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## **SURFACE QUALITY AND TOOL WEAR ANALYSIS ON THE TURNING OF HARDENED AISI 4340 STEEL USING EXPERIMENTAL CERAMIC CUTTING TOOLS**

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**Abstract.** *The work evaluates the performance of recently developed aluminum oxide cutting tools, analyzing the resulting surface quality and tool's wear on the turning of hardened AISI 4340 steel. The aim of this project is to explore different alternatives of more economical cutting tools developed with national technology, since currently in Brazil the ceramic cutting tools are mostly imported, increasing the total machining costs. The turning process was carried out varying the cutting speed (160 and 200m/min), feed rate (0.05, 0.10 and 0.15mm/rot) and cutting depth (0.15 and 0.25mm), in order to allow the application of the experimental tools and validate the replacement considering the grinding roughness results. The DOE applied was the full factorial design to ensure the analysis of all interactions. To determine all significant correlations whitening the applied cutting parameters a statistical analysis of variance was done. It was possible to verify the viability of the process and to find the cutting condition that best satisfies the roughness parameters. Better surface quality was found for smaller values of feed rate. It was observed the occurrence of tools chipping; however, the minimum flank wear  $V_b$  was 0.36mm for lower cutting depths and feed rate (0.15mm and 0.05mm/rot).*

**Keywords:** *Turning. AISI 4340 Steel. Ceramic cutting tools. Roughness. Tool's wear.*

### **1. INTRODUCTION**

Currently, the machining industries are facing a big challenge to achieve high quality, good surface finish and high material removal rate and, at the same time, achieve low operating costs. The goal of modern industries is to have low-cost manufacture processes that can result in high-quality products in short production time.

In response to this recurring need, the machining of hardened steels is increasingly on focus in the industrial sector due to the possibility of elimination of the grinding process, allowing the reduction of cost and time of the manufacture steps. To the grinding elimination to be possible, the machining process must be carried out in a rigid machine combined with cutting tools with high hardness and resistance to wear at high temperatures (Korn, 2004).

The possibility of eliminating a step on the total machining process of hardened steels is a critical machining point that can bring many benefits to the process. However, the elimination of the final finishing process of grinding can only be stated if good surface quality is achieved efficiently.

This work studies the possibility of the grinding process elimination, associated with the application of dry machining in turning. With the aim is to perform a more economical, cleaner, safer machining with fewer risks to the environment and to the worker, when compared to the conventional lubrication.

In general, turning processes require a lot of energy to remove material causing excessive heating of the cutting edge of the tool. This heating, if not controlled, reduce drastically the tool's life and the surface and dimensional quality of the components produced. For this reason, several studies are developed to analyze the performance of dry machining in the most varied machining processes. However, for these techniques to be advantageous to the industry they cannot significantly affect the process output variables (workpiece roughness, tool life, etc.) and especially productivity.

As a disadvantage, the machining of hardened steels decreases the life of the cutting tools, and enhance the high tool wear results, leading to a great error on the workpiece final dimensions, deformed geometries and low surface quality (Grzesik et al., 2007). More specifically, the hard turning imposes extreme requirements for the cutting tools due to the high hardness of the workpiece material and the high efforts and high temperatures generated into the tool/surface interface (More et al, 2006). Some disadvantages of the turning of hardened steels are the roughness dependence of cutting conditions (mainly feed rate) and the high risk of unexpected catastrophic tool failure at the end of the normal wear phase of the tool, mainly associated with the application of ceramic cutting tools.

Due to this need for cutting tools, there is a constant improvement and development of new tooling materials and different coating for cutting tools to contribute to the machining of steels in these conditions. A great effort has been observed to improve the properties of these materials to maintain high hot hardness, tenacity, wear resistance, and work at higher cutting speeds.

The ceramic tools have high resistance to wear, maintain hardness at high temperatures and are insensitive to oxidation. These characteristics make possible for the ceramic material to replace the cemented carbide, especially when high cutting speeds are applied to the machining of hardened materials (Souza, 2005). On the other hand, when subjected to intense mechanical stresses, the ceramic tools can suffer fracture without warning reducing their lifetime and generating complications in the machining.

To overcome this deficiency, enormous advances are made in the field of ceramic tools with the application of different dopants. The variety of dopants available help to enable the application of simpler ceramic tools on the machining process of hardened steels that lead to a great economic impact on machining processes when compared to more traditional and expensive tools such as PCBN. Which is considered the most suitable material for machining in these process conditions (turning), material (hardened steel) and lubrication (dry machining).

