THE EFFECT OF CUTTING TOOL SURFACE FINISH ON SURFACE TEXTURE AND INTEGRITY IN MILLING OF 6351 T6 ALUMINUM ALLOY

Eliene Oliveira Lucas, eliene.lucas@ufv.br
Rafael Borges Mundim, rafael.mundim@ufv.br
Universidade Federal de Viçosa
Departamento de Engenharia de Produção e Mecânica, Campus Universitário S/N, Viçosa, MG, Brazil.

Abstract. *The texture and integrity of a surface are considerably influenced by certain cutting tool properties. These properties include geometry, shape, material, and even the surface finish of the tool itself. The improvement of the tool's surface finish by polishing methods results in improved wear strength. This study's objective is to test the effect of integral carbide end mills on texture surface, based on tools with different surface finish. Two solid carbide end mills differing only with respect to surface finish were used. Face milling finish trials were carried out in a Romi® Discovery CNC milling machine. The material being milled was 6351 T6 aluminum alloy. The results were based on tool wear data and the corresponding acquired vertical roughness parameters (Ra, Rq, Rz, and Rt).*

Keywords*: finish-milling, surface roughness, subsurface integrity, post-coat treatment*

1. INTRODUCTION

Milling is usually adopted for generating plane surfaces, outlines, keyways, grooves, and slots in a cutting process that occurs intermittently by rotating a cutting tool. Endmilling is a continuous, circumferential, and frontal process that uses an endmill as the cutting tool and presents advantages when generating surfaces of different shapes. Endmilling tools have cutting edges on the face and periphery, varying according to application. These tools can be found as replaceable inserts or integral tools, made entirely of the same material (Polli, 2005).

Surface roughness generation in a machining process is generally due to certain phenomena that occur on the tool's edge during cutting. These phenomena are also directly related to the behavior of the machined material during cutting.

The great majority of non-hardenable aluminum alloys and some hardenable alloys have a greater tendency to form built-up-edges. It is possible to observe the built-up-edge phenomenon at cutting speeds of up to 300 m/min. Built-up-edge formation is due to adhesion of material particles that along with the heat generated during cutting form a transient cutting edge that damages the newly generated surface (Black, 2005).

Given a set of pre-defined cutting parameters, built-up-edge formation can be minimized by the use of cutting fluids and tools with superior surface finish. The search for improvements of endmills for machining aluminum alloys results in technological advances such as:

- Increase of the tool's helix angle from 30 º to 45 º, resulting in a larger and positive relief angle.
- Adoption of sharper edges with smooth surfaces and no grinding marks. In this case, the tool's surface finish is done by grinding and lapping the surface.
- Post coat treatment of specific regions of the cutting tool. Polishing the primary and secondary flanks along with the tool's face reduces adhesion thus improving chip flow over the tool's surface.

Tool wear when machining aluminum alloys occurs generally by corner deformation and loss of edge sharpness. Along with the decrease of the tool's cutting capability, an increase in cutting force and friction can also be observed. As friction increases so does temperature, and deformation due to heat is more evident between the workpiece and the tool's flank, damaging the recently formed surface (Klocke and König, 2008).

Milling of aluminum alloys using endmills of fewer teeth is due to the larger required room for lodging chips, which becomes relevant when there is a high material removal rate and high speeds are adopted. On the contrary, endmills with more teeth improve the simultaneous action of the cutting edges in a way that mechanical and thermal stresses are more uniformly distributed among all teeth, reducing the variability of machining forces and improving surface finish.

Geometrical deviations (roughness and undulation) have been adopted as general criteria for controlling and qualifying surfaces. Some vertical roughness parameters, such as the absolute arithmetic average roughness parameter (Ra), are very significant and widely accepted. However, it should be noted as a general rule that a single two-dimensional roughness parameter is not sufficient to characterize the complexity of a surface's topography (Davim, 2010; Bet, 1999).

Since polished surfaces and unpolished surfaces differ only in degree, this article's goal is to evaluate the effect of the quality of two endmills' surface finish on surface roughness of a milled 6351 T6 alloy workpiece. The influence of the endmill surface finish on the generated surface finish was evaluated based on vertical roughness parameters.

2. MATERIALS AND METHODS

The experimental work comprised finish milling 6351 T6 aluminum with two kinds of cylindrical endmills of varying surface finish and helix angle. The experiments were conducted in order to evaluate the effect of the tools' surface finish on roughness while also varying tooth feed rate (f_z) and depth of cut (a_p).

