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DESIGN, ANALYSIS AND MANUFACTURING OF A SPECIAL CUTTING TOOL FOR TITANIUM MILLING

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Abstract. *Titanium machining presents lots of difficulties because of the outstanding properties of these alloys. Besides the wear mechanisms that severely impair tool life, it is also common to face problems for obtaining a good surface finishing. In terms of machining parameters, feed rate is strongly related to surface roughness; in terms of tool geometry, nose radius does the same role. This work presents a study on design, analysis and manufacturing of special cutting tools for titanium milling, whose only variable was the nose radius, tested on three levels: 0.8 mm, 1.2 mm and 1.6 mm. The insert carbides were ground on a 4-axis grinding machine and characterized by a 3D image analysing system. Results showed that it was possible to manufacture inserts keeping a small error between actual nose radius and the nominal ones. Also surface roughness measurements on the clearance face of the cutting tools provided a good repeatability, as confirmed by the analysis of variance. Anyway, it seems that grinding lower nose radii may hinder the control of both dimensional and surface finishing, because of the error tendency that was observed here.*

Keywords: *Machining, grinding, carbide, nose radius, surface roughness.*

1. INTRODUCTION

Titanium alloys are excellent candidates in various sectors, such as automotive, aeronautics, chemical, petroleum and medical, as they have an excellent strength/weight ratio, in addition to good corrosion resistance and chemical stability. These alloys are increasingly replacing stainless steels in cardiovascular stents, catheters, bone plates and screws for osteosynthesis (Rack and Qazi, 2006).

Anyway, there are several difficulties that affect the machinability of titanium, such as its low thermal conductivity, high affinity with almost all known tool materials and low modulus of elasticity compared to other alloys with similar mechanical strength (Ezugwu et al., 2015). This last condition, which provides a wide range of elastic behavior, is closely related to high vibration amplitudes, especially with regard to machining processes characterized by interrupted cutting, such as milling. This is due to the intense variation in chip thickness along the contact between the tool and the part, responsible for a phenomenon called chatter (Ezugwu and Wang, 1995).

This phenomenon induces considerable cycling of cutting forces, which can cause premature wear of the cutting tool due to edge chipping. It is also responsible for significant damage to the integrity of the machined surface, such as the increase in roughness parameters. With regard to nose radius, when it is low there is an increase in the vibration amplitude, and when the radius increases, the tendency is for the vibration to decrease (Subramanian et al., 2013).

There are several ways to improve the damping capacity of a complex system consisting on machine tool, tool, fixtures and workpiece. One of them is the reduction of the tool clearance angle. While small clearance angles can be associated with rapid tool wear, they can also reduce vibration. On the other hand, increasing the tool nose radius can reduce the kinematic roughness of the machined surface, but provide an increase in the passive component of the cutting force.

As stated earlier, the machinability of titanium alloy is extremely low, making it difficult to achieve the expected finish. Due to its low thermal conductivity, and the high wear of the tool in the machining process, the surface integrity ends up being harmed. An important parameter to check is the machining force; theoretically, the greater this force, the higher the temperatures reached, and the greater the damage to surface integrity. With regard to the nose radius, Montassar et al. (2021), said that the nose radius interferes in the form of the progression of the force variation, it can make this progression of force fast or slow, so that the larger the nose radius, the more progressive will be the increase in force. This makes the nose radius an important variable in the machining process for various titanium alloys.

This work is related to the design, analysis and manufacturing of a special cutting tool for titanium milling to use customized carbides processed by grinding with only one variable: the nose radius. Although the selection of these radii was based on the most common values that are found on commercially available tools, it can be said that they are

special tools because the variation of nose radius is usually followed by other features, such as chipbreakers, in commercial products. In this study, nose radius was isolated from other variables in order to provide a better understanding of its effect on machining outputs. For that, the characterization of these special carbides is essential to certify that there are not any sources of variability that could also affect the results. It is expected that this analysis will be useful for identifying the better machining conditions (cutting speed, feed, axial and radial depth of cut) in which the proposed cutting tool may be more successful in terms of tool life and machined surface integrity.

