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Surface Quality Evaluation of Various Metals After Grinding with Aluminum Oxide Grinding Wheel

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Abstract: Different metals can respond differently when grinding using the same abrasive grinding wheel, especially in terms of surface quality. In this context, this work aims give a contribution to the metalworking industry by presenting the results of surface finishing after grinding the following metals: VP Atlas steel grade, Gray Cast Iron and two superalloys, Inconel 718 and Ti-6Al-4V. Tests were performed with the aluminum oxide grinding wheel and with following parameters: cutting speed of 37.6 m/s and workspeed of 10 m/min. Two values of depth of cut (15 µm and 30 µm) were tested. The surface roughness (Ra and Rz parameters) were analyzed and SEM images of the machined surfaces were taken and analyzed in order to identify the cutting mechanisms and provide better results discussion. The results showed that the surface roughness increased with the depth of cut; Ra values kept below 0.48 µm for all metals tested. Regarding the machined surface quality, some cracks were observed on the gray cast iron and Ti-6Al-4V surfaces, thereby indicating their relative lower grindability compared to VP Atlas steel under the investigated conditions. No visual thermal damage was observed in the machined surfaces of the samples.
Keywords: Grinding; Aluminum oxide grinding wheel; VP Atlas steel; Gray cast iron; Inconel 718; Ti-6Al-4V alloy.

1. Introduction

Grinding is a common name given to machining processes that use hard and non-metallic (ceramics) abrasive particles as cutting tool (grinding wheel). It is highlighted among the abrasive machining processes because of its importance for the metalworking industry, since it is capable of ensuring the production of components with narrower dimensional and geometric tolerances (IT6-IT4) than those obtained in operations which use cutting tools with defined geometry, such as turning and milling. During the grinding process, the abrasive grinding wheel rotates at high speeds that, generally above 30 m/s, to remove material of the workpiece with small depth of cut (a_e) values. The conventional abrasives employed in this operation have low thermal conductivity and the grits rake angle is predominantly negative during cutting [1].

The small depth of cut value and workspeed (v_w)/cutting speed (v_s) ratio are, in general, responsible for the maintenance of the low surface roughness values. These variables define another variable that is typically employed to measure the grinding severity and consequently with the grinding efficiency, that is called equivalent chip thickness (h_{eq}), which can be obtained using the Eq. (1), and physically corresponds to the volumetric removal rate per unit area of wheel surface passing through the grinding zone [1]:

$$h_{eq} = \frac{a_e \times v_w}{v_s} \quad [\mu m] \tag{1}$$

The increase of heq, either by the increase of ae or vw, or by the decrease of vs, usually lead to an increase in the cutting efforts and deterioration of the finish as well as the reduction of grinding wheel life [1].

According to Jackson and Davim [2], as narrower tolerances are required, the need for surface finish analysis is increased, which is measured through roughness using parameters that evaluate the effective profiles of the surface. The most common roughness parameter is the average roughness (Ra) which is defined as the mean value of the deviations of a profile in reference to a midline over a sampled length. However, by evaluating an average value, the Ra parameter may not point to extremes, not fully characterizing the distinction between peaks and valleys, so it is necessary to evaluate other roughness parameters. The surface roughness Rz parameter, in turn, refers to the arithmetic mean of the five largest distance values between peak and valley within a sampling length [3], thus, in some situations, it can respond better with respect to the profile roughness changes. However, Ra parameter is still the most common parameter for evaluating machined surfaces.

Da Silva et al .[4] states that, despite the large field of application of the cast irons, the literature lacks information about the grindability of these materials, with very fee works published. These authors evaluated the surface and subsurface quality of three cast iron grades (gray, nodular and compacted) after grinding under different machining conditions using a silicon carbide (SiC) grinding wheel and with a semi-synthetic vegetable oil-based. The authors reported that the gray cast iron outperformed the other cast irons in terms of low surface finish values. With respect the microhardness below the machined surfaces, the authors noticed that the gray and compacted graphite cast irons materials did not present microstructural alterations as a consequence of thermal damage. However, an increase in microhardness values up to 30% were observed in the nodular cast iron, which further indicates that the surface and sub-surface integrity in the grinding process of cast irons are strongly linked with the graphite shape, and thus, with the mechanical properties of the materials [4].