A portable roughness measuring device (Mitutoyo® SJ–201P) connected to a computer with proprietary data acquisition software was used to capture and treat the profile data, as shown in Fig. 1. A cutoff length of 0.25 mm was adopted along with a Gaussian filter in all measurements. The roughness parameters adopted were chosen based on their capacity to indicate surface properties such as friction, wear, and lubrication capacity.

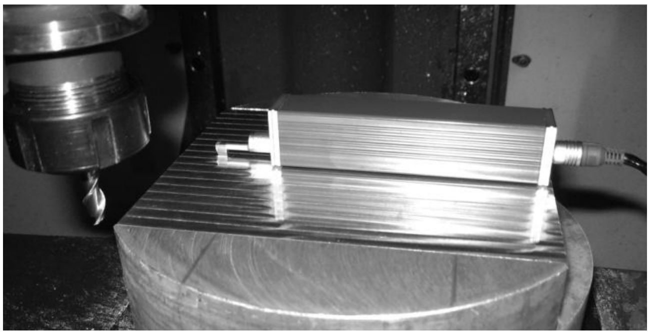


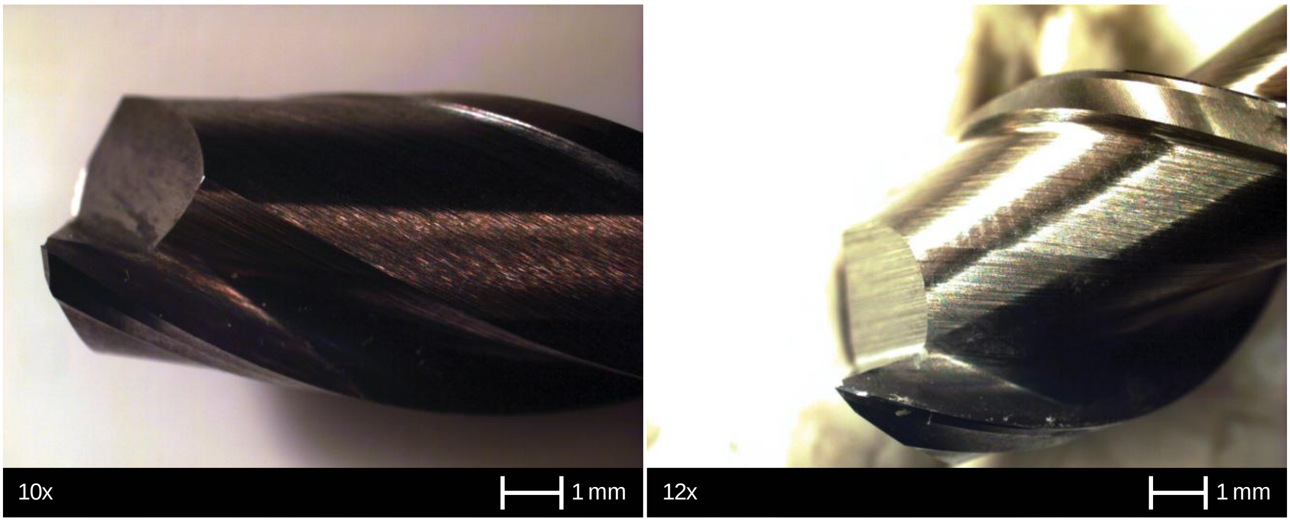
Figure 1. Roughness measuring device during surface data acquisition.

Evaluation of the tool's surface finish effect was done based on the following vertical roughness parameters: the absolute arithmetic average roughness (Ra), the root-mean-square roughness (Rq), the maximum height of the profile (Rt), and the mean average of the maximum distance from peak to valley (Rz). These parameters (Ra, Rq, Rz, and Rt) were measured over the feed direction. The roughness measurements were executed using a stylus measuring instrument (portable roughness measuring device) for different combinations of feed rate (f_z) and axial depth of cut (a_p).

The workpiece material adopted was 6351 T6 aluminum alloy, which has an ultimate tensile strength of 310 MPa and a yield strength of 282 MPa. The material's hardness was measured at 95HB. The workpiece was previously milled on two opposing sides in order to facilitate the beginning and end of the cutting process. The workpiece was rigidly clamped in order to avoid dynamic instabilities.

Trials were carried out in a Romi® machining center (Discovery 760) provided with a Siemens® control unit. Spindle velocities in this machine range from 10 RPM to 10000 RPM at a 9 kW available motor power.

