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CONTRIBUTION TO THE STUDY OF ROUGHNESS AND ELECTRICAL POWER IN THE GRINDING OF STAINLESS STEEL USED FOR MOLDS AND DIES

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Abstract. Grinding attract attention in the metalworking industry as it allows obtaining parts from the automotive sector, among others, whose surface texture and combination of low dimensional and geometric deviations which generally cannot be achieved by another machining process with a defined geometry cutting tool. In grinding, the most important parameters are the radial depth of cut and workspeed, because they directly affect the equivalent chip thickness, and consequently the surface finish of the workpiece. Another parameter is the grinding power that influences the costs of the process and which is often neglected to be monitored. This work presents a contribution on the influence of radial depth of cut and workspeed on the roughness parameters R_a , R_b , R_z and R_q , and the electrical power consumed during the tangential flat grinding process of VP 80 stainless steel. The tests were carried out with a white aluminum oxide grinding wheel and using a semisynthetic cutting fluid that was applied in flooding. The radial depth of cut (a_e) and the workspeed (v_w) varied in two levels. The results indicated that all roughness parameters were higher when grinding was performed combining the highest a_e and v_w . The main contribution of this work was that it is also necessary to monitor the consumed power of the process, because even if a finish practically does not vary when doubling the a_e , for a lower v_w , the electrical power increased by about 270 %.

Keywords: Grinding, Radial depth of cut, Workspeed, Roughness, Electrical power.

1. INTRODUCTION

The global scenario presents a highly competitive environment for the metalworking industry, with increasing pressure to optimize the useful life of products and reduce environmental impact and production costs. This behavior is related to the study of machining process control parameters (Kahraman and Öztürk, 2019). In addition to efficiency, accuracy is of utmost importance in the environment where companies must maintain standards and procedures that conform to international norms. In terms of accuracy, grinding stands out as one of the most essential finishing processes in manufacturing (Cao et al., 2022), corresponding to approximately 20 % of the total cost of machining operations in developed countries (Kahraman and Öztürk, 2019).

Grinding is recognized as the fundamental representative of the finishing process group (Kopytowski et al., 2023). It is also considered one of the most complex machining processes due to the large number of variables involved, such as the undefined geometry of the abrasive grains, the stages of chip formation (friction, plowing and shearing) (Mukhopadhyay and Kundu, 2019), grinding wheel wear (attritional wear, crushing of abrasives, and shedding of abrasive grains caused by damage of binding agents) (Luo et al., 2021), dressing parameters (Mukhopadhyay et al., 2019), machine tool parametric limitations, techniques and application conditions of the cutting fluid, in addition to the machining parameters (radial depth of cut, tool speeds, grinding wheel and machining depth). Experimental studies focus mainly on evaluating the effects of these parameters on response variables (Kopytowski et al., 2023).

Surface grinding is one of the highest-quality mechanical parts manufacturing processes, especially in the automotive sector, where deviations in surface properties, dimensions, and shapes play an important role in mechanical functionality. (Sanjeevi et al., 2021). Parameters such as radial depth of cut and workspeed are often used to control the process in terms

of output variables, one of the main ones in this regard is the machined surface's roughness (Kahraman and Öztürk, 2019). The distribution of peaks and valleys of different dimensions specific to the processing conditions describes surface roughness. Generally, the arithmetic mean R_a is used to quantify roughness, in which values between 0.2 and 1.6 μm are expected (finishing classes N4 to N7, according to the ABNT ISO 219920-1:2021 standard), in general, in grinding (Diniz et al., 2010). Despite already being one of the most used parameters, according to Abrão et al. (2021), R_a does not represent the roughness profile precisely because it is an arithmetic mean. So other parameters are necessary to characterize roughness, such as the maximum profile height parameter: R_z . Abrão et al. (2021) yet point out that the roughness values R_a and R_z increase along with the radial depth of cut, and this relationship is best visualized with R_z . It should be noted that during the measurement process, it is essential to measure the roughness at different points on a surface to subsequently obtain the measurement uncertainty: an important measurement result quality indicator (Kahraman and Öztürk, 2019).

According to Sanjeevi et al. (2021), radial depth of cut is one of the main parameters of the influence of roughness. In the study carried out by the authors, the results of the Analysis of Variance (ANOVA) indicated a greater influence of this parameter on roughness. The maximum and minimum conditions of workspeed and radial depth of cut provided higher roughness values. Similar results were also observed by Abrão et al. (2021).

