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AN INVESTIGATION OF THE EFFECTS OF LASER TEXTURING PARAMETERS ON TEXTURED CERAMIC TOOLS APPLIED IN HARD TURNING

Larissa Juliana Sirtuli
Leonardo Faust Antonio
Claudio Abilio da Silveira
Precision Engineering Laboratory, Federal University of Santa Catarina, Eng. Agronômico Andrei Cristian Ferreira St, Trindade, 88040-900, Florianópolis - SC, Brazil
sirtuli.larissa@gmail.com
leonardo.faust.a@gmail.com
claudio.silveira@posgrad.ufsc.br

Denis Boing
AB Sandvik Coromant R&D, Lerkrogsvägen 19, SE-126 80, Stockholm, Sweden
denis.boing@gmail.com

Rolf Bertrand Schroeter
Precision Engineering Laboratory, Federal University of Santa Catarina, Eng. Agronômico Andrei Cristian Ferreira St, Trindade, 88040-900, Florianópolis - SC, Brazil
rolf.schroeter@ufsc.br

Abstract. *Textured tools have the potential to reduce friction and temperature in the cutting zone, promoting lower machining force, tool wear and surface roughness. Nevertheless, the use of textured ceramic tools remains a challenge, mainly due to the difficulties related to the texturing process of these materials that can cause the embrittlement of the tool cutting edge. Therefore, the selection of suitable laser texturing parameters is essential to obtain textured tools with good properties to withstand the tribological conditions in the machining process. In this scenario, this research investigated the impact of laser texturing parameters on the performance of textured ceramic tools in turning. Textured tools manufactured with different laser parameters were evaluated in turning of the hardened steel AISI 4340 (55 HRC) by studying the tool wear. The texture on the mixed-ceramic tools were fabricated with a nanosecond pulsed ytterbium fiber laser. It was found that the laser texturing process has a great influence on the performance of the tools, since the laser parameters cause different levels of thermal damage to the ceramic material. There is a heat input limit from which the modifications caused in the ceramic material make turning unfeasible. Textured tools produced with a pulse duration of 8 ns and laser power of 30 W presented premature failure while tools manufactured with 2 ns and 50 W showed stable behavior during turning. Moreover, the number of laser scans also impacted the tool performance. At 2 ns and 50 W, the highest number of scans (1000 scans) promoted higher changes in the ceramic material, causing higher tool wear in turning. On the other hand, the smallest number of scans (11 scans) created minimal superficial textures, which were easily removed by abrasion wear. The best tool performance in turning was found for the textured ceramic tools manufactured with 2 ns, 50 W and 333 scans.*

Keywords: *textured tool; ceramic tool; laser surface texturing; nanosecond pulsed laser; hard turning*

1. INTRODUCTION

Inspirations in textures of animals and plants that perform specific functions such as anti-adhesion, anti-wear, anti-friction, and anti-vibration have led to the use of textured surfaces in many fields, from the pharmaceutical industry to the automotive and aerospace industries. Surface texturing is commonly used to improve load-carrying capacity and lubrication, as well as to reduction of wear (Bruzzone *et al.*, 2008; Pettersson and Jacobson, 2003; Hutchings and Shipway, 2017; Evans and Bryan, 1999). Therefore, surface texturing of cutting tools has been widely studied to improve the tribological properties in the cutting zone (Ranjan and Hiremath, 2019; Gajrani and Sankar, 2017; Sharma and Pandey, 2016; Machado *et al*, 2021)

Textured tools have potential to decrease friction and temperature in the cutting zone, generating lower cutting forces, tool wear and machined surface roughness. The basic mechanisms that cause better tribological properties when used textured tools are debris entrapment and reduction of the effective contact length between chip and tool. The textures can range from nanometers to micrometers and the textures patterns more investigated are the dimples and grooves. Textures are created on both flank surface and rake surface of the cutting tool. However, textures on the rake face are more used since the advantages of texturing mainly occur in the region of chip flows (Sharma and Pandey, 2016; Ranjan and Hiremath, 2019; Machado *et al.*, 2021; Ribeiro *et al.*, 2020; Gajrani and Sankar, 2017). According to Fatima and Mativenga (2013), the optimal rake face texture decreases the length of the sticking zone and reduces the material adhesion on the tool.