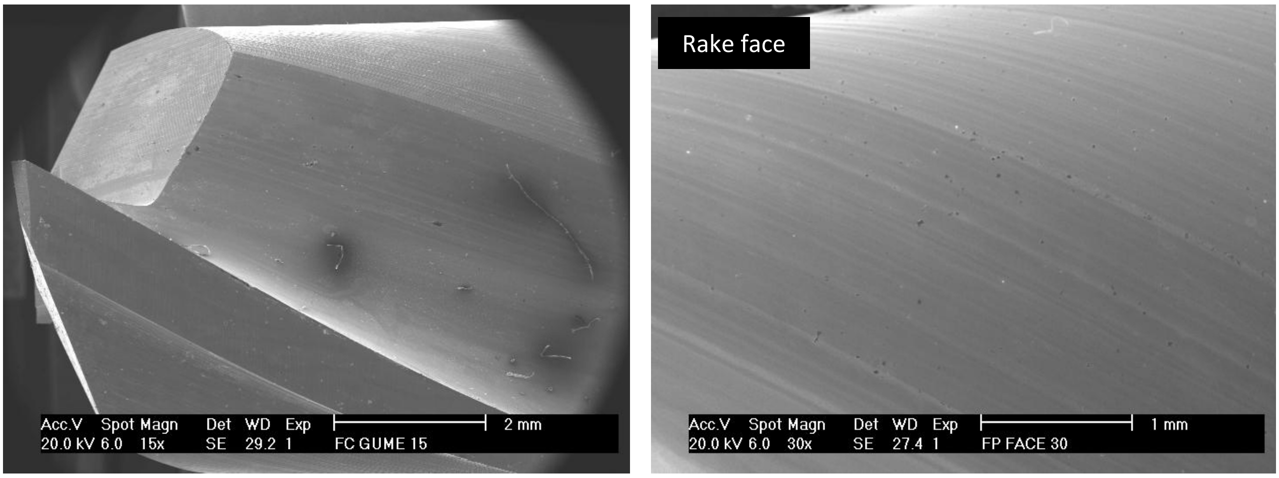
The cutting tools adopted were square shoulder endmills that differed by helix angle and surface finish quality, as shown in Fig. 2.



(A) (B)

Figure 2. Integral carbide square shoulder endmills adopted in the experiments. Non-polished (A) and polished (B).

Figure 3 shows microscopic images of the polished endmill adopted in the experiments, obtained with scanning electron microscopy (SEM).



(A) (B)

Figure 3. Scanning electron microscope (SEM) images of post finished surface of polished endmill at different amplifications. Flank and edge (left) and rake face region (right).

Geometrical data of both tools can be found in Tab. 1. The terminology adopted to describe the two tools hereafter will be intuitively "polished" and "non-polished".

Table 1. Geometry of cutting tools adopted in the experiments.

Surface Treatment	Diameter (mm)	Helix angle (°)	Flutes	Active cutting edge length [1] (mm)	Total length (mm)
Polished	8	45	2	20	63
Non-polished	8	30	2	20	63

[1] Overhang length: 35 mm.

Trials were done for different combinations of feed per tooth rate (f_z) and axial cutting depth (a_p). Radial cutting depth (a_e) and cutting speed (v_c) were kept constant. Cutting conditions adopted can be found in Tab. 2.

Table 2. Cutting conditions adopted in the experiments.

Trial	Feed/Tooth (f_z) (mm/tooth)	Cutting Speed v_c (m/min)	Spindle Speed (N) (RPM)	Depth of cut (a_p) (mm)	Width of cut (a_e) (mm)	Total Cutting Length (L) (mm)	Table Speed (v_f) (mm/min)
1	0.031	180	7162	0.5	7	2916	473
2	0.031	180	7162	1.0	7	2916	473
3	0.056	180	7162	0.5	7	2916	802
4	0.056	180	7162	1.0	7	2916	802
5	0.09	180	7162	0.5	7	2916	802

Milling trials were done randomly, resulting in surfaces with a sequence of 162 mm long channels, amounting to a total cut length of 2916 mm for each evaluated combination of cutting parameters. Twelve regions were defined for sampling roughness of the generated surfaces as shown in Fig. 4, and three roughness measurements were done for each region along the feed direction.

As previously stated, only two endmills were adopted (polished and non-polished) for each of the evaluated cutting conditions. Tool wear conditions were evaluated after each trial using a stereo microscope (Olympus® SZ61).