As a finishing process, the material removal rate is generally low and, combined with high cutting speeds (above 30 m/s), results in high specific cutting energy, which can be 2 to 20 times higher when compared to machining processes with defined geometry tools (Mukhopadhyay and Kundu, 2019; De Paiva et al., 2021). Due to the small dimensions of the chips, which vary between 1 μm and 1 mm (Yoshida et al., 2021), formed during machining and the low thermal conductivity of conventional abrasive materials (40 W/m.K), such as aluminum oxide (Al_2O_3), most of the energy dissipated in the form of heat is directed to the workpiece (from 60 % to 80 %) (Malkin and Guo, 2008). The integrity of the machined surface can be compromised due to thermal damage, which is the main limiting factor in grinding (De Paiva et al., 2021). In this way, the process is still a subject of great interest in the scientific community (Mukhopadhyay and Kundu, 2019), which also study variables such as the electrical power consumed during machining.

Grinding power is correlated with tangential cutting force, wheel speed, and specific energy of grinding. It can be used as an output variable to dimension machine tools, estimate the consumption energy of the process, assisting in the selection of the ideal grinding wheel for machining, predicting the cutting conditions that provide a better finish on the machined surface, and less wear on the grinding wheel or workpiece, among others. Sato et al. (2022) measured the cutting power during external cylindrical grinding of VP50IM steel, seeking correlation with the resulting machining efforts in this process. Analyzing the results, the authors observed that cutting power increases as radial depth of cut increases. Furthermore, the volume of material removed indicated that the roughing operation is more severe when compared to the finishing operation. In other words, selecting processes requiring less consumed power implies lower process costs.

In this context, this study contributes to the influence of radial depth of cut and the workspeed in roughness R_a , R_i , R_z , and R_q parameters, and electrical power consumed during the grinding process tangential plane of stainless-steel VP 80.

2. METHODOLOGY

A flat tangential grinding machine model P36, manufacturer Mello, was used to carry out the grinding tests, with a power of 2237.1 W, rotation of the grinding wheel axis constant equal to 2400 rpm, and resolution of 0.005 mm in the Z axis which is responsible for grinding wheel motion. The grinding wheel used was the straight type, produced in white aluminum oxide (Al_2O_3), with the specification AA46K6V and dimensions of 297 mm (outer diameter), 25.4 mm (width), and 76 mm (inner diameter). The workpiece material was a solubilized stainless-steel VP 80 (35 HRC), similar to the materials investigated by Anjos et al. (2016) and De Paiva et al. (2017), having rectangular geometry measuring 12 mm (height), 45 mm (width) and 118 mm (length). A semi-synthetic vegetable oil VASCO 7000 from the manufacturer Blaser Swisslube, prepared in the proportion of 1:19 parts of water cutting fluid was employed. It was applied in the machining process at a flow rate of approximately 8.8 L/min. Its concentration was monitored after each test, considering the BRIX of approximately 4 % with aid of a N1 refractometer, ATAGO. Only one dressing cycle was carried out prior to each grinding tests to ensure that the grinding wheel surface presented a similar topography in all tested conditions. In this process, was used a single-tip diamond dresser was used with a dressing depth (a_d) of 25 μm , overlap ratio (U_d) with a constant reference value of 3, and dressing speed (V_d) of 240 mm/min, with three passes.

With regard the cutting parameters used in the tests, the grinding wheel speed (v_s) and the depth of cut (a_p) were kept constant and equal to 37 m/s and 25.4 mm, respectively. As shown in Table 1, were radial depth of cut (a_e) and workspeed (v_w) levels were controlled, only one grinding cycle was adopted as the stopping point for grinding tests, that is, no replications of the tests were carried out.

Table 1. Experimental plan prepared for the grinding tests.

| Test | a_p (mm) | a_e (μm) | v_w (m/min) |
|------|------------|-------------------------|---------------|
| 1 | 25.4 | 15 | 2.7 |
| 2 | | | 7.5 |
| 3 | | 30 | 2.7 |
| 4 | | | 7.5 |

The experimental plan shown in Table 1 was performed on a single specimen. For that, they were four equidistant machining areas are demarcated on the surface to be ground, each corresponding to a test, as shown in Figure 1.

