prolong the machine's cutting capacity and the high thermal conductivity helps reduce the uncontrolled increase of heat, thus reducing the possibility of metallurgical damage to the part.

According to Metzger[11], the fast growth and advances in high performance production, allied to the progressive substitution of skilled workers by computerized or microprocessed controls, make it increasingly important to determine, with precision and reliability, the real performance of high technology tools used for working with ever more complex and superior materials.

The need for precise and continuous control of cutting tool performance is understandable when one considers that management focuses on greater productivity with resulting economic improvements. However, this also implies the urgent need for greater efforts on the part of members of the technical and management staff of manufacturers. Daily experience has demonstrated that, in a company's manufacturing area, every machining process, including turning, is subject to some degree of dispersion, which may transform a reliable performance measure into a Utopian value that is difficult to achieve, doubtful and often frustrating.

The purpose of this study is to make a comparative analysis of CBN grinding wheels produced with three different types of bond and a alumina wheel. To this end, resin bonds, high performance resins and vitrified resins were used on abrasive grinding wheels. This comparative analysis was based on tangential cutting force, surface roughness of the part and the G ratio.

2. Machining of Surfaces with CBN Grinding Wheel

CBN grinding wheels are more cost efficient for the machining of a variety of metals that are usually considered difficult to grind. This category includes any carbon steel or alloy hardened to 50 HRc or more, extremely hard and abrasion-resistant cast irons and abrasion-resistant steel alloys, nickel or cobalt superalloys with a hardness of or above 35 HRc, and special metals such as Stellite.

The benefits of surface machining with CBN grinding wheels are: more consistent precision of the components, better surface quality, greater productivity and lower machining costs. The cost-benefit ratio of CBN grinding wheels is based on surface machining operations on hardened steel components. Although the cost of machining per part may be higher when machining with the CBN grinding wheel than with the aluminum oxide one, the work costs and overall expenses per tool may be lower due to the shorter machining time required, fewer tool changes, less conditioning of the grinding wheel, less tool changes and machine adjustments to compensate for the wear of the grinding wheel, and faster finishing cycles. The total cost of machining per tool may be 40% lower, which makes the CBN grinding wheel an excellent investment[4,6].

A comparison was made of the diametral wear of superabrasive CBN and conventional aluminum oxide grinding wheels subjected to several machining conditions. To this end, laboratory tests were carried out on a CBN grinding wheel manufactured with high performance resin bond and a alumina grinding wheel typically used in precision machining.

3. Types of Bonds

The machining of a large number of parts requires the use of a variety of bond systems to fix the abrasive grains on the surface of the grinding wheel's core. The four most commonly employed bonds materials currently used by superabrasive grinding wheel manufacturers are: resin, vitrified, metallic and electroplated types. It is important to understand how each type of grinding wheel is manufactured and the effect that the manufacturing process exerts on the grinding wheel's properties. These properties determine the procedures of recovery and sharpening, which are possibly the most important determining factors for grinding wheel effectiveness.

Grinding wheels with resin bond are manufactured by mixing measured amounts of phenolic resin or polyamide and fillers with the proper weight and size of the CBN abrasive with a metallic layer. The mixture is then used to fill the mold of the cavity and form the section of the machining end around the core of the grinding wheel. After the cavity is filled, the resin and abrasive mixture is subjected to pressures and temperatures of up to 400 °C, which fixes the abrasive to the core of the grinding wheel. After the grinding wheel is removed from the mold, a second heat treatment polymerizes and reinforces the resin bond[6].

Grinding wheels with resin bond remove material rapidly but have limited characteristics of aggregation and shape. The main characteristics of grinding wheels with resin bond are the following[6]:

- They can be used for a large variety of applications;
- They are available in a great many shapes and sizes;
- They can be used for both refrigerated and dry machining;
- They possess good cutting qualities.

Electroplated CBN grinding wheels have a single layer of abrasive grains that are bonded to a metallic core by means of an electrodeposited nickel bath. The electrodeposited nickel matrix provides excellent retention for the abrasive.