De Mello, et al. [5] studied the grindability of the Ti-6Al-4V under several machining parameters and atmospheres using a silicon carbide grinding wheel. According to the authors, this alloy is especially difficult-to-machine, since it has a unique combination of low thermal conductivity, high work hardening rate and high chemical reactivity with most cutting tool materials. This is especially critical in the grinding process since the combination of these properties with the high specific cutting energy and small chip characteristic of this machining process could lead to thermal damage. The authors found that, despite the lowest values of surface roughness (Ra parameter) achieved using the minimum quantity of lubricant (MQL) technique and the lower depth of cut, machining with convention flood coolant technique outperformed the MQL one in terms of surface finish at the most severe cutting conditions.

According to Machado and Diniz [6], mold steels are a steel class with particularly complex machinability especially due to the usually high surface finish requirements. Since they are usually found in the hardened state and are highly susceptible to thermal damage, the grinding process of these materials are even more challenging. Da Silva et al. [7] evaluated the performance in terms of surface finish of the grinding process of the VP ATLAS hardened steel with aluminum oxide grinding wheel and various cutting parameters. They also tested two cooling-lubrication techniques: the MQL and the conventional coolant delivery (flood). They reported that, regardless the cutting atmosphere, the surface roughness increased with the depth of cut. However, in general, the MQL technique outperformed the flood in relation to surface finish for most of the cutting conditions.

According to Da Silva [8] the low grindability of the nickel alloys can be explained by the combination of the intrinsic higher thermal input of the cutting zone of this machining process with the low thermal conductivity of these alloys. In their work, the Al_2O_3 grinding wheel was employed in the grinding of the Inconel 718 under different grinding parameters, including two cooling-lubrication techniques: MQL and the flood. The output parameters were the surface and sub-surface integrities. The authors found that the flood technique outperformed the MQL one in terms of both surface and sub-surface integrities. The authors also affirmed that grinding of the Inconel 718 alloy is recommended when using depth of cut values in excess of 20 µm.

In this context, this work aims to evaluate the surface quality of different metals after peripheral surface grinding with white aluminum oxide grinding wheel with two different values of equivalent chip thickness. Surface roughness (Ra and Rz) parameters and the surface quality of the machined surfaces via Scanning Electron Microscopy (SEM) were used to assess the surface quality of the metals.

2. Methodology

Grinding tests were performed on a peripheral surface grinding machine, model P36, from Mello manufacturer, with a power of 3 HP and maximum wheel speed rotation of 2400 rpm. The workpiece material metals tested were VP Atlas steel, Inconel 718, Gray Cast iron FC 250 and Ti-6Al-4V alloy, whose dimensions and mechanical properties are presented in Table 1.

The grinding tests were carried out with the aluminum oxide grinding wheel with the designation of AA60K6V and with the following dimensions: 299 mm of external diameter x 76 mm of internal diameter x 25 mm of thickness. A vegetable-based semi-synthetic Vasco 7000 coolant, manufactured by Blaser Swisslube, was used at a dilution of 1:19 in water. This coolant was delivered to the cutting zone by the conventional flood coolant technique at a flow rate of 540 L/h. A precision vise, that was placed on the magnetic table of the grinding machine, was used to hold each workpiece during grinding, as it is shown in Fig.1(a). The cutting speed (v_s) of 37.6 m/s and workspeed (v_w) of 10 m/min were kept constant during all tests. Two depth of cut values (a_e), 15 µm and 30 µm, were tested, that from Eq. (1) were calculated the equivalent chip thickness (h_{eq}), resulting two h_{eq} values of 0.07 µm and 0.14 µm, respectively.

Table 1. Details of the metals and their mechanical properties.

Material	Dimensions (mm)	Density (g/cm³)	Hardness (HB)	Thermal Conductivity (W/m.k) [1]	Yeld Strength (MPa)	UTS (MPa)	Elong. (%)
VP Atlas Steel	19 x 15 x 48	6.8-7.4	350-390	-	1087 [9]	1246 [9]	10 [9]
Inconel 718	19 x 15 x 30	8.2-8.9	250-410	11.4	1186 [10]	1435 [10]	<15[10]
Gray Cast Iron	19 x 15 x 30	6.8-7.6	150-187	49	-	~ 400 [11]	-
Ti-6Al-4V	19 x 15 x 36	3.8-4.5	334-353	6.7	880 [12]	950 [12]	14 [12]

Prior to each grinding test, dressing operation of the grinding wheel was carried out with a single-point dresser of synthetic diamond. It was used an overlap ratio (U_d) of 3 and the dressing operation was conducted in the presence of cutting fluid, as shown in Fig. 1(b). According to Marinescu et al. [13], this operation is necessary to reconstitute the outer layer of the grinding wheel and to make the edges of the grains sharp.