The quality of the textures depends on the surface texturing process. Several techniques have been used for texturing cutting tools, such as thermal energy-based micromachining, mechanical micromachining, electrochemical micromachining, etc. (Ranjan and Hiremath, 2019; Sharma and Pandey, 2016). Among these techniques, the laser surface texturing (LST) stands out due to advantages such as better surface topography and lesser contamination of the surface in comparison to other methods (Ranjan and Hiremath, 2019; Gajrani and Sankar, 2017). Furthermore, LST is suitable for micromachining of hard and brittle materials (such as ceramics) that are difficult to process with mechanical micromachining (Samant and Dahotre, 2009). Since the laser is basically a thermal process, the efficiency of machining depends on the thermal and optical properties of the material. Likewise, laser is a non-contact process, so energy transfer from the laser to the ceramic via irradiation eliminates cutting forces, tool wear, and machine vibration. However, the laser process has some drawbacks such as heat affected zone (HAZ) and surface defects, which are directly influenced by processing parameters, such as pulse duration (Xing *et al.*, 2018).

A study about the effects of laser material removal on cutting tool materials performed by Breidenstein *et al.* (2018) indicates that mixed-ceramic tools can be processed with nanosecond lasers to create chip breakers or other complicated geometries since, within a wide range of laser parameters, no damage of the tool integrity is observed. Nonetheless, at a certain threshold of heat input, the tool wear behavior changes drastically, leading to a rapid failure due to cutting-edge chipping. In general, nanosecond lasers have a wide application due to the lower costs compared to femtosecond and picosecond lasers, as well as a higher machining precision compared to millisecond lasers (Xing *et al.*, 2018).

Machado *et al.* (2021) highlight that the use of textured tools of ceramic, PcBN, and PCD materials is a challenge due to the still scarce literature covering the surface texturing methods for these materials. The main reason for this is the possibility of embrittlement of the tool close to the cutting edges resulting from the texturing process. Therefore, the selection of suitable laser texturing parameters is essential to obtain textured tools with good properties to withstand the tribological conditions in the machining process. Thus, this research investigated the impact of laser-texturing parameters on the performance of textured ceramic tools used in turning of the AISI 4340 hardened steel (55 HRC).

2. EXPERIMENTAL PROCEDURES

Mixed-ceramic cutting tools (70% Al_2O_3 + 29% TiC + 1% others) manufactured by Sandvik Coromant, grade 650, code SNGA 120408T01020, were textured using a nanosecond pulsed ytterbium fiber laser manufactured by IPG, model YLPN-1-1x120-50-M. The laser has a wavelength of 1064 nm, maximum average power of 50 W, and beam quality (M^2) of 1.8. The focus and scan of the laser beam were performed with two mirrors galvanometric scanner with f-θ lens (f = 170 mm), Aerotech AGV-14HPO. The angle of incidence of the laser beam was 90° with the surface of the tools.

The textures (crossed grooves) were created on the rake face and chamfer of the cutting tools. The crossed grooves were selected due to the substantial reduction of the effective contact length between chip and tool.

Firstly, were evaluated textured tools manufactured with two combinations of pulse duration and laser power: i) 2 ns + 50 W and ii) 8 ns + 30 W. The other laser parameters were pulse frequency = 120 kHz, laser pulse overlap = 95%, and number of scans = 333, which were selected based on the results obtained by Sirtuli *et al.* (2021) for the same ceramic material and laser configuration. In the second step of experiments, were evaluated textured tools manufactured with 2 ns + 50 W and a different number of scans (11, 333, and 1000).

The turning experiments were carried out in a horizontal turning center (Heyligendstaedt, model Heynumat 10U), with a spindle motor power of 75 kW, speed rotation maximum of 4500 rpm, and clamping system with three-jaw chuck with a maximum chucking pressure of 45 bar. The cutting tools were assembled on a DSBNR-2020K-12 tool holder and clamped with a center pin and top clamp combination. The workpieces (disk-shaped with a central hole) were manufactured in AISI 4340 steel (55 HRC) with a martensitic microstructure and a low level of bainite and austenite. The cutting parameters applied were cutting speed (v_c) = 150 m/min, feed (f) = 0.08 mm/rev, depth of cut (a_p) = 0.20 mm, and dry cutting. Each experiment consisted of four radial turning passes on the workpiece surface from the largest to the smallest diameter (machining time = 3.6 min), applying a variation in the spindle rotation to maintain a constant cutting speed.