Tool holder was manufactured using hardened H13-type tool steel based on narrow dimensional and geometric tolerances considering an individual seat (for only one carbide insert). A modal analysis of this new design was led on both computer-aided engineering environments and validated by experimental testing using instrumented hammer and accelerometer for the transfer function on frequency domain. But this characterization will be the aim for further publications.

2. MATERIAL AND METHODS

The tools for face milling were prepared from uncoated carbide blanks; therefore, consisting essentially of tungsten carbide and cobalt (WC + Co) that have been ground only on the clearance face, maintaining a 20° clearance angle, considering the unique variable nose radius, performed at three levels: 0.8 mm, 1.2 mm or 1.6 mm. For the preparation of inserts, two of each radius configuration, a four-axis CNC grinding machine, model Agathon DOM Plus, with a maximum power of 16 kW and a maximum speed of 3,400 rpm, was used. Figure 1 shows a photo of the CNC grinding machine used in this research.



Figure 1. Photo of the CNC grinding machine (Pivotto, 2020).

For the grinding process, a cup-type diamond grinding wheel was chosen, with resinoid binder and C100 concentration. The grinding wheel granulometry, as well as the parameters used, were chosen based on the work carried out by Pivotto (2020), with the grain size chosen for the grinding wheel being 15 μm (D15), the grinding speed of the grinding wheel (v_c) is 20 m/s, the axial feed rate (v_{fa}) is 4 mm/min, the insert rotation speed for the nose radius grinding (v_r) is 50°/min and flood application of mineral-based oil. For each insert manufactured, the grinding wheel was dressed using alumina, following a particle size of 220# and constant parameters with a tangential dresser speed (v_{cd}) of 10 m/min and a dresser feed speed (v_{fd}) of 3 $\mu\text{m/s}$, for 5 seconds. A schematic of how the rectification was done, can be seen in Figure 2.

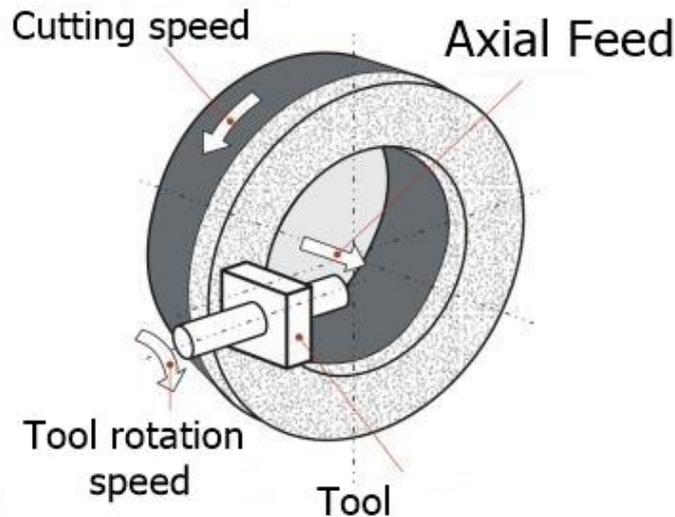


Figure 2. Insert grinding scheme (Cruz, Sordi and Ventura, 2020).

After preparation, the inserts were characterized using a microscope for three-dimensional image analysis called Alicona InfiniteFocus SL, located in the Mechanical and Dimensional Metrology Laboratory, within the Manufacturing Processes Laboratory (LPF) at the Department of Mechanical Engineering of the Federal University of São Carlos (DEMec/UFSCar). This equipment works through a focus variation system, making possible, therefore, to evaluate surface defects, dimensional characteristics and even roughness parameters, which are the object of this work. For this, a 10x magnification objective lens will be used, although 20x and 50x magnification lenses are also available in the same laboratory.

The same characterization was also performed on the blanks; three raw inserts have been chosen for that. For greater measurement reliability, the characterization was conducted on two intact cutting edges of each insert. In each of them, different roughness parameters were evaluated, on the clearance surface (surface in front of the workpiece during machining) and on the rake surface (surface where the chip just removed from the workpiece slips). The details of the position of these two surfaces are shown in Figure 3.