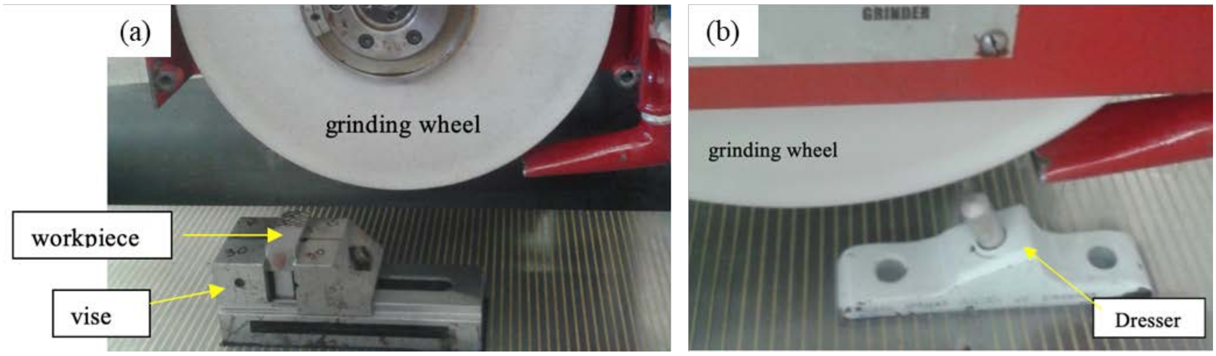

Fig. 1. Used setup (a) for the grinding tests and (b) for the dressing operation

After the grinding tests, measurements of the roughness parameters Ra and Rz of the workpieces surfaces were carried out using a portable surface profiler model SJ-201P, manufactured by Mitutoyo with a resolution of 0.01 µm. The cut-off filter used was 0.25 mm. Three profiles with evaluation length of 5.0 mm were measured from each ground surface, perpendicular to the grinding direction and in three different equidistant regions. After the roughness measurement, Scanning Electron Microscope (SEM) imagens of each machined surface was acquired using a TM 3000 model, manufactured by Hitachi.

3. Results and discussion

In this session the surface roughness results are presented according to the equivalent chip thickness (h_{eq}) and the surface images obtained after the grinding of all the materials. The surface roughness results in function of the equivalent chip thickness (h_{eq}) for the four different metals are shown in Fig. 2 for the Ra and Rz parameters, in Fig. 2(a) and Fig. 2(b), respectively.

From graphs of Fig. 2(a) and b is possible to observe that the average values of all the roughness parameters for the equivalent chip thickness of 0.14 µm present higher values of roughness compared to those obtained with h_{eq} of 0.07 µm. Similar behaviors were observed in the works in peripheral surface grinding carried out by Da Silva et al.[4] for the gray cast iron, De Mello et al.[5] for the titanium-base, Ti-6Al-4V, alloy, Da Silva [7] for the VP atlas steel and Da Silva [8] for the nickel-base, Inconel 718, alloy. As the depth of cut increases and the grinding wheel abrasive grits penetrates deeper into the workpiece surface, so the contact length increases as well as the number of active grits in contact with the workpiece material. This will lead to increase in the average width of the top of the abrasive grits and raises the tangential cutting forces [2] and, consequently, causing deterioration of surface finish. According to Jackson and Davim [2] as depth of cut ae increases, there is also an increase on contact time of the abrasive grit and the surface of the workpiece and, consequently, an increase in the heat generation in this region. The greater amount of heat going to the workpiece raises its temperature and, in turn, increases the amount of plastically deformed material on the surface. Depending on the properties of the machined material, evidence of severe plastic deformation at the surface may be observed by interrupted marks or lateral flow of excessive material. Thus, worst surface roughness results (Fig. 2) of Ti-6Al-4V in relation to the other materials can be also observed by the SEM images (Figs. 3 to 5). According to Trent [14], this material is considered to have poor machinability in machining processes with defined tool geometry, mostly due to factors such as high chemical affinity with most cutting tool materials, especially with ceramics. As conventional grinding wheels (aluminum oxide and silicon carbide) are composed by ceramic grits, it can be observed that titanium alloy exhibited poor machinability during grinding with aluminum oxide grinding wheel. In general, abrasive grinding wheels based on silicon carbide (SiC) or synthetic diamond (superabrasive) are recommended for the grinding of this alloy. Also, new ceramic grains combined with new bond systems, could leverage significantly the results of grinding over this type of material, bringing to the grinding zone less heat generation. But in this work, the alumina grinding wheel was intentionally selected for research and comparison purposes for the other materials tested. As for the other materials, VP Atlas steel, Gray Cast Iron and Inconel 718, it can be stated that, based on the mean values and standard deviation, there was no difference between their performance in terms of finishing.