The textured surfaces of the cutting tools and the tool wear were evaluated using scanning electron microscope (SEM) HITACHI, model TM3030. The tool wear parameter VB_B (average flank wear) was determined as described in ISO 3685:1993.

3. RESULTS AND DISCUSSION

Textured tools manufactured with 2 ns + 50 W and 8 ns + 30 W are shown in Fig. 1. Both pulse durations (2 ns and 8 ns) generated microcracks in the ceramic tools. The formation of microcracks occurs because of the high laser energy that promotes thermal shock and tensile stresses in the ceramic material (Xing *et al.*, 2018). Although the cutting tool material has additions of titanium carbide (29% TiC) that provide an increase in thermal shock resistance, the main phase is alumina (70% Al_2O_3). Alumina is a ceramic material with a high thermal expansion coefficient and, consequently, low thermal shock resistance (Richerson and Lee, 2018).

When used 2 ns to surface texturing of the tools (Fig. 1a), the microcracks and the heat affect zone are lower than for 8 ns (Fig. 1b). For the lowest pulse duration (2 ns) the energy dissipation time for the material structure was shorter, so the thermal effects were more restricted to the area directly exposed to the laser beam. When four times longer pulse duration (8 ns) was used, despite the lower laser power (30 W), intense thermal damage occurred, and the grooves were deeper.