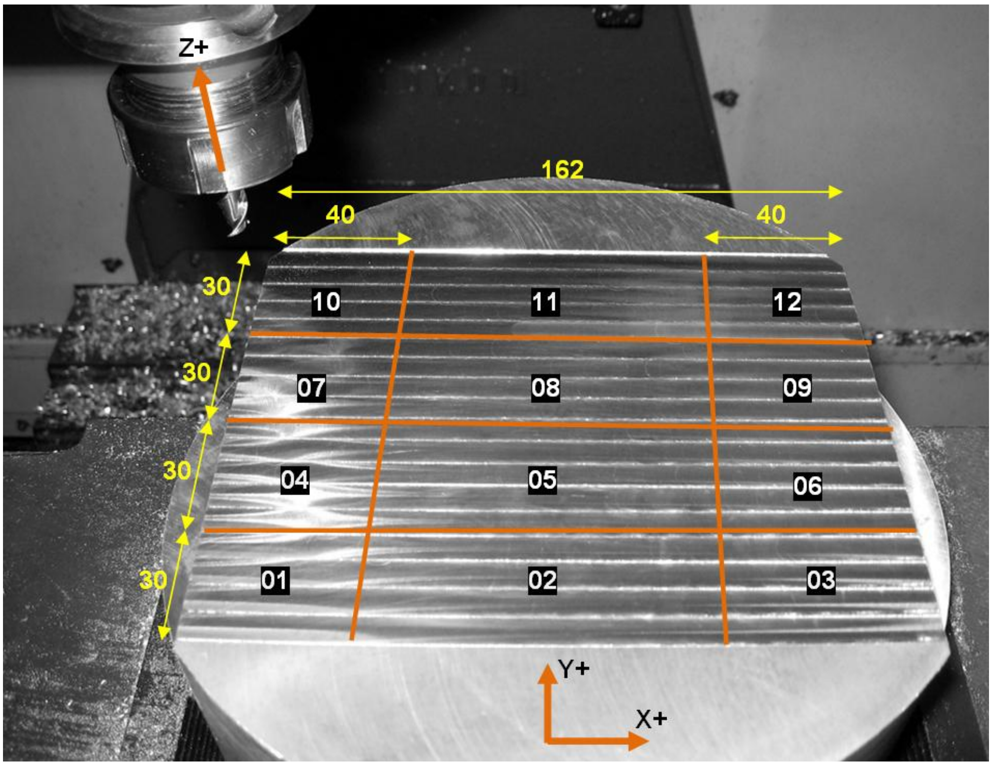


Figure 4. Limits of surface profile data acquisition regions.

3. RESULTS AND DISCUSSION

Figure 5 shows surface roughness data plotted against different feed per tooth rates (f_z) for the polished and non-polished endmills for a cutting depth of a_p=0.5 mm.

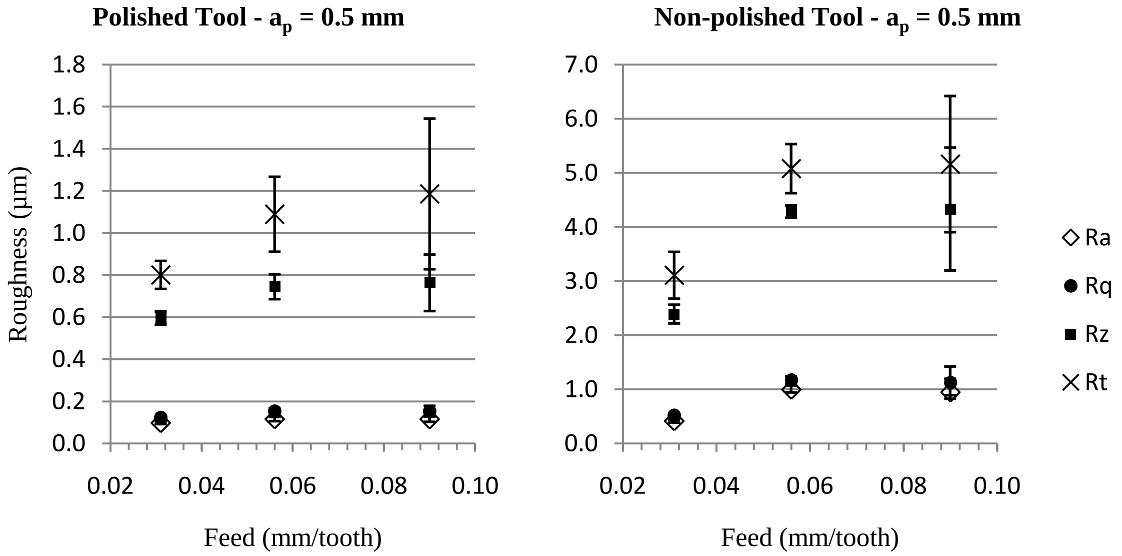


Figure 5. Roughness values for polished and non-polished tools for a cutting depth of a_p = 0.5 mm and three different feed rates. Error bars are based on the standard error of 12 samples for a confidence interval of 95%.