The manufacturing process of grinding wheels with vitrified bond consists of the following steps[6]:

1. The appropriate amount of powdered vitrified material, known as "FRIT", is mixed with the desired type, weight and grain size of CBN;
2. The mixture is carefully placed in a mold around the core of the grinding wheel, which is made of ceramic which can withstand temperatures of up to 1000 °C;
3. The "green grinding wheel" is also carefully removed and placed in a furnace with controlled temperature and atmosphere, with the time factor also carefully controlled;
4. While the grinding wheel is inside the furnace, a chemical reaction causes the bond to transform into hard vitrified bond that fixes the CBN abrasive to the grinding wheel's core;
5. Vitrified grinding wheels with greater width can be made of small radial segments that are carefully placed and cemented around the periphery of the grinding wheel's core.

These grinding wheels display a good cutting capacity, producing good surface finishing, have good wear resistance and maintain the geometrical profile of the grinding wheel. The porosity or open structure of vitrified grinding wheels can be controlled to provide chip output, allow for the flow of cooling fluids, and prevent clogging of the grinding wheel's pores. The main characteristics of superabrasive grinding wheels with vitrified bond are[6]:

- Good abrasion resistance;
- Good capacity to maintain their geometrical shape;
- Long service life;
- They are usually easier to recover and sharpen than other bonds;
- They produce better surface finishing - concentrations of 150 to 200 can produce the best results;
- They display lower resistance to inappropriate use.

3.1 High performance surface machining - The bond's influence on the abrasive process

According to Brinksmeier & Minke[3], much attention in recent years has been focused on the development of high performance machining to gain a better understanding of the process and to apply this technology in industrial applications. Today, specially designed CBN machines and tools are available and basic knowledge about machining and dressing processes has been gained. However, there are a number of problems relating to this process, which will require redoubled efforts to be overcome in the future. The application of this method to difficult to grind materials such as high-speed steels, tungsten carbide, nickel alloys, titanium, ceramics and glass, will open up a vast new field. In practical research, several issues will require a closer investigation, namely, the machining forces and the power required by the process, the temperature, the damages caused to the subsurface and the quality of workmanship. The effects and possibilities of replacing the mineral oil commonly used so far with soluble oil or alternative fluids will also have to be looked into.

3.2 Abrasive strength

The strength of CBN crystal particles affect the self-sharpening properties and may exert a significant effect on CBN grinding wheel performance in certain machining operations. Although CBN crystals are highly wear resistant, their sharp edges may lose their sharpness if the abrasive, the bond or the machining conditions are incompatible. Ideally, the crystal should fracture in a controlled manner to expose new, sharp cutting edges.

If the crystal is too strong for the application, fracturing may not occur. As a result, its wear renders it polished and flat, preventing it from providing effective cutting. On the other hand, if the crystal is not sufficiently strong for a given application, it may fracture prematurely, wasting abrasive, shortening the service life of the grinding wheel, and producing a rougher surface finishing.

Medium-strength crystals should be used for most operations while higher strength crystals are recommended for operations in which the machining forces are greater. Microcrystalline CBN types are recommended for exceptionally severe machining conditions[4,6].

3.3 Superabrasive properties

Superabrasives, diamonds and CBN have properties that conventional abrasives such as aluminum oxide and silicium carbide do not possess. The hardness, abrasive strength, compression strength and thermal conductivity of superabrasives render them the logical choice for many difficult machining operations[10].

3.4 Development of cubic boron nitride (CBN)

In the periodic table of the elements, boron lies adjacent to the diamond (carbon) on its left while nitrogen lies on its right. If these elements were combined into a bonding structure as dense as that of the diamond, its crystals would almost as hard or even harder than those of carbon. The quest for a new hard material has led to the development of a new superabrasive not found in nature - cubic boron nitride, which has been called *Borazon* (CBN)[6].