Nevertheless, among the machining processes, turning is one of the most used machining process in the industry, which motivates the deepening of studies in this area. This work also proposes the associated study of an extremely industrially applied material, the AISI 4340 steel, which is widely used in the automotive and aeronautical sector, due to its favorable characteristics for components that suffer dynamic efforts, such as crankshafts and landing gear for airplanes, tractors, shafts with high mechanical demands and vehicles in general. This steel has high fatigue strength, high hardenability, good forging and tenacity properties.

It is important to highlight that machining processes, in this case the turning process, being one of the most used manufacturing processes in the modern world, consumes billions of dollars annually. Moreover, it is known that among the elements that have the most influence on the results and the costs of machining, the cutting tools stand out. The correlation between the tools and the materials to be machined is extremely critical, due to the generation of shear and friction between the tool, the workpiece and the chip that promote high temperatures, vibrations, efforts, acoustic emission, besides other mechanisms that interfere in the results of surface finishing and tools wear. In Brazil, the ceramic tools used are in totality imported, a fact that limits their use. Important advances could be achieved if Brazil developed its own tool manufacturing technology, reducing costs and providing the country with new scientific and technological advances, which is proposed in this work, through the performance analysis of the experimental ceramic tools developed in the Materials and Technology Department at FEG-UNESP.

Nevertheless, this work has as justificative the innovative potential, analyzing the performance of national experimental tools, to replace more traditional tools. Since, according to Machado et al. (2011), the material considered as suitable for tooling in hardened steels is the PCBN (polycrystalline boron nitride), however, each insert can cost around 80 times a cemented carbide insert and about 15 to 20 times the price of the ceramic.

Therefore, due to the current scenario presented, the challenge of this work was to establish machining conditions that could contribute simultaneously to the mentioned issues. That is, to enable the turning of hardened AISI 4340 steel, without the use of lubricants (dry machining), through the analysis of the performance of the application of alumina-based ceramic tools ( $Al_2O_3$ ), verifying their consequences on the process output variables, validating or not the elimination of the rectification process.

## 2. OBJECTIVES

The main objective of this work is to analyze the performance of ceramic tools composed of aluminum oxide with magnesium oxide in the turning of hardened AISI 4340 steel. The performance will be verified through the surface quality analysis and the wear of the tools.

The specific objectives are:

- Enable finishing machining in the turning process of hardened AISI 4340 steel with newly developed ceramic tools using dry machining, contributing to the reduction of manufacturing processes such as grinding.
- Analyze the final roughness and wear of the tools in the different machining conditions.
- Check the performance of the experimental ceramic tools by analyzing the wear of the tools. Analyze wear progression through image analysis. Analyze also possible depositions of materials on the tool.
- Analyze the influence of cutting parameters (cutting speed, feed rate, and cutting depth) in the machining of hardened AISI 4340 steel.

## 3. MATERIALS AND METHODS

This work aims to enable and validate the application of national experimental material as a cutting tool on the turning machining process for hardened AISI 4340 steel, in order to analyze the performance of the  $Al_2O_3$ -MgO ceramic tools. To achieve the proposed objectives, the project was developed through experimentation, starting from preliminary

tests to determine the parameters and variables most appropriate to begin the testing phase such as cutting speed, feed rate and cutting depth.

### 3.1 Test samples

It was used a cylindrical test sample of AISI 4340 steel with a diameter of 100 mm and length of 210 mm. The material suffered heat treatment of quenching and annealing to achieve the desirable mechanical and physical properties.

The quenching process began at 850 °C and was carried out for a total period of 4 hours to ensure the process of austenitization. The stage time duration was set according to the recommendation of 1 hour for each 25 mm of thickness. Therefore, for the 100 mm diameter of the test sample, it was needed 4 hours. After the quenching, when the material cooled to 70°C, the annealing process started. The temperature of 150°C was maintained for 2 hours to promote stress relief. The time and temperature were set to provide, at the end of the process, a hardness of approximately 56 HRc, equivalent to approx. 577 HB (613 HV).