For the polished tool (Fig. 2), with an increase in feed from f_z=0.031 mm/tooth to f_z=0.056 mm/tooth, it was observed a slight increase of the average parameters (Ra, Rq) and a substantial increase of the extreme parameters (Rz, Rt). At the next feed increment, from f_z=0.056 mm/tooth to f_z=0.09 mm/tooth, no significant variation of the studied parameters was observed. Aside, it can be noticed from Fig. 5 that the statistical dispersion increased significantly for this second feed increase.

The calculated extreme parameters Rt and Rz also showed significantly smaller values for the polished tool, as compared to the non-polished one.

As can be noticed from Fig. 5, Rz and Rt roughness parameters values obtained for a feed of f_z=0.056 mm/tooth and a cutting depth of 0.5 mm for the polished tool were Rz = 0.75 ± 0.06 µm and Rt = 1.09 ± 0.18 µm.

Average roughness parameters Ra and Rq were also lower for the polished tool. However, since there is a geometrical difference between both tools in regard to their helix angle, the lower roughness values cannot be attributed to the tool's post coat polishing treatment. Despite this geometrical difference, the characteristic surfaces generated for the same cutting conditions could be clearly distinguished, as can be seen in Fig. 6. The surface generated by the polished tool was significantly smoother and more regular than the one generated by the non-polished tool.

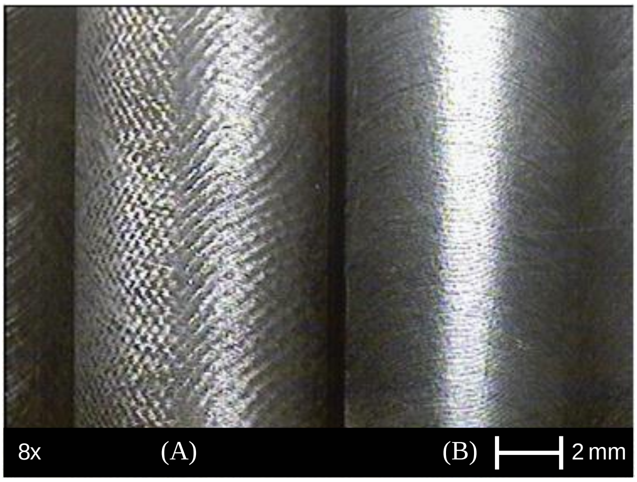


Figure 6. Characteristic surfaces obtained with non-polished (A) and polished (B) integral carbide endmills. Cutting conditions: f_z = 0.031 mm/tooth; a_p = 0.5mm and v_c = 180 m/min.

Extreme parameters Rt and Rz had lower values for the polished tool as compared to the non-polished one for a cutting depth of a_p=1 mm. When feed rate was increased, Rt and Rz values increased expressively for the non-polished tool, whereas average values Ra and Rq did not change significantly. Part of this increase in roughness can be attributed to the slight tool wear observed. This increase is shown in Fig. 7.

A slight decrease in all roughness parameters was observed for the polished tool at a cutting depth of a_p=1 mm when feed rate was increased. This increase in roughness for the lower feed rate can be attributed to the reduction of the critical chip thickness, which generates unstable chip flow and allows the machined material to adhere more easily to the tool's edge, causing an increase in surface roughness.