Before CBN was synthesized at GE's research and development laboratory, the shape of boron nitride (known as hexagonal boron nitride) was very similar to that of graphite, which was commercially available. The atoms of hexagonal boron nitride are arranged similarly to those of graphite, with alternate boron and nitrogen instead of only carbon. This suggests that such an arrangement, like that of the diamond with alternate boron and nitrogen, should also exist.

3.5 Types of cubic boron nitride

According to GE's catalogue[6], like diamond, CBN is transformed into a variety of products for different applications. Unlike diamond, however, all the CBN products are used in the metallurgical industry. There are currently seven different types of CBN abrasives commercially available, each manufactured specifically according to one or both of the primary criteria, i.e., type of bond and machining mode or material removal rate.

Type I - This is a monocrystal CBN abrasive designed for use in vitrified, metallic or electroplated grinding wheels.

Type II - The surfaces of the Type I crystal are too smooth to hold resin bond properly; hence, they must be located in a heavy layer of nickel metal so that they can be used in systems with resin bond. The Type II crystal is the Type I crystal with a nickel layer of 60% in weight covering its surface. This layer allows the Type II abrasive to be utilized only in systems with resin bond. Because grinding wheels with resin bond are the CBN grinding wheels most commonly used today, Type II is the CBN abrasive most widely employed. Both crystals (Types I and II) wear through the controlled division of the grains, leaving sharp cutting points.

Type 500 - This is a high resistance monocrystalline CBN abrasive especially designed for applications involving vitrified and electroplated bond systems.

Type 510 - This abrasive grain is produced by the application of a thin layer of titanium on the crystal.

CBN *Borazon* Types I, II, 500 and 510 consist of monocrystals with a large number of indentations where fracturing occurs. This macrofracturing (large break) is essential for the grains to resharpen when they lose their cutting capacity (loss of shine). This macrofracturing, which may occur several times during the crystal's service life, keeps it sharp for effective removal of steel.

Type 550 - This high strength microcrystalline abrasive is designed for almost every application requiring vitrified or metallic bonds. Because the thermal stability of the Type 550 abrasive is greater than that of the other CBN abrasives, it offers unique advantages in the manufacture and use of grinding wheels with metallic and vitrified bond.

Type 560 - This CBN abrasive is manufactured by the application of a 60% weight layer of nickel on the Type 550 crystal, rendering the Type 560 applicable only for use in grinding wheels with resin bond.

Type 570 - Is a CBN abrasive produced by applying a special treatment on the surface of the Type 550 crystal, rendering it useful only for electroplated grinding wheels.

The Types 550, 560 and 570 *Borazon* are microcrystalline CBN superabrasives that resharpen more through microfracturing (very small breaks) than by macrofracturing. Each particle consists of thousands of microparticles of CBN regions strongly bonded to each other to form a 100% dense particle. When the sharp edges of individual abrasive particles begin to lose their shine, machining forces produce an indentation the size of a sub-micron in the crystalline region of the CBN. This microfracture continually resharpens each superabrasive particle as it loses its shine, resulting in a consistent and efficient cutting action with a minimum of heating by friction.

4. Methodology

A system, consisting of a torque gauge to calibrate the system and measure the tangential cutting force, was built to perform the tests. This system is discussed later herein, as are the measurements of the surface roughness and radial wear.

4.1 Dynamic gauging of the test bench

A fixing device was built to couple the crown wheel, the dynamometer and the shoe brake, as illustrated in Fig. 1.

The grinding wheel, fixed to the grinder's main spindle, was replaced by a crown wheel with a d_1 diameter. This crown wheel was coupled to another one with a d_2 diameter by means of a chain. The d_2 diameter crown wheel was then coupled to the torque gauge exit shaft, which had a shoe brake connected to its entry shaft. The torque gauge to be used allowed readings from 0 to 20 N.m, whose correlation equation of the exit tension values as a function of the applied torque had already been determined experimentally. There was also a signal conditioning circuit to transform the signals from the torque gauge into values compatible to those of the data acquisition program.