### 3.2 Cutting Tools

The experimental ceramic cutting tools used are inserts made of aluminum oxide doped with magnesium oxide ( $\text{Al}_2\text{O}_3 + \text{MgO}$ ). The total composition in mass percentage was 95% of aluminum oxide ( $\text{Al}_2\text{O}_3$ ) and 0,25% of magnesium oxide (MgO). The experimental tools are inserts with square geometry and a bright-white color due to the main composition of aluminum oxide as can be seen in Fig.1.

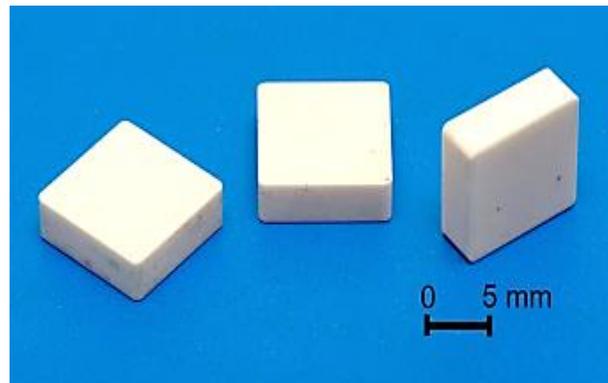


Figure 1. Experimental ceramic cutting tools  $\text{Al}_2\text{O}_3+\text{MgO}$ .

The experimental tool's code is SNMG120408, which explains its main characteristics and dimensions. The nomenclature "S" stands for square, that means, it is a square design insert. The "N" of neutral, which means that the tool can be used on both sides as an insert without a chip breaker. The "M" is the tolerance class cataloged and the "G" means that the insert do not have any kind of chip breaker. The numerical data found in the code mean respectively: 12 mm of edge, 4 mm of height and 8 mm radius on tools tip. The end-cutting edge angle (ECEA) and the inclination angle of the tool are  $-6^\circ$  with a side-cutting edge (SCEA) angle of  $6^\circ$ .

Before the beginning of the tests, the insert was positioned in the tool holder to start the machining as shown in Figure 2.



Figure 2. Experimental scheme of the insert and workpiece position.

### 3.3 Testing methodology

The project was developed through experimentation, starting from preliminary tests in order to determine the most adequate cutting parameters. During the preliminary tests, different cutting speeds were applied in the range of 100 to 600m/min. The feed rates applied were in a range between 0.05 and 0.2mm/rot and cutting depths in the range of 0.05 to 0.50mm.

The cutting parameters selected on the preliminary tests and applied on the definitive tests were: cutting speed ( $V_c$ ) = 160 and 200m / min; feed rate ( $f$ ) = 0.05 mm/rot, 0.10 mm/rot and 0.15 mm/rot; cutting depth ( $a_p$ )= 0.15mm and 0.25mm. The cutting speed and feed parameters were varied according to the planning of full factorial type experiments, and all combinations of these conditions were performed in replicate. No cutting fluid was used to execute the machining process.

The tests were performed at the Machining Study Laboratory of UNESP-Guaratinguetá, using a Romi CNC turning center, model GL 240M with a main engine of 15 kW.

### 3.4 Design of experiments

It was applied a design of experiments (DOE) of full factorial design. The full factorial consists of three main factors (Cutting Speed, Feed rate and cutting depth) which one with a certain number of levels. The levels have the function of presenting the variation of condition or situation within the factor. To the Cutting Speed factor, there were two levels. To the Feed rate factor, there were three levels and to the cutting speed factor, there were 2 levels.

The experiments were performed using two cutting speeds “ $V_c$ ” (160 and 200m / min), three feed “ $f$ ” (0.1, 0.15 and 0.25mm / rot) and two cutting depths “ $a_p$ ” (0.15 and 0.25mm) for the ceramic tools with two replicates for each condition, totaling the 24 tests.

### 3.5 Statistical analysis methodology

For a better understanding of results, a data treatment and a statistical analysis were applied to all the data obtained during the machining tests.

It was applied an analysis of variance (ANOVA) to investigate all influences of the three main factors (Cutting Speed, Cutting Depth and Feed rate) and their levels on the output variables. The levels have the function of presenting the variation of the factor. The Kolmogorov-Smirnov normality test was also applied. The analysis of Variance (ANOVA) is a statistical technique that allows the evaluation of the means of data populations. The analysis aims, fundamentally, to verify if there is a significant difference between the means and if the factors have influence in some dependent output variable. Therefore, the ANOVA analysis was applied as a procedure used to compare all variation within the input variables of the process.