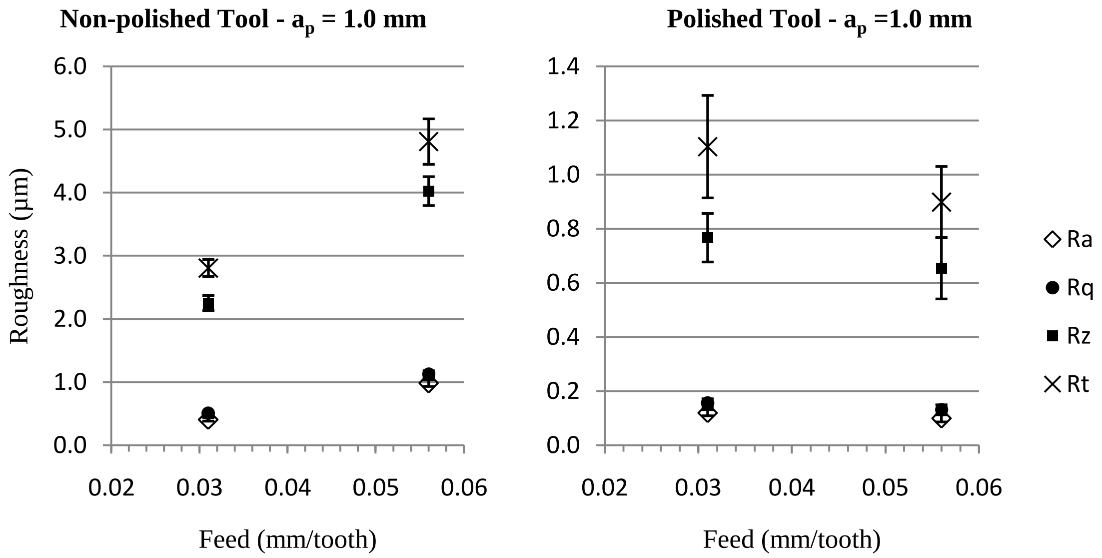


Figure 7. Roughness values for polished and non-polished tools for a cutting depth of a_p = 1.0 mm and two different feed rates. Error bars are based on the standard error of 12 samples for a confidence interval of 95%.

Figure 8 shows the wear condition of the polished endmill after tests 1, 2, 3, and 5, as per Tab. 2. The presence of chip metal particles adhered to the flank and face regions in tests 2 and 5 can be observed. Clear adhesion signs were not observed for the other testing conditions. The absence of adhesions when observing the tool is not an indicator that adhesion did not occur since this phenomenon is knowingly unstable and the adhered particles can easily break away when cleaning and handling the tools after testing.