The shoe brake was activated according to a frequency selected on the converter, which corresponded to a given rotation of the grinding wheel's starter motor, reducing the rotation of crown wheel d_2 and, thus, that of crown wheel d_1. The value of the instantaneous torque on the shaft of crown wheel 2 was then read by the data acquisition software program (*Labview* 5.0.1) as a function of the voltage transmitted by the torque gauge to the microcomputer. According to the d_1 and d_2 diameters of the crown wheels and the transmission ratio between them, it was possible to determine the instantaneous value of the tangential cutting force on the d_1 crown wheel ($Ft_{c\ torq}$). Concomitantly, the instantaneous voltage and electric current values from the grinding wheel's starter motor were measured as a function of the torque contrary to the movement of the shaft applied by the brake. Based on these voltage and current values, the conditioning circuit multiplied these signals, calculated the electric power consumed, sending a voltage value proportional to that power to the microcomputer. This enabled us to determine, based on the voltage value sent, which was proportional to the power consumed and the above described procedures, the tangential cutting force value ($Ft_{c\ pot}$) in crown wheel 1, as a function of its d_1 diameter and rotation, using the data acquisition software program.

The above-described dynamic gauging of the tangential cutting force data acquisition system was carried out by mounting the system shown in Fig. 1, which was then turned on and the shoe brake gradually activated, allowing for several $Ft_{c\ torq}$ values (through T_{torq}) and for the corresponding $Ft_{c\ pot}$ to be found (through T_{pot}). The graph shown in Fig. 2 was drawn up based on these values.

An analysis of the dynamic gauging of the tangential force data acquisition system resulted in the following correlation equation of the torques supplied by the system:

$$T_{torq} = -\ 0.88866 + 1.96883T_{pot} \qquad (1)$$

This will therefore be the correlation equation employed to correct the tangential cutting force values.

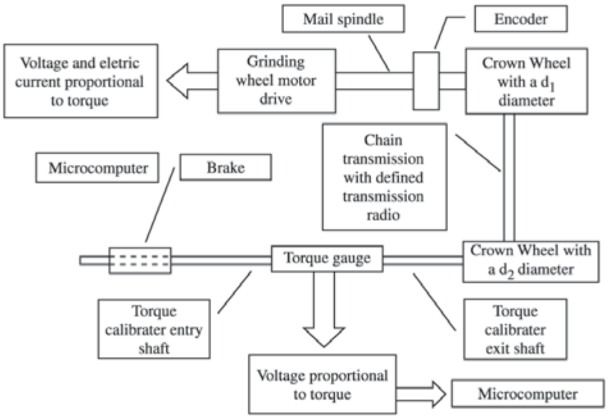

Figure 1. Diagram of the calibrating procedure.

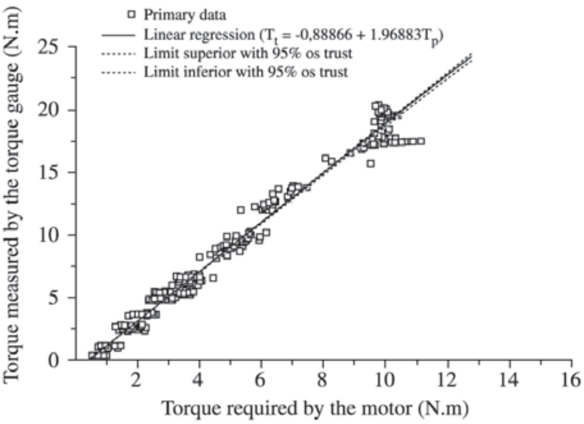

Figure 2. Equation of the correlation between T_{torq} and T_{pot}.

5. Results and Discussion

The results of the tests on CBN grinding wheels with resin, vitrified, and high performance resin bonds and on the alumina grinding wheel are shown in the form of graphs of tangential cutting force. The results of the radial wear and surface roughness as a function of the machining conditions are presented in Table 1.