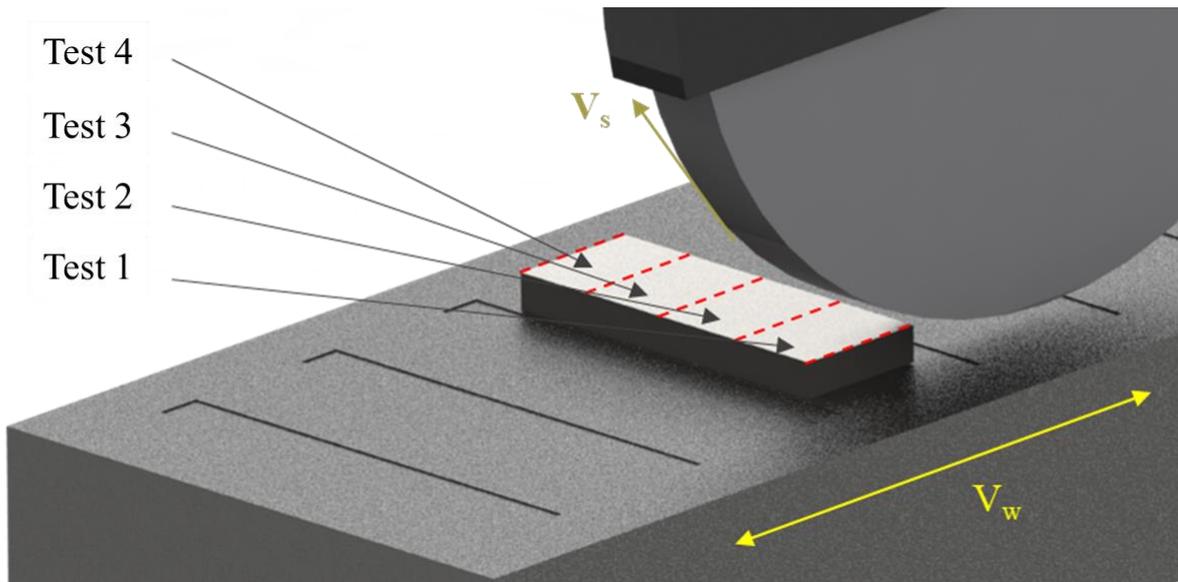


Figure 1. Schematic illustration of workpiece-grinding wheel system and the experimental plan carried out on the specimen.

The output variables analyzed in the grinding tests were roughness values and electrical power consumed by the machine tool. The roughness parameters analyzed were the R_a parameters (Arithmetic deviation average roughness), R_t (Total profile height), R_z (Maximum profile height), and R_q (Arithmetic Mean Square Deviation). To measure the roughness parameters, a portable profilometer model SJ-201P, Mitutoyo, was used. It was selected a cut-off of 0.8 mm and evaluation length equal to 5.0 mm for each condition. Five roughness measurements perpendicular to the feed marks were performed. The electrical power consumed during the machining was monitored in real-time through the interaction between voltage and electric current, measured separately on the drive motor of the grinding machine's spindle. Data acquisition was initially carried out in an analog converter, and subsequently, in the system's circuit, the signal was amplified, and noise was reduced. Then, the data was processed in the LABVIEW software. More detailed information can be found in the study by Oliveira (2017).

3. RESULTS AND DISCUSSION

This session presents the results of roughness and consumed electrical power.

3.1 Roughness

In Figures 2 (a, b c, and d) are shown the results obtained for roughness R_a , R_t , R_z , and R_q measured after the tests of tangential flat grinding of stainless-steel VP 80, depending on the radial depth of cut (a_e) and the workspeed (v_w).