### 3.6 Roughness measurement

After the machining tests, the surface integrity was evaluated by roughness measurement. The parameter analyzed was the average roughness value “ $R_a$ ” and total roughness value “ $R_t$ ”. The sampling length adopted was 0.8 mm (cut-off). The measuring path ( $l_m$ ) for the applied cut-off 0.8 mm was 4 mm.

To analyze the mean and total roughness, the measurement was in triplicate to reduce the experimental error and to provide data reliability. Therefore, to the twenty-four measurements with three replicates for each one, seventy-two measurements were done with twelve different combinations analyzed in the full-factorial design.

A rugosimeter brand Mahr model Marsurf M300 with a Diamant cone tip with a tip radius of 2  $\mu\text{m}$  was used to the evaluation of the surface quality of the workpiece.

### 3.7 Wear measurement

Qualitative and quantitative evaluation of tool wear was also carried out with the identification of mechanisms. And the identification of the types of malfunctions that occurred during the tests. For the evaluation of the wear that occurred during the process and observation of generated faults, it was used the MAHR microscope model MarVision MM200 of Laboratory of Machining Studies of the Department of Materials and Technology of FEG-UNESP.

## 4. RESULTS AND DISCUSSION

### 4.1 Surface quality analysis

#### 4.1.1 Average roughness ( $R_a$ )

For the average roughness values, the Kolmogorov-Smirnov normality test was used to verify if the probability distribution associated to this data could be approximated by the normal distribution (Figure 3).

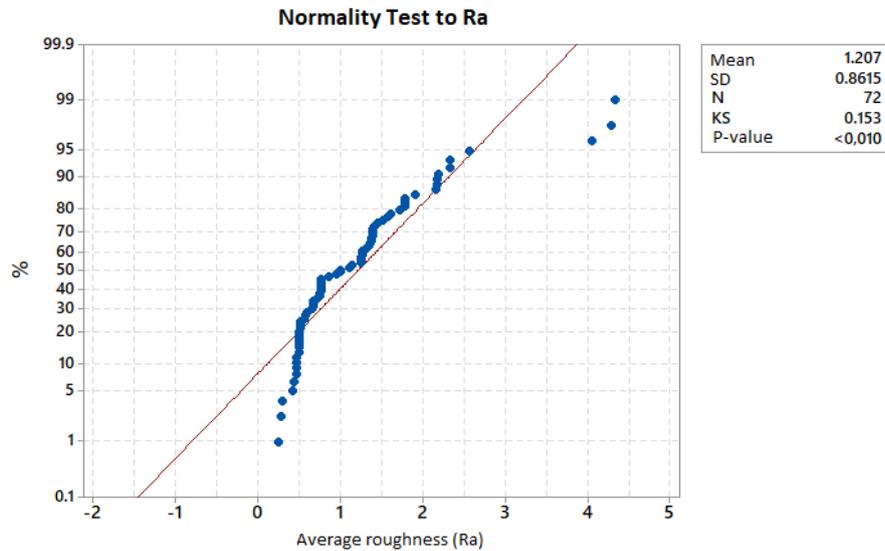


Figure 3. Normality test for the average roughness (Ra).

Considering the normality test graph in Fig. 3, it can be observed that for the average roughness the P-value found is less than 0.010, that means that in a significance level of 5%, the data obtained can not be considered as part of a normal population. Since the value of P corresponds to the lowest level of significance in which the null hypothesis  $H_0$  is not rejected, with ( $H_0$ : values are normally distributed and  $H_1$ : this does not occur). However, It is known that a normal distribution of data is difficult to obtain experimentally. A non-normal data population can be worked if the sample is large enough, the sample size of  $n \geq 20$  is often adequate, since the relationship between robustness for normality and sample size is based on the central limit theorem, which proves that the distribution of the mean data of any distribution approaches the normal distribution as the sample size increases. Therefore, since the total data analyzed were 72 responses, with a standard deviation of 0.8615 indicating the low dispersion of the population mean, the data can be considered as part of a normal population.