5.1 Tangential cutting force values obtained for the CBN grinding wheels with vitrified, resin and high performance resin bonds and for the alumina grinding wheel

Figures 3, 4, 5, and 6 show the experimental values of tangential cutting force as a function of the specific volume of removed material in the machining conditions as indicated in the legends.

An analysis of the performance of the alumina grinding wheel showed a bond hardness classified as soft, which is appropriate for the machining of DTG materials with alumina grinding wheels. grinding wheels used for hard materials should be soft while those used for soft materials should be hard[12]. When a material with a high degree of hardness is cut, the wear of the grain is more intense, which makes self-sharpening desirable (so that the part does not burn). Moreover, the wear on the bond caused by the chips is not as evident, since hard materials normally produce short, brittle chips. In contrast, when a material with low hardness is cut, the wear on the abrasive grains is slower and, therefore, there is less need for new layers of grains. Added to this is the possibility of new cutting edges appearing as a result of grain fracturing (depending on the grain's friability), and the fact that the chips produced in the cutting of soft materials are usually long and ductile, acting with greater intensity on the bond (friction).

The choice of a soft grinding wheel allows the machining forces and roughness to remain stable during machining through the constant release and renewal of abrasive grains, since it increases in the cutting force resulting from the wear of the abrasive grains lead to their release, owing to the low hardness and retention capacity of the grinding wheel's bond. However, this constant release of abrasive grains results in a diametral loss of the grinding wheel and, hence, a drop in the G ratio. Otherwise, if a grinding wheel with a bond classified as hard is used, the excessive increase in tangential cutting force caused by the wear of the abrasive grains and by the greater retention capacity of the worn grains may lead to an increase in the machining energy required, an increase in cutting region temperature, probable thermal damage, greater surface roughness and higher levels of vibration, etc.

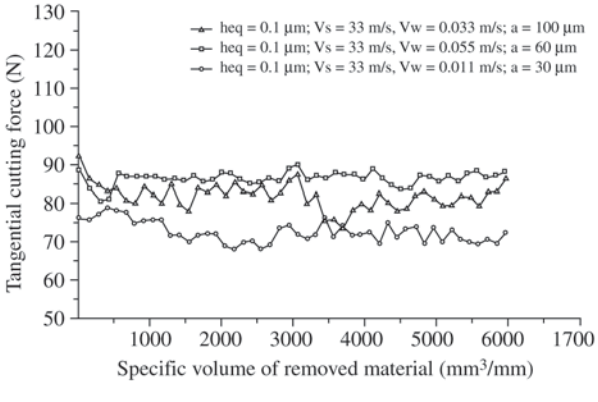

Figure 3. Tangential cutting force values obtained using the grinding wheel with vitrified bond.

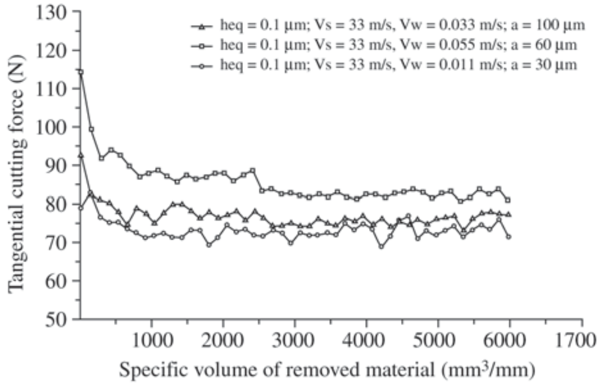

Figure 4. Tangential cutting force values obtained using the grinding wheel with resin bond.