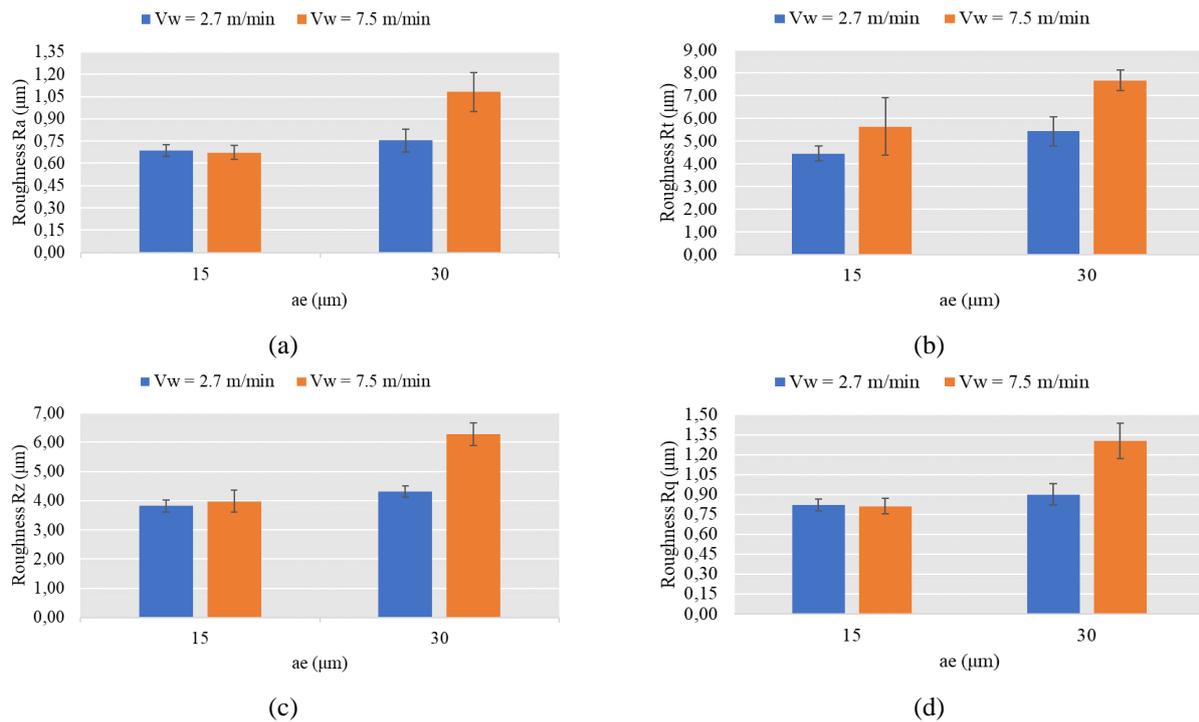


Figure 2. Results of the roughness parameters R_a (a), R_t (b), R_z (c), and R_q (d) obtained in the grinding tests of the VP 80 stainless steel depending on radial depth of cut (a_e) and workspeed (v_w).

As observed in Figure 2, when using the highest part speed ($v_w = 7.5$ m/min), roughness values increased with radial depth of cut. Increased radial depth of cut results in more abrasive grains active during grinding what makes that amount of material removed by each abrasive will be smaller, resulting in more elongated chips. In this sense, there is greater friction between the chips arising from the process and the machined component, thereby deteriorating the ground surface (Malkin, 2007). It is known that increasing chip thickness (and also cutting thickness) leads to increased cutting efforts and, as a consequence, also to increased roughness. In this sense, the effect of cutting thickness is superimposed by the effect of the length of the chip formed, which results from the increase in the contact length of the grinding wheel on the machined surface. Bianchi et al. (1996) emphasize that there is a greater proportion of friction and scratching from the beginning of chip formation until its expulsion, thus increasing the temperature in the cutting region and consequently deteriorating the finish. In other words, more abrasives from the tool in contact with the part generate more heat during the process, resulting in worse tribological conditions (Klocke, 2009).

With v_w constant at 2.7 m/min and a_e varying from 15 μm to 30 μm, percentage increases were observed (if considering the lowest value as a reference) approximately 9 % in R_a and R_q , 13 % in R_z , and 22 % in R_t . Increasing the workspeed to 7.5 m/min, a greater effect of a_e on the roughness was observed, increasing approximately 36 % in R_t , 60 % in R_a and R_q , and 69 % in R_z . A similar behavior was obtained in the study carried out by Abrão et al. (2021), in which the increase in a_e provided an average increase of 24.53 % in R_a and 32.34 % in R_z . Therefore, by increasing work penetration, by increasing the radial depth of cut, the deformation of the part is high, consequently, the heat in the grinding zone intensifies. This heating on the surface of the part increases thermal expansion and displacement of the outer surface towards the grinding wheel at which high temperatures arise and therefore produce surfaces with low quality, that is, high roughness (De Paiva et al., 2017).