In the analysis of variance for the average roughness in Tab. 1, it can be observed that the majority of the P-value indicated that the influences between the cutting parameters were significant, due to the P-value was lower than the level of significance adopted of 5%. It is observed that the Cutting Speed was not significant and does not interfere with the resulting average roughness values, as well as the interaction of the cutting speed ( $V_c$ ) and cutting depth ( $a_p$ ). However, the feed rate and cutting depth factors were very significant interfering directly in the roughness results. There was no significant third order interaction for the factors in the average roughness results at the significance level of 5%. However, it is guaranteed by the adjusted coefficient of determination (value of R-sq) that the final determinations are valid for most of the data since the model explains about 62.9% of the results which can be found according to the dispersion line.

Table 1. ANOVA analysis to the average roughness (Ra)

	<i>DF</i>	<i>Adj SQ</i>	<i>Adj QM</i>	<i>F-value</i>	<i>P-value</i>
Model	16	37,5494	2,3468	8,520	0,000
Blocks	5	0,8888	0,1778	0,650	0,666
Linear	4	29,1844	7,2961	26,500	0,000
Cutting speed “ $V_c$ ” (m/min)	1	0,001	0,001	0,000	0,952
Feed rate “ $f$ ” (mm/rot)	2	24,8773	12,4386	45,180	0,000
Cutting depth “ $a_p$ ” (mm)	1	4,3061	4,3061	15,640	0,000
2nd order interactions	5	7,4102	1,482	5,380	0,000
$V_c * f$	2	2,7771	1,3885	5,040	0,010
$V_c * a_p$	1	0,0246	0,0246	0,090	0,766
$f * a_p$	2	4,6085	2,3042	8,370	0,001
3rd order interactions	2	0,0661	0,033	0,120	0,887
$V_c * f * a_p$	2	0,0661	0,033	0,120	0,887
Error	55	15,1415	0,2753		
Total	71	52,691			

R-Sq(adj) =62,9%

For the total roughness “Rt”, the Cutting speed factor was not significant as well as for the average roughness “Ra”, as can be seen in the Tab. 2. There was no third order interaction, which means that each factor acted in isolation, except for feed rate interactions with cutting depth and cutting speed. This does not mean the cutting parameters did not influence the surface finish, it just means that when compared together they do not observe any difference in statistical optics. It is notable that the value of R-sq does not fully explain the data, presenting a correspondence of only 49.83% of the values, a smaller correspondence than for the values of the average roughness.

Table 2. ANOVA analysis to the total roughness (Rt)

	<i>DF</i>	<i>Adj SQ</i>	<i>Adj QM</i>	<i>F-value</i>	<i>P-value</i>
Model	16	1086,98	2,3468	67,936	0,000
Blocks	5	35,62	0,1778	7,124	0,725
Linear	4	519,66	7,2961	129,916	0,000
Cutting speed “Vc” (m/min)	1	1,82	0,001	1,824	0,705
Feed rate “f” (mm/rot)	2	367,66	12,4386	183,828	0,000
Cutting depth “ap” (mm)	1	150,18	4,3061	150,185	0,001
2nd order interactions	5	531,21	1,482	106,242	0,000
Vc*f	2	218,78	1,3885	109,391	0,001
Vc*ap	1	31,50	0,0246	31,505	0,119
f*ap	2	280,92	2,3042	140,461	0,000
3rd order interactions	2	0,49	0,033	0,245	0,981
Vc*f*ap	2	0,49	0,033	0,245	0,981
Error	55	691,04	0,2753		
Total	71	1778,02			

R-Sq(adj) =49,83%

In the main effects graph for the average roughness “Ra” and total roughness “Rt” (Fig. 4), there is a tendency change in the roughness results with the variation of cutting speed, with best roughness results at higher cutting speeds.

However, the difference on the roughness values is very small, due to the surface quality becomes insensitive to variations in cutting speed, as evidenced by the application of ANOVA with a P-value of 0.952.

A direct influence of the feed rate “f” on roughness was observed, the values obtained from P-value for the factor (f) and their interactions (f\*Vc and f\*ap) were 0.000, 0.000 and 0.010, respectively, proving that the interactions were significant at the level of adopted significance of 5%. The lower feed rate applied, better the surface quality results are observed, with a little variation up to 0.10mm/rot. However, when the feed rate is greater than 0.10 mm/rot, there is a large increase in values and considerable loss of surface quality, where the roughness is about 3 times higher for “Ra”.