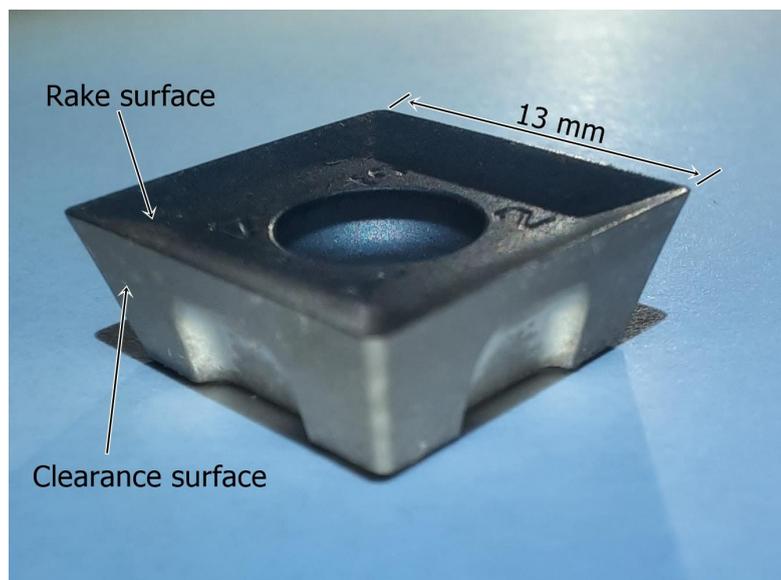


Figure 3. Location of clearance and rake surfaces.

Nose radius is the curvature of the tool nose, which refers to a certain radius. This, in theory, the larger the nose radius, the smaller the surface roughness of the part, however, the machining force is directly proportional to it. When it comes to a smaller radius, there is a tendency for increased vibration during machining. The nose radius is measured in the tool reference plane (Pr) (NBR ISO 3002-1, 2013).

According to Dagnall (1986), Rz consists of an average relative to ten points within the sampling length: the five highest peaks and the five lowest valleys, with the result being the average height of these ten points. In turn, Rsk is described by a numerical value that represents the surface asymmetry, so that positive values mean wide valleys, and negative values mean wide peaks. Rku (kurtosis) provides a measure of surface sharpness, such that a surface with high repeatability for the length of peaks and valleys is described with a high Rku value, and a surface with high variability with a low Rku value; Rku = 3, for example, denotes a normal distribution about the length of peaks and valleys. Tables 4, 5 and 6 present the results of the characterization referring to terms of roughness, in addition to appearing the parameters described above (Rz, Rsk and Rku), other parameters related to surface roughness are also presented. It is worth emphasizing the parameters Ra, Rq, Rt and Rmax, which are mentioned throughout this work. According to the ABNT NBR ISO 1302 standard (2002), Ra, is the arithmetic mean of the absolute values of the ordinates in the sampling length, Rq is the square root of the mean of the values of the ordinates in the sampling length and Rt is described as the sum of the highest profile peak heights and the highest profile valley depths. Rmax or maximum roughness is the highest value of the partial roughness present in the measurement path.

After characterization, all data was tabulated. In the tables regarding the nose radius, overall mean and standard deviation are presented. Regarding the different roughness parameters and also edge irregularity parameter, an analysis of variance (ANOVA) was performed to verify if the parameters are statistically equivalent or not.

3. RESULTS AND DISCUSSION

As already mentioned in the previous topic, carbide inserts were ground with different nose radii; that way, two inserts with a nose radius of 0.8 mm, two inserts with a nose radius of 1.2 mm and two inserts (Reply 1 and 2) with a nose radius of 1.6 mm were obtained, and all of them maintaining a 20° clearance angle. After the grinding process, the four tips of each insert were characterized. Characterization was, first of all, carried out to measure the nose radius; this is important to make sure that the nose radius programmed in the grinding machine was achieved indeed. Tables 1, 2 and 3 show the values achieved for each nose radius. Circumferences 1, 2 and 3, presented on each table, are related to the measurement procedure of the microscope because, obviously, the accuracy of the measurement is not completely error-free. Three measurements were done at each insert tip and then averaged, to get as close as possible to the real values.

Table 1. Nose radius results for tool ground to 0.8 mm.