Another factor that contributed to the increase in roughness was $v_w = 7.5$ m/min, a result resulting from the equivalent chip thickness (h_{eq}) increase due to the tensile stress in the abrasive grains increasing and generating greater force of shear and, therefore, increasing the roughness of the part (Abrão et al., 2021). The workspeed showed a greater effect keeping (a_e) constant at 30 μm. In this condition, there was an increase of approximately 40 % in the parameters R_a , R_t , R_z , and R_q . In the results obtained in the study by Abrão et al. (2021), the parameters R_a and R_z increased, respectively, by 40.21 % and 13.97 % with the increase in v_w . De Paiva et al. (2020) also observed a similar behavior of R_a as a function of a_e (10 for 30 μm) and v_w (3 for 7 m/min), with the statistical results indicating a greater influence of v_w .

3.2 Electrical Power

In Figures 3 (a and b) are shown the electrical power curves monitored during the machining of steel VP 80 stainless steel for radial depth of cut equal to 15 μm and workspeed of 2.7 m/min and 7.5 m/min. In (a), the peak power is located around 800 W, and in (b), with the increase in v_w , the peak power approaches 1000 W. In Figure 4, the electric power

curves were obtained over the same v_w variations, with a_e equal to $30\ \mu\text{m}$. The behavior is similar to Figure 4, that is, an increase in power peaks is observed using the highest v_w value. With $a_e = 30\ \mu\text{m}$, around $1800\ \text{W}$ and $2000\ \text{W}$ for $v_w = 2.7\ \text{m/min}$ and $7.5\ \text{m/min}$, respectively. In Figures 3 (a, b) and 4 (a, b), it is possible to identify in each graph, as machining progresses, two power peaks can be noted. The first (between $1\ \text{s}$ and $1.5\ \text{s}$) refers to the cutting action of the grinding wheel in a direction inconsistent with the advance of the workpiece, while the second (between $1.5\ \text{s}$ and $2\ \text{s}$) refers to the return of the wheel (down-grinding), also called spark-out. Spark-out occurs due to the elastic recovery of the material (Pawlowski et al., 2022; Röttger et al., 2022).

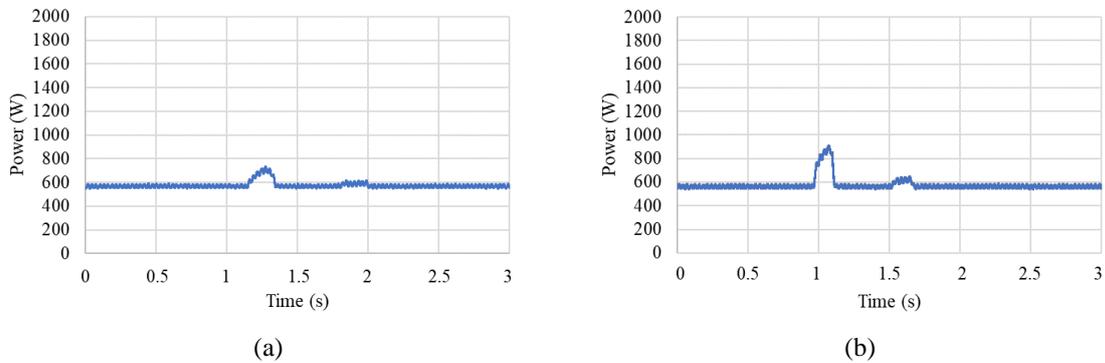


Figure 3. Electrical power (W) of VP 80 stainless steel over time (s): (a) $a_e = 15\ \mu\text{m}$ and $v_w = 2.7\ \text{m/min}$; (b) $a_e = 15\ \mu\text{m}$ and $v_w = 7.5\ \text{m/min}$