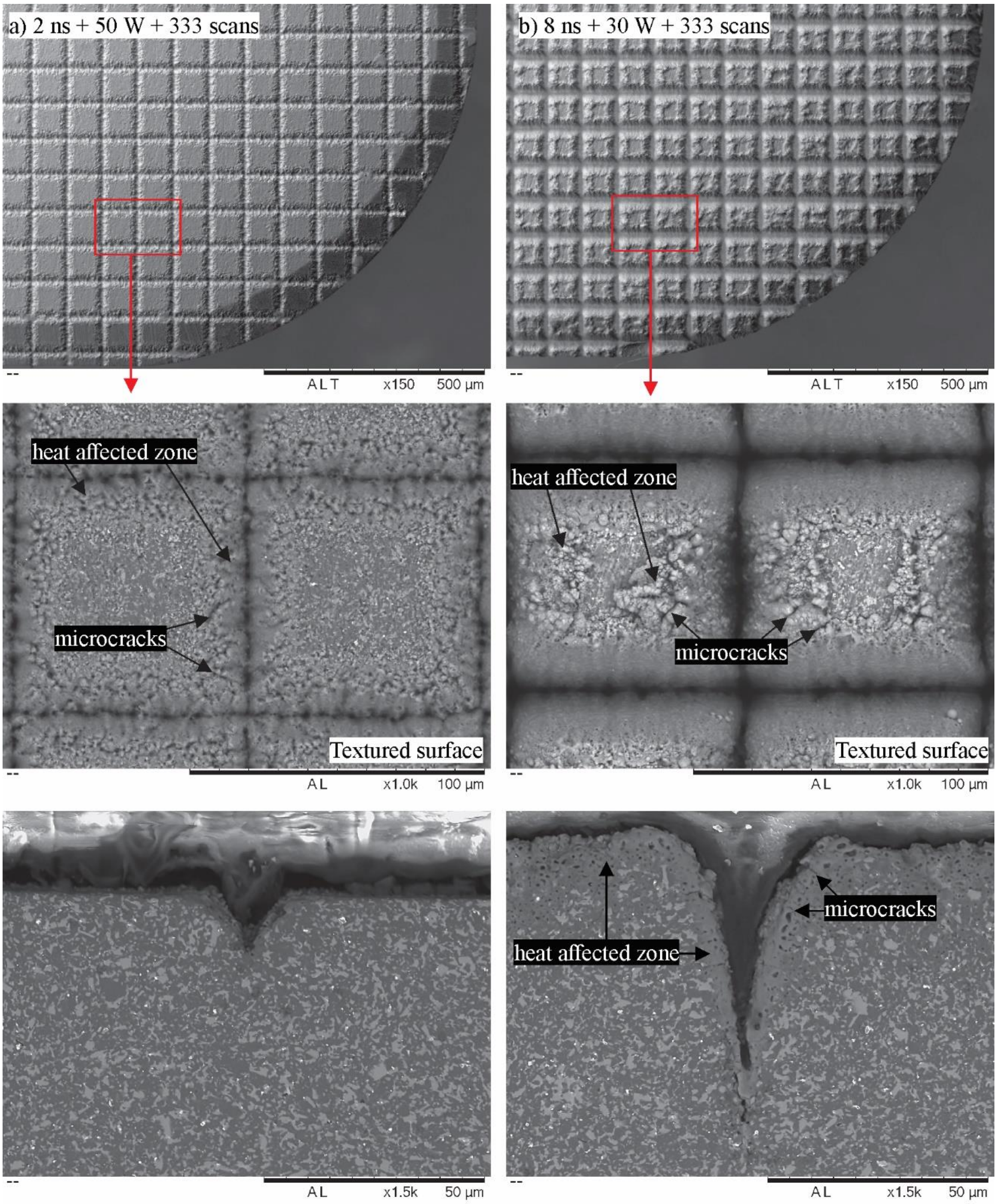

Figure 1. Textured cutting tools manufactured with a) 2ns + 50 W + 333 scans and b) 8 ns + 30 W + 333 scans.

As a result of the intense modifications in the tool material induced by the texturing process with 8 ns + 30 W, the tool did not present adequate properties to withstand the high stresses to which the cutting edge was subjected during turning (machining force (F_u) ≈ 110 N and specific cutting force (K_{sc}) ≈ 4633 N/mm², according to force measurement during the turning experiments). Therefore, in turning process with these tools (8 ns + 30 W) occurred the formation and/or propagation of microcracks in the textures, leading to premature tool wear (machining time = 0.9 min, Fig. 2). On the other hand, tools textured with 2 ns + 50 W showed regular wear during turning, exhibiting abrasive marks on the chamfer and flank face, and adhered material on the rake face. Breidenstein *et al.* (2018) indicate there is a certain heat input limit that cannot be exceeded to guarantee the integrity of the ceramic tool, since from this limit the tool wear behavior changes drastically, leading to a rapid failure due to cutting-edge chipping. Thus, it can be concluded that in the experiments of this research the heat input limit is greater than 2 ns + 50 W and less than 8 ns + 30 W for pulse frequency = 120 kHz, laser pulse overlap = 95%, and number of scans = 333 (considering the settings of the laser used for texturing).

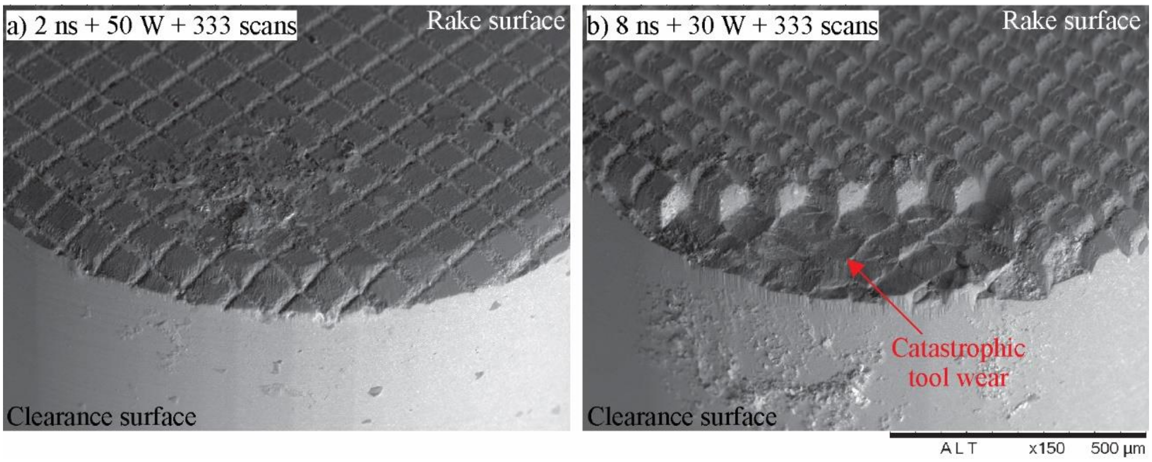

Figure 2. Tool wear of textured cutting tools manufactured with a) 2ns + 50 W + 333 scans (machining time = 3.6 min) and b) 8 ns + 30 W + 333 scans (machining time = 0.9 min).