Parameter	Reply1				Reply 2			
	Tip 1	Tip 2	Tip 3	Tip 4	Tip 1	Tip 2	Tip 3	Tip 4
Circumference 1 (mm)	0.853	0.753	0.856	0.825	0.829	0.853	0.861	0.854
Circumference 2 (mm)	0.900	0.750	0.862	0.795	0.834	0.849	0.842	0.853
Circumference 3 (mm)	0.863	0.740	0.865	0.786	0.832	0.849	0.859	0.844
Average (mm)	0.863	0.750	0.862	0.795	0.832	0.849	0.859	0.853
Overall Average	0.849 mm							
Standard deviation	0.040 mm							

Table 2. Nose radius results for tool ground to 1.2 mm.

Parameter	Reply1				Reply 2			
	Tip 1	Tip 2	Tip 3	Tip 4	Tip 1	Tip 2	Tip 3	Tip 4
Circumference 1 (mm)	1.239	1.272	1.277	1.184	1.256	1.209	1.237	1.152
Circumference 2 (mm)	1.248	1.277	1.280	1.180	1.240	1.207	1.202	1.128
Circumference 3 (mm)	1.258	1.274	1.276	1.196	1.236	1.210	1.232	1.148
Average (mm)	1.248	1.274	1.277	1.184	1.240	1.209	1.232	1.148
Overall Average	1.237 mm							
Standard deviation	0.044 mm							

Table 3. Nose radius results for tool ground to 1.6 mm.

Parameter	Reply1				Reply 2			
	Tip 1	Tip 2	Tip 3	Tip 4	Tip 1	Tip 2	Tip 3	Tip 4
Circumference 1 (mm)	1.549	1.552	1.571	1.510	1.554	1.614	1.571	1.547
Circumference 2 (mm)	1.526	1.505	1.575	1.518	1.574	1.620	1.566	1.533
Circumference 3 (mm)	1.540	1.516	1.562	1.494	1.572	1.623	1.576	1.552
Average (mm)	1.540	1.516	1.571	1.510	1.572	1.620	1.571	1.547
Overall Average	1.553 mm							
Standard deviation	0.034 mm							

It was noticed that the grinding process proved to be efficient, reaching values very close to the nominal nose radius variables that were proposed in the grinding of tools. The error between overall average and nominal nose radius is + 6.1 % for 0.8 mm, + 3.0 % for 1.2 mm and - 2.9 % for 1.6 mm radius. Fig. 4 presents the compilation of these results.