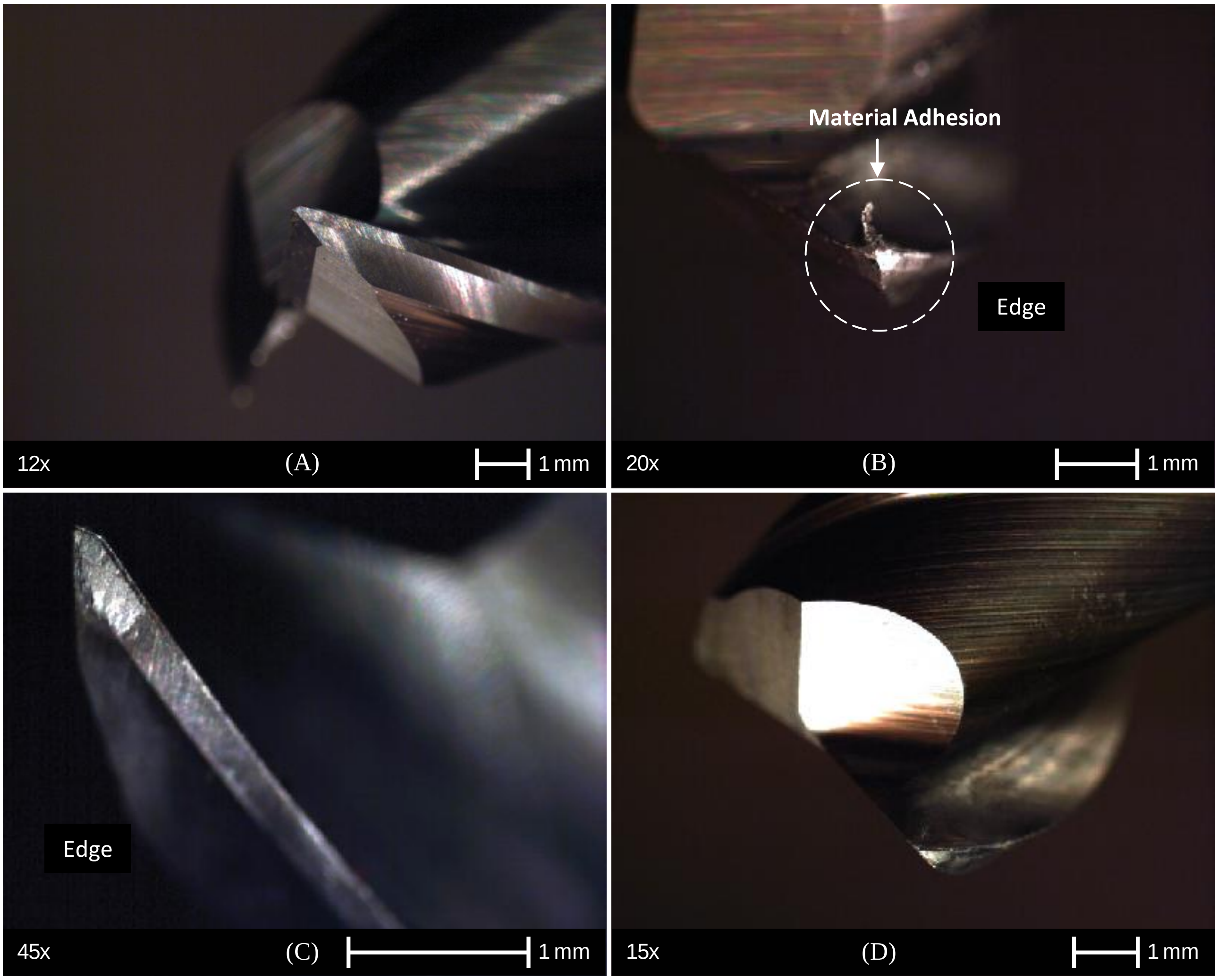


Figure 8. Tool wear conditions of polished endmill after testing. First trial (A), edge on second trial (B), edge on third trial (C), and fifth trial (D).

Figure 9 shows images of different regions of the non-polished endmill after trials 2, 3, 4, and 5, as per Tab. 2. Grooves due to tool wear were observed on the flank and face after the second test. For the lowest feed rate adopted (f_z= 0.03 mm/tooth) and considering that during the first test the contact pair suffered tribological accomodation, it can be suspected that the tool's polishing degree influences surface roughness.

At low cutting speeds (low temperatures) and low feed rates built-up-edge (BUE) formation is likely to occur. Its formation occurs due to the cyclic process of material deposition and successive cold work suffered by the cut material. Other conditions, however, contribute for BUE to occur. Chemical affinity between the contact pair along with contact time and pressure can be crucial factors for BUE formation. The formation of adhesions is a phenomenon that occurs for a wide range of cutting conditions. The transition between these two deformation modes, where BUE formation becomes less dominant than adhesion formation is not clearly defined. However, when maching certain materials this transition is noticeable for certain combinations of cutting conditions (Trent and Wright, 2000). When turning 2024 aluminum alloy (copper-aluminum), List *et al*. (2005) observed this transition for cutting speeds above 120 m/min.

Tool wear when machining aluminum alloys occurs generally due to BUE formation and due to the presence of adhesions at the tool-chip interface which consequently affects the quality of the machined surface. As previously mentioned, adhesion signs were observed during testing (Fig. 8), being easily removed by scrapping the tool. According to List *et al*. (2005), the efficiency of polished tools is more evident for low cutting speeds, where BUE formation is dominant. The importance and the occurrence of the wear mechanism happen according to the cutting speed adopted (temperature) where tool wear can also occur more significantly as a function of diffusion and oxidation.