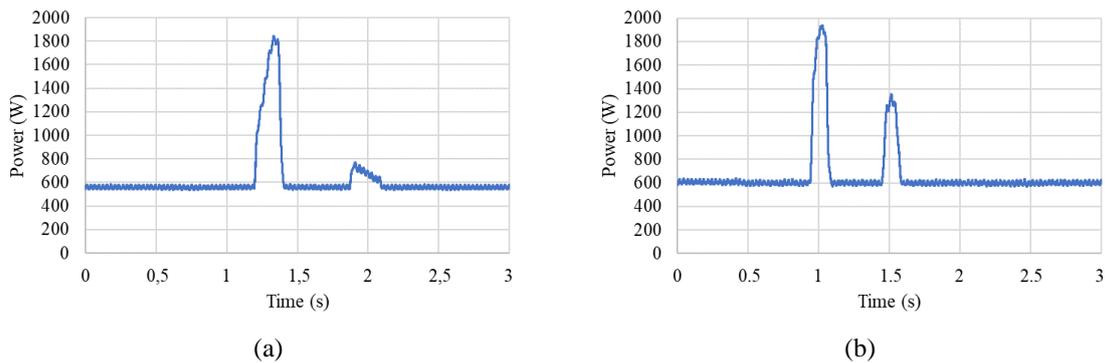


Figure 4. Electrical power (W) of VP 80 stainless steel over time (s): (a) $a_e = 30\ \mu\text{m}$ and $v_w = 2.7\ \text{m/min}$; (b) $a_e = 30\ \mu\text{m}$ and $v_w = 7.5\ \text{m/min}$.

Comparing the power peaks during machining tests in up-grinding, observed between graphs (a) of Figures 3 and 4, highlighted between graphs (b), the effect of radial depth of cut a_e (from $15\ \mu\text{m}$ to $30\ \mu\text{m}$) provided increases of 270 % and 211 %, respectively, in the electrical power consumed during grinding. During the spark-out, this increase was approximately 133 % between graphs (a) and 217 % between graphs (b). In Figure 3, the variation of v_w (graphs (a) and (b)) provided a 129 % increase in power during up-down machining. In the spark-out, this increase is less than 115 %. In Figure 4, the power measured in the interval from $1\ \text{s}$ to $1.5\ \text{s}$ increased by approximately 106 % between graphs (a) and (b). In the spark-out, this value was 162 %, which may indicate a probable increase in material removals as a result of the thermal expansion of the part (Röttger et al., 2022), compared to that observed in Figure 3 (b). these results demonstrate, in general, that the electrical power consumed during machining is proportional to the grinding parameters considered here, with radial depth of cut apparently being more dominant compared to workspeed.

Figures 3 and 4 show an increase in the peak referring to the grinding test when a greater radial depth of cut $a_e = 30\ \mu\text{m}$ is applied, inferring the increase in the tangential cutting force due to the friction caused by the increase in thickness. Equivalent cut, a result found by Anjos et al. (2016). They carried out grinding tests on a VP 50 class steel using 3 different conventional grinding wheels (white aluminum oxide, green silicon carbide, and black silicon carbide with white aluminum oxide) using different cooling methods. They observed that when v_w increased from $2.5\ \text{m/min}$ to $7.5\ \text{m/min}$, equivalent cutting thickness also increased what lead to power electricity increase. Canarim (2018) carried out an external cylindrical plunge grinding of AISI 4340 steel with CBN grinding wheel and observed that cutting power signals increased with material removal rate, similarly to that behavior observed in this work when both depth of cut and workspeed were increased.

4. CONCLUSIONS

Based on the experimental results obtained through tangential plane grinding of VP 80 steel under different cutting conditions, the following conclusions were obtained:

- In general, the increase in radial depth of cut (a_c) did not play strong influence on the surface roughness values of the parameters R_z , and R_q , except for the parameters R_t and R_a , in which increased by about 60 % and 69 %, respectively, when a_c was increased from 15 μm to 30 μm ;
- Regarding the workspeed (v_w), its variation leads to increase in roughness up to 40 % for roughness parameters R_a , R_t , R_z , and R_q , that is, the results indicated that roughness increases when radial depth of cut and workspeed are maximized;
- For the R_a parameter, in general, the absolute roughness values obtained in the tests fall into the finishing classes N6 (0.4 μm to 0.8 μm) and N7 (0.8 μm to 1.6 μm). It was also possible to notice a R_a roughness lower than 1.21 μm for all cutting conditions used, which is well below the value of 1.6 μm , which is the reference base in grinding concerning the semi-finishing grinding process;
- The power results obtained in the tests showed a greater intensity in the energy peaks. The consumed power increased about 270 % when radial depth of cut was increased from 15 to 30 μm , regardless of workspeed tested.

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