It is observed in the main effects graph that “Rt” makes possible to identify more clearly the interference of the factors in the average total roughness obtained. For example, increasing the feed rate by 0.05mm/rot causes the total roughness to double its amplitude. Increasing the feed rate has a geometric effect on roughness, as it contributes to increasing the distance between peaks in the roughness profile, thereby increasing the value of the average and total roughness amplitude.

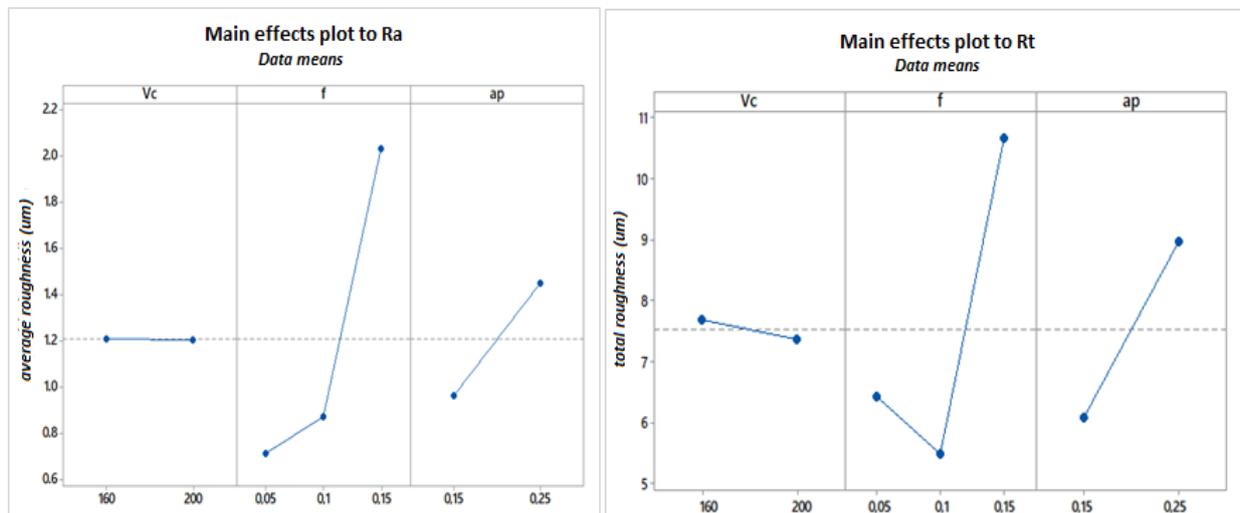


Figure 4. Main effects plot to the average roughness and total roughness.

Similar to the feed rate, worse surface quality was found for higher values of cutting depth as expected. It is important to highlight that the average roughness values observed are in the order of  $1.0 \mu\text{m}$  for the use of the ceramic tools. These high values prove the resulting low surface quality for higher feed values ( $f$ ) in conjunction with higher cutting depths ( $a_p$ ).

Figure 5 presents the interaction graph for the average roughness and total roughness. It is clearly observed that the interactions for the factors ( $V_c * f$ ) and ( $a_p * f$ ) were significant, confirming that the feed rate is a critical factor in the turning process of hardened 4340 steel.

Only the interaction between cutting speed and cutting depth ( $V_c * a_p$ ) was not significant for both “ $R_a$ ” and “ $R_t$ ” as well as 3rd order interaction with P-value of 0.981, which means that when factors are compared together there is no difference in statistical optics.

Correlating the roughness results with the observed tool wear, it can also be stated from the analysis of tool wear that the formation of the edge built-up on the tools contributed to the worst surface quality. For the cutting speeds used, both 160 m/min and 200m/min, there was an increase on the incidence of edge built-up and chipping as the feed rate increased. However, due to the geometry of the tool, as shown by the preliminary tests performed, the increase in cutting speed also led to increased vibration during machining by increasing machine rotation axis, leading to deteriorate the surface and providing a worse surface quality.

About the cutting depth factor, higher values of cutting depths increase the machining efforts, leading to higher values of roughness and therefore worse surface quality. However, it is clear that for the tested conditions, the feed rate factor was more critical than the cutting depth.