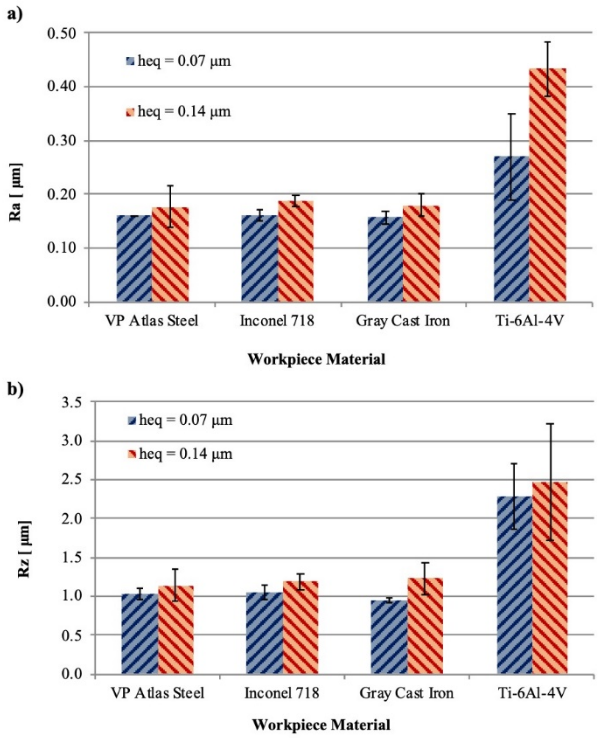

Fig. 2. Surface roughness versus equivalent chip thickness after grinding various metals. (a) Ra parameter. (b) Rz parameter.

Another important factor to evaluate the influence of cutting parameters during grinding is the analysis of the surface quality of the machined component. A detailed analysis of the surface of the machined material shows several micro defects or cracks. According to Hecker and Liang[15], the main defects are cracks caused by abrupt thermal variations (common in the grinding process with conventional grinding wheels) and craters caused by abrasive grit fractures.

In Figs. 3-6 are shown the images of the ground surfaces as a function of the equivalent chip thickness, obtained by SEM, for VP Atlas, Inconel 718, Gray Cast Iron and Ti- 6Al-4V, respectively.

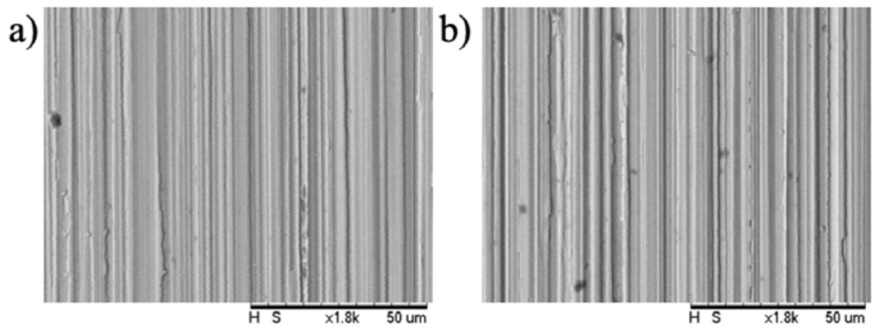

Fig. 3. Surfaces of VP Atlas steel after grinding with h_{eq}: (a) 0.07 µm and (b) 0.14 µm.