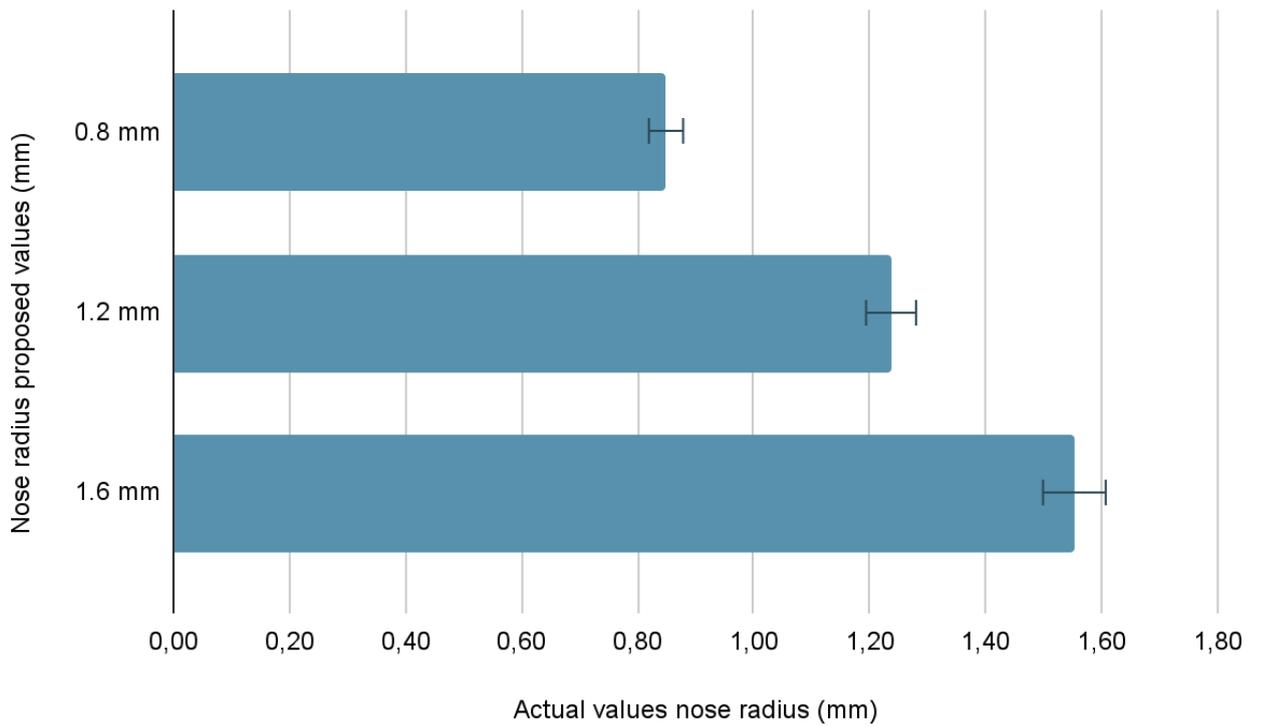


Figure 4. Compilation of results nose radius.

The following tables show the clearance surface roughness data as well as the achieved values for the nose radii variations. Tables 4, 5 and 6 show the roughness values on the clearance surface of tools with a nose radius of 0.8mm 1.2mm and 1.6mm respectively.

Table 4. Clearance surface roughness results for the ground tool with 0.8 mm nose radius.

Parameter	Unity	Reply 1				Reply 2				Average	St dev
		Tip 1	Tip 2	Tip 3	Tip 4	Tip 1	Tip 2	Tip 3	Tip 4		
Ra	μm	1.903	1.872	1.957	3.820	4.208	3.840	3.449	3.394	3.422	0.981
Rq	μm	2.375	2.330	2.482	4.691	5.219	5.268	4.304	4.236	4.270	1.271
Rt	μm	13.233	11.766	12.913	21.615	25.151	28.561	21.108	20.256	20.682	6.140
Rz	μm	9.879	8.510	9.798	14.826	17.719	16.587	15.250	14.391	14.609	3.475
Rmax	μm	12.372	11.184	12.028	19.367	23.460	24.185	20.248	18.961	19.164	5.198
Rsk	-	-0.026	-0.033	0.202	-0.183	-0.024	1.580	0.110	-0.024	-0.024	0.569
Rku	-	3.004	2.825	3.041	2.678	2.760	5.160	2.864	2.792	2.845	0.825

Table 5. Clearance surface roughness results for the ground tool with 1.2 mm nose radius.

Parameter	Unity	Reply 1				Reply 2				Average	St dev
		Tip 1	Tip 2	Tip 3	Tip 4	Tip 1	Tip 2	Tip 3	Tip 4		
Ra	μm	2.088	2.055	2.100	2.240	2.074	1.819	2.146	1.999	2.081	0.122
Rq	μm	2.675	2.680	2.652	2.821	2.564	2.274	2.678	2.492	2.664	0.164
Rt	μm	14.959	16.648	15.027	14.995	13.235	12.241	13.663	12.528	14.311	1.499
Rz	μm	10.744	10.550	10.829	11.342	10.566	9.365	10.628	8.916	10.597	0.807
Rmax	μm	14.599	15.393	14.045	13.987	12.356	11.274	12.682	12.169	13.335	1.402
Rsk	-	0.048	0.432	0.056	0.030	-0.037	0.206	0.123	0.244	0.090	0.151
Rku	-	3.434	4.259	3.104	2.993	2.781	2.906	2.764	2.874	2.950	0.501

Table 6. Clearance surface roughness results for the ground tool with 1.6 mm nose radius.