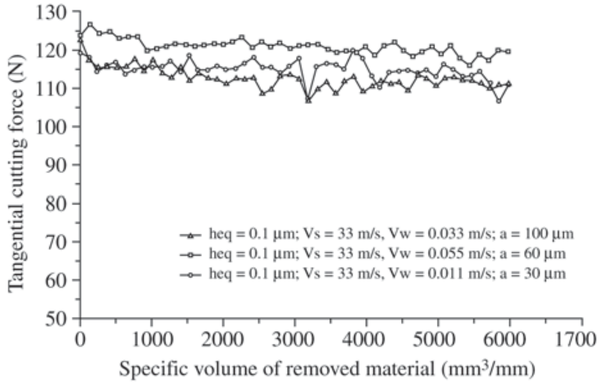

Figure 5. Tangential cutting force values obtained using the grinding wheel with the high performance resin bond.

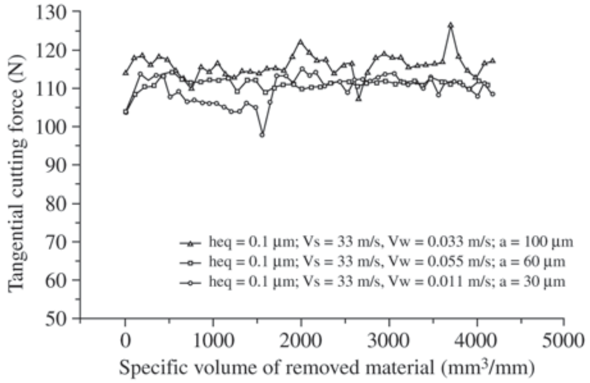

Figure 6. Tangential cutting force values obtained using the alumina grinding wheel.

Table 1. Radial wear and roughness of CBN grinding wheels with vitrified, resin, and high performance resin bonds and of the alumina grinding wheel.

Vitrified bond			h_{eq} = 0.1 µm		
Test	Radial wear (µm)	R_a (µm)	a (µm)	V_s (m/s)	V_w (m/s)
1	34.2	0.91	100	33	0.033
6	35.3	0.89	60	33	0.055
10	36.3	0.79	30	33	0.11

Resin bond			h_{eq} = 0.1 µm		
Test	Radial wear (µm)	R_a (µm)	a (µm)	V_s (m/s)	V_w (m/s)
4	39.7	0.73	100	33	0.033
2	42.5	0.71	60	33	0.055
12	46.4	0.70	30	33	0.11

High performance resin bond			h_{eq} = 0.1 µm		
Test	Radial wear (µm)	R_a (µm)	a (µm)	V_s (m/s)	V_w (m/s)
9	10.0	0.46	100	33	0.033
7	50.0	0.50	60	33	0.055
3	80.0	0.52	30	33	0.11

Alumina grinding wheel			h_{eq} = 0.1 µm		
Test	Radial wear (µm)	R_a (µm)	a (µm)	V_s (m/s)	V_w (m/s)
5	300.0	0.74	100	33	0.033
8	550.0	0.72	60	33	0.055
11	800.0	0.61	30	33	0.11

Due to these factors, the use of a alumina grinding wheel classified as soft (hardness of the soft bond) allowed the tangential cutting force values, which were close to those obtained with the superabrasive CBN grinding wheels, to remain stable throughout the tests. After the initial period of reduced tangential cutting force, which originates from the profiling operation itself, all the tests showed a tendency for the tangential cutting forces to stabilize due to the greater wear resistance of the cutting edges of the superabrasive CBN grains. These new cutting edges showed greater wear resistance owing to the better mechanical properties of the superabrasive CBN grain compared to those of aluminum oxide[5]. Thus, the cutting tool remained active (with a high cutting capacity) for a longer period of time, for the CBN grain has a slow micro-wear. A characteristic of these tools is the combined effect of slow micro-wear coupled with the generation of new cutting edges produced by microfracturing. These phenomena can be identified as responsible for the tool's low radial wear during the tests, as shown in Table 1, and subsequently confirmed by the values found for the G ratio.

The results of these tests indicate that, for the same value of h_{eq}, the increase in the penetration of the grinding wheel into the part did not significantly alter the latter's surface roughness values, R_a. Significant modifications in roughness, when the penetration into the part is altered while maintaining the h_{eq} value, are more marked in deep machining operations than in machining operations of the pendular type[9].