Noted from Fig. 3(a) and 3(b) that marks left by the abrasive grits that have passed through the surface of the workpiece. It can also be emphasized the presence of plastic deformation on the surface, which according to Marinescu et al. [13], occurs due to the penetration of the abrasive grits into the workpiece material that causes some material to be pushed and placed on the side by the cutting edges (workpiece material side flow). Consequently, it is formed cavities on the surface of the material (lateral grooves), without material removal, only plastic deformation occurring.

Similar behavior to that observed for surface of the VP Atlas steel was also observed for the Inconel 718, Figs. 4(a) and 4(b), there is evidence of micro-cutting and microploughing (plastic deformation) wear mechanisms caused by the passage of the abrasive grits. However, it has been observed that the grooves on the surfaces of the Inconel 718 are smoother than those observed for VP Atlas steel, contrary to what was expected. This could be explained by the high workhardenability of the Inconel 718, with shifts the tribosystem more towards the microcutting than the microploughing, leading to less pronounced grooves on the surface.

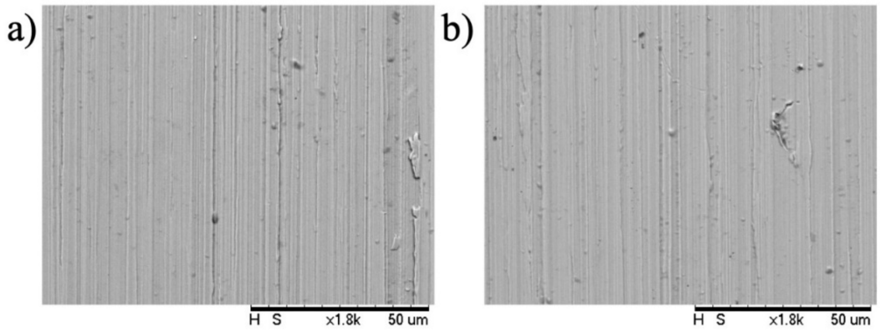

Fig. 4. Surfaces of the Inconel 718 after grinding with h_{eq}: (a) 0.07 µm and (b) 0.14 µm.

Surface images of the gray cast iron workpieces after grinding with different values of equivalent chip thickness are shown in In Figs. 5(a) and 5(b). Unlike the VP Atlas steel and the Inconel 718 steel workpieces, the presence of cracks and evidence of detachment of the surface material were noticed on the gray cast iron ground surfaces, regardless of the equivalent chip thickness used. Gray cast iron is a brittle material and because of its low ductility, the plastic deformation region is quite small. Thus, instead of initially only deforming with the penetration of the cutting edge of the abrasive grits, this material fractures and detaches from the surface [13]. Marinescu et al. [16] reported that the specific energy generated in the process during grinding of gray cast iron with alumina grinding wheel might be higher than that for other materials of similar hardness under the same cutting conditions as medium carbon steel. It is worth noting that the specific literature also recommends the use of SiC grinding wheels for the machining of gray cast iron, which has low tensile strength, thus demonstrating that the correct selection of a grinding wheel is essential. This grinding wheel class generally has a sharper shape and has sharper edges than aluminum oxide, and, thus, has a greater ability to penetrate the material and remove smaller amounts of it through shearing [16]. Another possible explanation for the microcracks in the surface is the open-grain phenomenon, described by Guesser et al. [17], as the graphite ejection during the machining process due to the high shearing stresses in the cutting region, with lead to surface microcracks. As previously mentioned in this work, the selection of the alumina grinding wheel for all materials was only used to determine the machinability between the ferrous and non-ferrous materials and, therefore, only with scientific purposes.

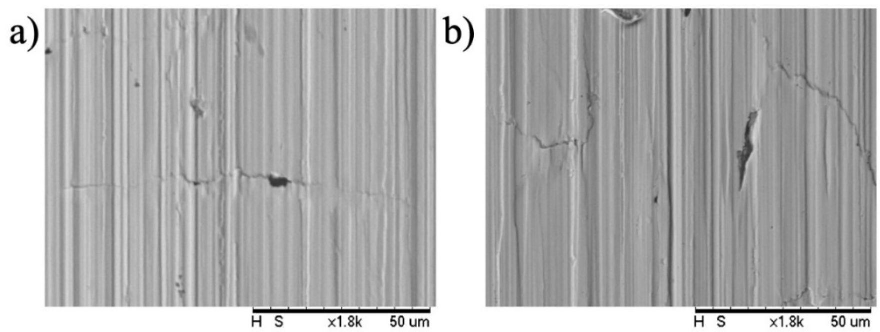

Fig. 5. Surfaces of the gray cast iron after grinding with h_{eq}: (a) 0.07 µm and (b) 0.14 µm.