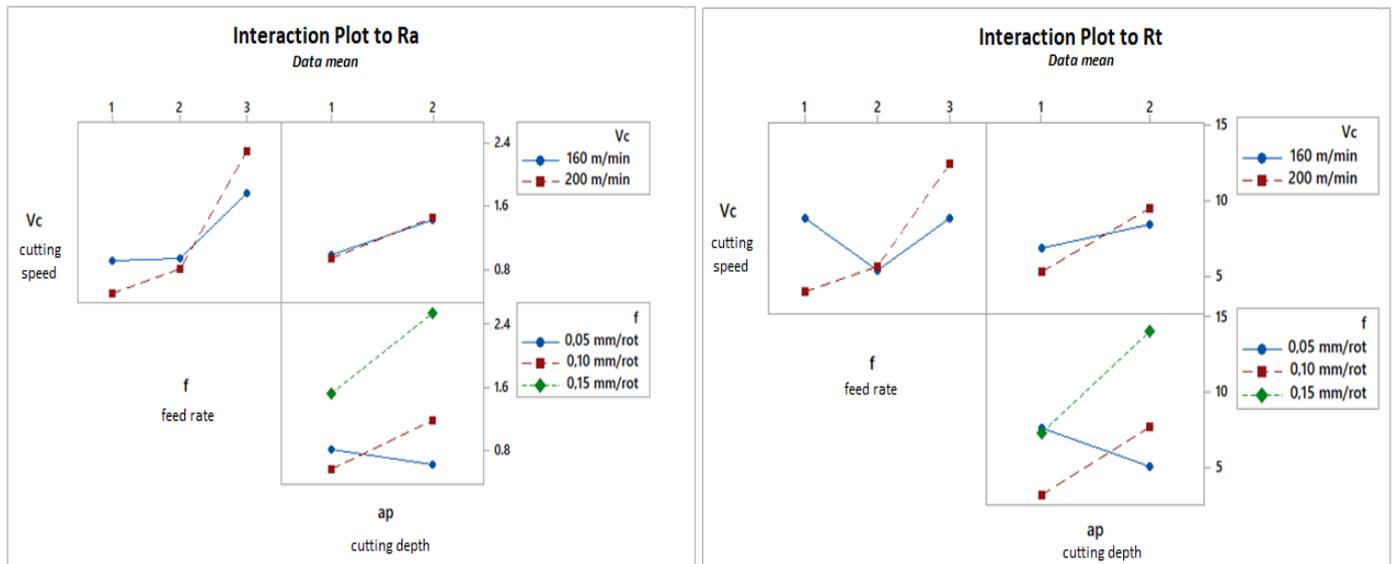


Figure 5. Interaction plot to the average roughness and total roughness.

#### 4.2 Tool Wear analysis

For the evaluation of the resulting tool wear it was analyzed the flank wear since it is generally the main factor limiting the life of the cutting tools and occurs in all machining processes.

It was observed that the flank wear per machined meter results increase progressively with the increase of the feed rate used, for all the tested conditions. The increase on the flank wear is due to the higher friction that occurs between the tool and workpiece as the tool loses its cutting angle (Side cutting edge angle SCEA) and widens the tool-workpiece contact area which increases the friction generated. For the highest cutting speeds and depths used there was even greater occurrence of cracks and chipping as can be seen in Figure 6.



Figure 6. Tool edge for the tests with cutting speed  $V_c=200\text{m/min}$ .

It can be concluded that the crack that allowed the chipping has a mechanical origin due to the parallel position to the cutting edge. The incidence of cracks may have occurred due to excessive variation of stresses on the tools edge due to the low tenacity of the ceramic tools. Abrasive wear was found for the combination of high cutting depth and speed.

Figure 7 presents clearly the abrasive wear marks on the tools. The abrasive wear has occurred due to material loss due to microchipping caused by the high hardness particles present in the tool that were torn away by abrasion during turning.

During the tests it was verified that with the increase of the feed rate led to a higher occurrence of abrasive wear, when the value of the depth of cut was kept constant. For the highest feed value and depth of cut, a high incidence of chipping was observed, regardless of the speed used. For the highest feed rate of  $0.15\text{ mm/rot}$  and cutting depth of  $0.25\text{mm}$  several chipping damages were observed, probably due to the combination of adhesion wear mechanisms on the tool surface during chip sliding.