With an h_{eq} = 0.1 µm, a reasonably severe machining condition, there is a slight difference between the roughness, R_a, value of 0.86 µm for the grinding wheel with vitrified bond and that of the 0.71 µm for the resin bond, 0.50 µm for the high performance resin bond and 0.69 µm for the alumina grinding wheel.

As shown in Table 1, the reduction in the grinding wheel's penetration into the part, coupled with the rise in the latter's speed, resulted in an increase of the tool's radial wear due to the greater number of shocks caused by the increase of V_w, thus producing a reduction in the G ratio. This occurred for the same volume of removed material ($Q_w = 30{,}000\ mm^3$), which remained constant in all the tests, while the greater radial wear led to an increased rate of tool wear (Q_s). Because the G ratio is defined as the ratio between Q_w (stock removal rate) and Q_s, an increase of Q_s with a constant Q_w will lead to a reduction in the G ratio. In other words, the tool presents a greater volumetric wear for the removal of the same volume of material.

Under the same machining conditions, the grinding wheel with vitrified bond showed trend of less volumetric wear, presenting a higher G ratio. This was due to the greater induced porosity of the vitrified grinding wheel, which allows for a better fit of the torn away chips. In addition, the vitrified bond is less susceptible to the erosive wear caused by the action of the chips on the bond, providing greater bond retention strength on the abrasive grain and, thus, reducing the radial loss of the grinding wheel[7]. In the case of grinding wheels with resin bond, the torn away chips cause greater wear of the bond owing to the grinding wheel's lower porosity and the greater difficulty of fitting the torn away chips, leading the chips to produce greater friction on the bond and thereby degrading it. However, the maximum radial wear of the tool was found to be 46.4 µm for the tool with conventional resin bond, among the several penetration conditions under which the tool was tested. Nevertheless, based on the order of magnitude of the values observed, the tool's radial wear was attributed to the combined effect of the phenomena of microfracturing and slow micro-wear. Thus, the amount of diametral loss of abrasive grains was low. However, the lower radial wear observed in the grinding wheels with vitrified bond, coupled with the higher tangential cutting force, was attributed to the fact that the renewal operation, which is commonly done on tools with resin bond that are more exposed to abrasive grains because of bond wear, was not carried out. On the other hand, this reduces the anchoring strength exerted by the bond on the grain and may even cause loosening of poorly anchored grains. The greater abrasive grain retention capacity of the vitrified bond owing to its better mechanical properties and resistance to the heat generated by machining was not very significant because of the apparent underuse of the tools tested here, which resulted from the low volume of material removal proposed in this study. This underuse was evidenced by the stability of the values of forces and roughness and the low cutting temperatures measured during the tests compared to the temperatures measured for the CBN grinding wheels[8].

The most significant differences were found in the analysis of the values of the G ratio, which confirmed that CBN grinding wheel performance is many times superior to that of the alumina grinding wheel, i.e., CBN grinding wheels allow for the removal of the same amount of material as the alumina grinding wheel, but their wear is many times inferior to that of the alumina tool.

6. Conclusions

The analysis of the radial wear values indicated the superior performance of vitrified CBN grinding wheel when compared to the resin bond one. In terms of roughness and G ratio, more pronounced differences in favor of the vitrified one would be observed if it had been produced with a concentration of 150 to 200. Therefore, this wheel is the most suitable one to grinding this steel (VC 131).

The most strongly marked differences were found in the analysis of the G ratio values, which demonstrated that the performance of the CBN grinding wheel with high performance resin bond was many times superior to that of the alumina tool (up to 30 times better). In other words, the CBN grinding wheel tested here allows for the removal of the same amount of material as the alumina grinding wheel, but the wear on the tool is many times inferior to that of the alumina tool. As for our findings on surface roughness, the CBN grinding wheel showed better values under the same machining conditions.

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