Parameter	Unity	Reply 1				Reply 2				Average	St dev
		Tip 1	Tip 2	Tip 3	Tip 4	Tip 1	Tip 2	Tip 3	Tip 4		
Ra	μm	2.730	2.105	1.969	2.153	2.131	1.790	2.035	2.025	2.070	0.273
Rq	μm	4.269	2.641	2.461	2.678	2.670	2.277	2.552	2.526	2.597	0.624
Rt	μm	26.809	13.865	12.759	13.389	14.190	13.162	13.636	12.793	13.513	4.767
Rz	μm	12.873	10.288	9.493	10.573	10.442	9.046	10.081	9.646	10.185	1.160
Rmax	μm	24.370	13.617	11.964	12.817	13.417	12.929	13.190	12.188	13.060	4.104
Rsk	-	-2.511	0.005	0.044	-0.036	-0.042	-0.081	-0.095	0.025	-0.039	0.880
Rku	-	10.045	2.974	2.903	2.757	2.891	3.312	2.948	2.803	2.926	2.517

It was noticed that, in Table 4, reply 2 regarding a 0.8 mm nose radius, values for R_a as well as the values for the other parameters regarding peak highness and valley deepness, were somehow far from expected. Considering the ABNT NBR ISO 1302 standard (2002), the clearance surface of every insert meets the requirements for a N8 surface grade ($R_a < 3.2 \mu\text{m}$), unless reply 2 for 0.8 mm nose radius. Regarding the width of the peaks and valleys, the values for R_{sk} and R_{ku} showed no great variability, reaching the conclusion that for these values, the ground tools are very similar to each other.

Anyway, due to the discrepancy in the result of reply 2 in Table 4, the analysis of variance was performed only with the values of reply 1. For that, p-value regarding each roughness parameter presented in the lines of Tables 4, 5 and 6 was calculated. All p-values were higher than 0.05, which means grinding different nose radii present no significant effect over those roughness parameters, as follows: R_a p-value 0.815, R_q p-value 0.853, R_t p-value 0.855, R_z p-value 0.996, R_{max} p-value 0.792, R_{sk} p-value 0.345 and R_{ku} p-value 0.497. Fig. 5 presents the compilation of results regarding R_a , R_q , R_t , R_z and R_{max} while Fig. 6 results for R_{sk} and R_{ku} regarding clearance surface roughness.

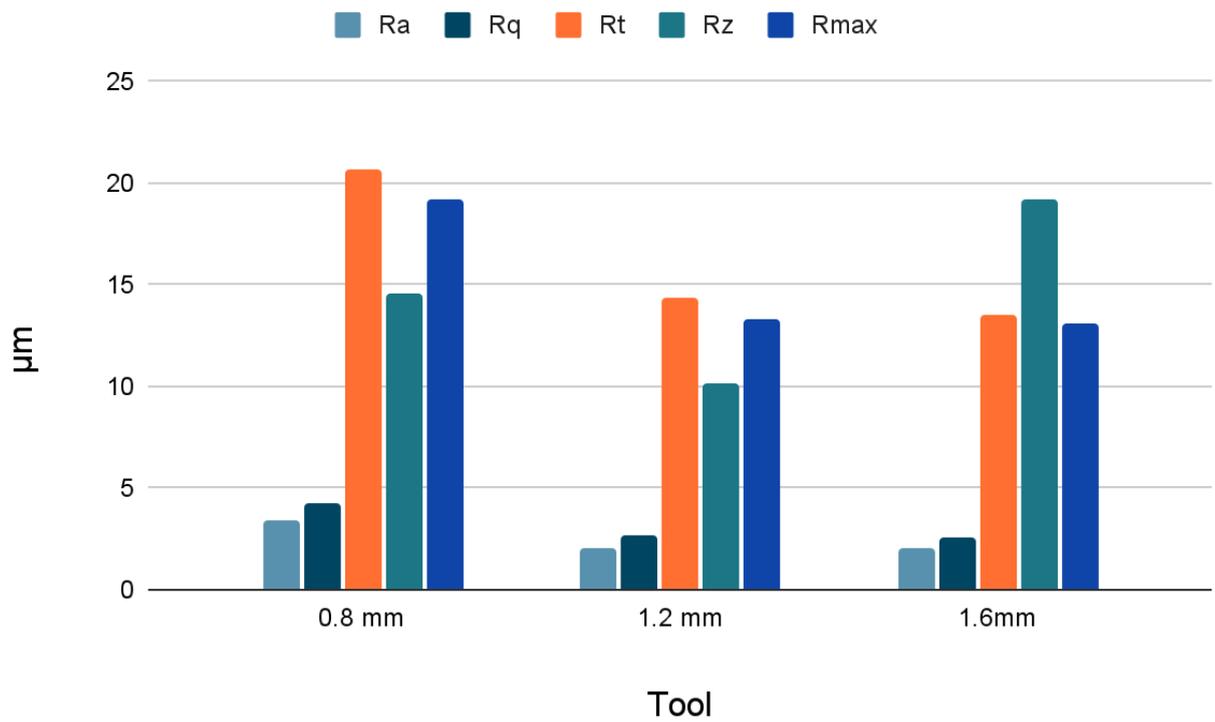


Figure 5. Compilation of results regarding Ra, Rq, Rt , Rz and Rmax.