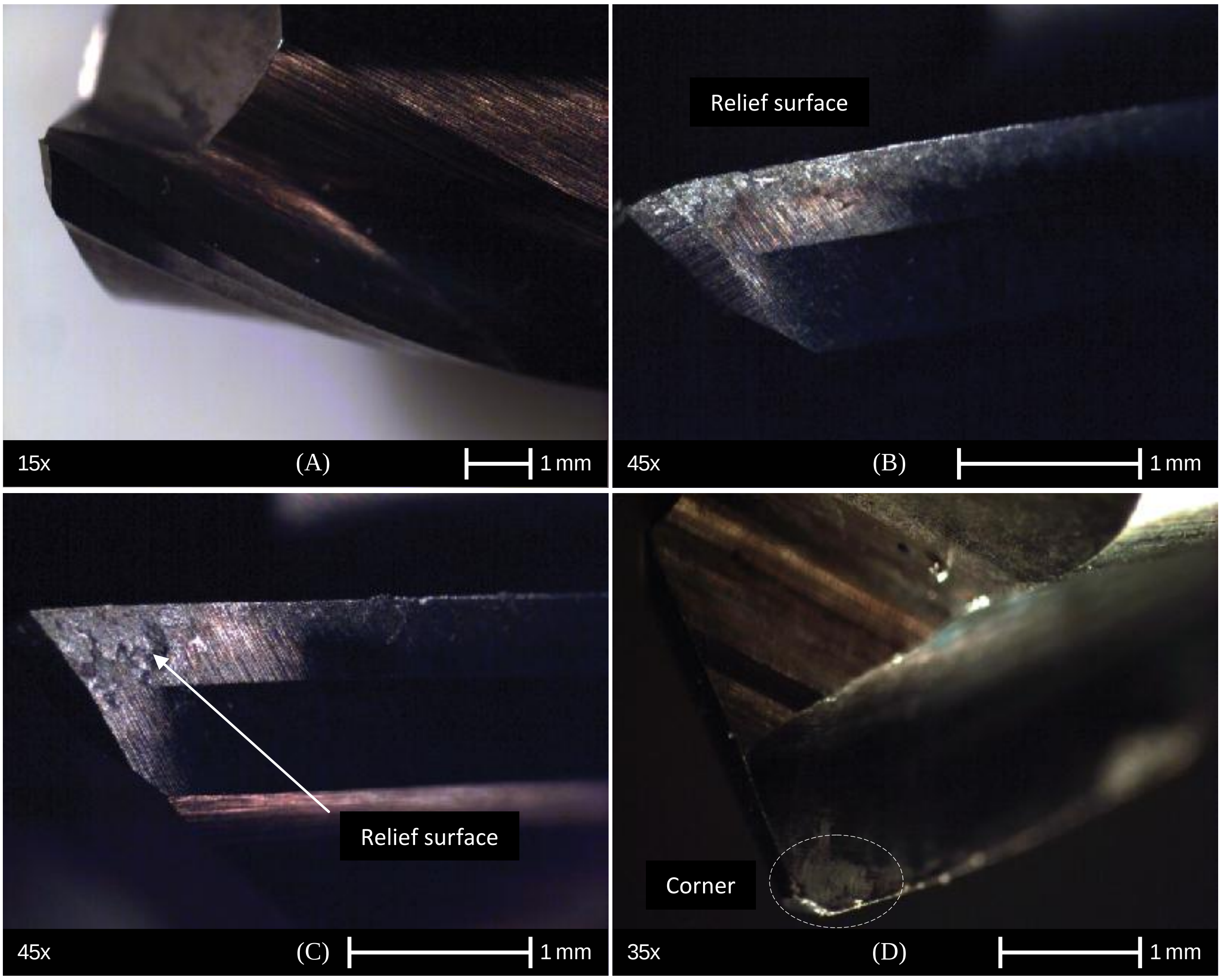


Figure 9. Tool wear conditions of non-polished endmill after testing. After the second trial (A), third trial (B), fourth trial (C), and fifth trial (D). All figures show one of the tool's edges.

With increased cutting speeds there is a tendency to occur diffusion of alloy elements to the tool through the presence of cobalt (binder) in tungsten carbide tools. According to List *et al.* (2005), at high cutting speeds, the presence of adhesions increase the efficiency of chip flow while also acting as a barrier to material diffusion.

It should be noted however that the dominant wear conditions acting on the tool-chip interface are difficult to be experimentally evaluated through traditional methods. In order for a stable film made up of the machined material to act as a barrier to diffusive wear, considerations about the alloys, plasticity and tool material must take place since the increase in cutting speed and consequently temperature and contact pressure can inhibit the formation of this supposed film.

Wear occurs when material is removed from the tool through the flow of material over its surface, causing loss of the original geometry. This loss of geometry can also contribute to deterioration of the recently formed surface`s finish quality. It was verified during testing the presence of small, localized wear grooves on the flank of the non-polished tool (Figure 9). The observed tool wear is likely caused by the abrasive effect of particles over the tools surface when cutting at the speed of 180 m/min.

4. CONCLUSIONS

The surface finish quality of the tested integral carbide endmills tested in the experiments has an influence on the roughness of milled 6351 T6 alloy's surface for the cutting conditions adopted.

For a cutting depth of a_p=0.5 mm the effect of increasing the feed rate on roughness is evident for both of the tested tools. However, the lowest roughness values were obtained for the polished tool. When cutting depth was doubled, the increase in feed rate resulted in lower roughness values for the surfaces generated by the polished tool.

Extreme vertical parameters Rz and Rt were more representative when studying the influence of tool surface finish on roughness.

When machining aluminum alloys, the presence of adhesions influences the behavior of tool wear and consequently the machined surface's roughness.

In order to express with more certainty the prepositions about the presence of adhesion of aluminum particles at the tool-chip interface and its influence on tool wear and surface roughness, complementary testing methods are necessary, such as quick-stop and tool life tests.

5. ACKNOWLEDGEMENTS

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