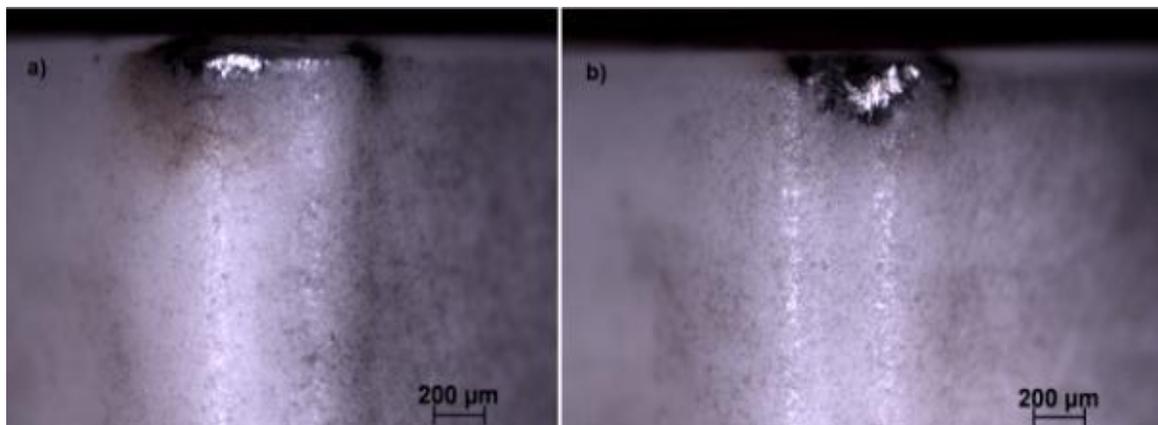


Figure 7. Abrasive wear a) For cutting speed ( $V_c$ )= $200\text{m/min}$ , feed rate ( $f$ )= $0,05\text{mm/rot}$  and cutting depth ( $a_p$ )= $0,15\text{mm}$ . b) For cutting speed ( $V_c$ )= $200\text{m/min}$ , feed rate ( $f$ )= $0,15\text{mm/rot}$  and cutting depth ( $a_p$ )= $0,15\text{mm}$ .

The cutting edge breakage occurred in preliminary tests when applied cutting speeds above  $500\text{m/min}$ . This type of damage occurs due to the weakening of the edge by the effect of the action of several chipping. Simultaneously with wear, the temperature fluctuation in the workpiece interface may have led to a change in the stress distribution in the cutting region which may have facilitated breakage as the tool has the characteristic of being very fragile. The several chipping may also have occurred due to the tool geometry that contribute to generate vibrations during machining leading to the tool impact with the workpiece during the turning process. It is important to highlight that the edge geometry has great effect even on the resulting roughness, especially the tip radius which, being a high value (greater than twice the feed rate) may have induced the vibrations.

In conclusion, lower flank wear values and lower tool breakdowns were found only for lower feed rate values combined with lower cutting depths, as shown in Fig. 8.



Figure 8. Flank wear for cutting speed ( $V_c$ )=160m/min, feed rate ( $f$ )=0,05mm/rot and cutting depth ( $a_p$ )=0,15mm.

## 5. CONCLUSION

The feed rate was the most critical and influential factor in the results of roughness and, therefore, in the final surface quality, with the best results obtained for the condition of lower advance (0.05 mm/rot) with the average roughness value of  $0.27\mu\text{m}$ . Lower flank wear was obtained with an association of smaller depths of cut with  $V_b$  amplitude of 0.36 to 0.38mm. However, the mean amplitude of the mean Roughness values was in the order of  $1.0\mu\text{m}$ , which proves the general low surface quality resulting for the combination of the machining parameters tested, mainly for higher values of feed and depth of cut, factor was more critical than the depth of cut for the surface finish.

Therefore to the  $\text{Al}_2\text{O}_3+\text{MgO}$  tools, the best condition considering the roughness was found with  $V_c=160\text{ m/min}$ ,  $f = 0.05\text{ mm/rot}$  and  $a_p=0.15\text{ mm}$ . When applied the use of lower feed rates, regardless the cutting speed, the average roughness values fall to the order of  $0.3\mu\text{m}$ , which are acceptable values when evaluating the replacement of the grinding process to the AISI 4340 steel. It was also observed the high incidence of severe damages and wear, as well as the end of the tool life due to edge breaks, which indicate, mainly, the need to review the machining parameters, in particular, to speed increase of cut according to literature for ceramic tools under these conditions. However, such changes must be applied in conjunction with the change in tool geometry to reduce the stresses generated so as not only to allow surface grinding equivalent quality but also to prevent excessive wear and failure occurrence.

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