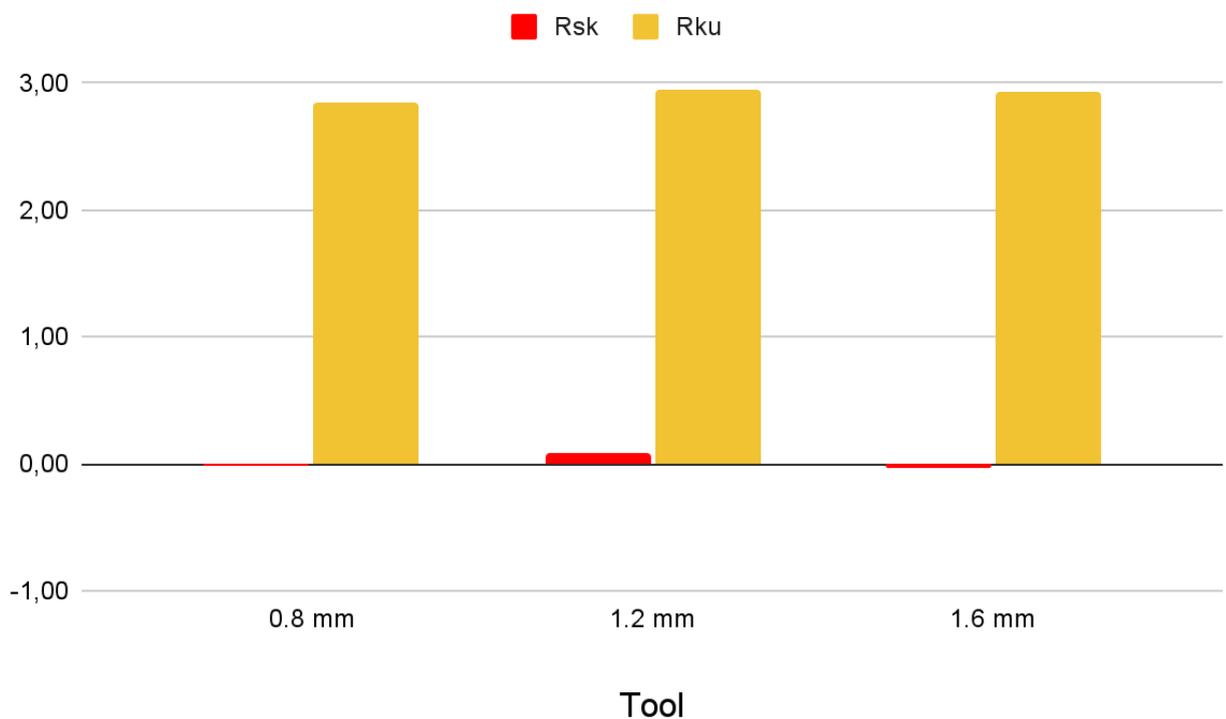


Figure 6. Compilation of results regarding Rsk and Rku.

4. CONCLUSIONS

This work shows that it is quite possible to grind insert carbides with different nose radius with a good repeatability between 0.8 mm and 1.6 mm. Error between the actual nose radius and nominal nose radius was always kept under 10%.

Regarding the various surface roughness parameters, no considerable difference was obtained between the different carbide inserts, as shown in the ANOVA approach.

Anyway, it was observed that there may be some difficulty for grinding smaller nose radii. First because the error between measured and nominal dimension was maximized when the lower radius applied in this work was manufactured. Second because reply 2 for this condition provided higher roughness parameters than the other conditions; so that it was excluded for the statistical analysis. For better understanding of this hypothesis, further tests will be necessary.

5. ACKNOWLEDGEMENTS

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