In Figs. 6(a) and 6(b) are shown the ground surfaces of the titanium-based, Ti-6Al-4V, alloy. From these figures can be observed that the quality of the texture for this material is worse than that for the other materials tested and that the marks of the abrasive grits are not as evident as those of the other materials. In addition, evidence of severe plastic deformation on the surface may be noted by the material aspect of the workpiece, having the appearance of crushing rather than shearing. This phenomenon reflected by the higher values of roughness (Ra and Rz) in relation to the other materials (Fig. 2). The equivalent chip thickness practically did not affect the texture, but it is known from machining theory that increasing the grinding depth results in a larger heq and intensifies the thermal-induced plastic deformation, thus raising the levels of residual tensile stress on the ground surface [13]. If the thermal expansion is sufficient to cause plastic deformation and at the same time the subsequent cooling promoted by the coolant occurs, this will lead to a contraction on the workpiece surface and, thereby, resulting in residual stresses. Thus, the change in the microstructure of the material will cause a difference in the volume of crystalline arrangement which, in turn, will generate tensile or compressive stresses on the surface. In extreme cases, this phenomenon can lead to crack formation on the workpiece surface, as can be observed in Fig. 6(b). Similar results as for that current work (Fig. 6(b)) were found by Mello et al. [18] who also observed cracks on the surface of a Ti-6Al-4V workpieces and in the perpendicular direction to the cutting direction of the abrasive grits after grinding with white aluminum oxide grinding wheel, These authors concluded that these cracks may be related to combined thermal, mechanical and chemical factors in the process.

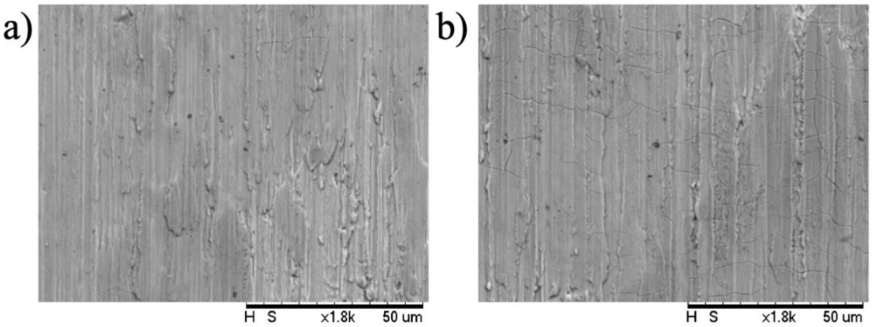

Fig. 6. Surfaces of the Ti-6Al-4V after grinding with h_{eq}: (a) 0.07 µm and (b) 0.14 µm.

4. Conclusions

After the peripheral surface grinding of various metals with aluminum oxide grinding the following conclusions could be drawn:

1) The lowest roughness (Ra and Rz) parameters values were obtained after grinding with the lowest equivalent chip thickness (0.07 µm). Practically no difference between the roughness values (Ra) for the VP Atlas, Inconel 718 and Gray Cast Iron (0.16 µm) was observed, unlike the Ti-6Al-4V in which the highest value for Ra = 0.48 µm was recorded after grinding under the severest condition;

2) Both Inconel 718 and the VP Atlas steel regular grinding marks on their surfaces after analyzes through the SEM;

3) Presence of cracks and material detachment were observed on the ground surfaces of gray cast iron;

4) Ti-6Al-4V presented the inferior performance in terms of roughness and surface quality in relation to other metals tested, since cracks were formed in its surface, thus presenting the poorest machinability under the conditions tested. From this is possible to infer that conventional aluminum oxide grinding wheel is not recommended for grinding this material;

5) The cutting parameters used in this research may be considered suitable for the grinding of VP Atlas and Inconel 718 materials.

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