The texturing process with 2 ns + 50 W was analyzed more deeply in the second step of the experiments. Textured tools manufactured with 2 ns + 50 W and a different number of scans (11, 333 and 1000) were evaluated in turning (Figure 3). The use of 11, 333 and 1000 scans in laser texturing generated textures with a depth of approximately 4, 13 and 15 µm, respectively. In turning the main tool wear mechanism was abrasion for all textured tools. The tool manufactured with only 11 scans exhibited intense abrasive marks on the chamfer and rake face, indicating that shallow textures are easily removed by abrasive wear. Therefore, the textured tool with 11 laser scans likely starts to act similarly to a conventional tool early during machining, not justifying the texturing process. It cannot be statistically stated (95% confidence level) that there is a significant difference between the VB_B values for the textured tools manufactured with 11 and 333 scans. The tool with deeper textures (manufactured with 1000 scans) showed higher flank wear.

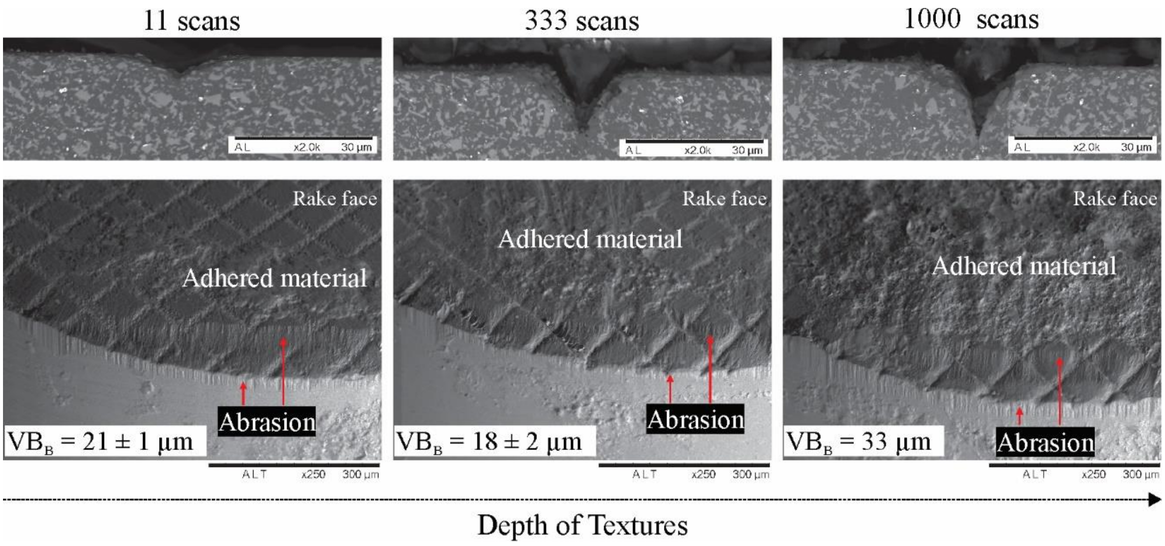

Figure 3. Tool wear of textured cutting tools manufactured with 2 ns + 50 W and different number of scans (machining time = 3.6 min).

Despite the higher VB_B of the tool manufactured with 1000 scans, the difference in texture depth between the tools with 333 and 1000 scans is very small (≅ 2 µm). Thus, the higher wear on the tool made with 1000 scans can hardly be explained based on the depth of the textures. Moreover, Patel *et al.* (2019) (turning of the AISI 4340) found that the variation in texture depth from 10 to 30 µm has a limited impact on the tool performance. While the increase in the number of scans from 333 to 1000 did not substantially impact the depth of textures, the increase in the number of scans increased the heat affected zone on the tools (Fig. 4). When using 1000 laser scans the material was exposed to the thermal process for a longer time than when using 333 scans, so the texturing process with 1000 scans caused more embrittlement of the tool.

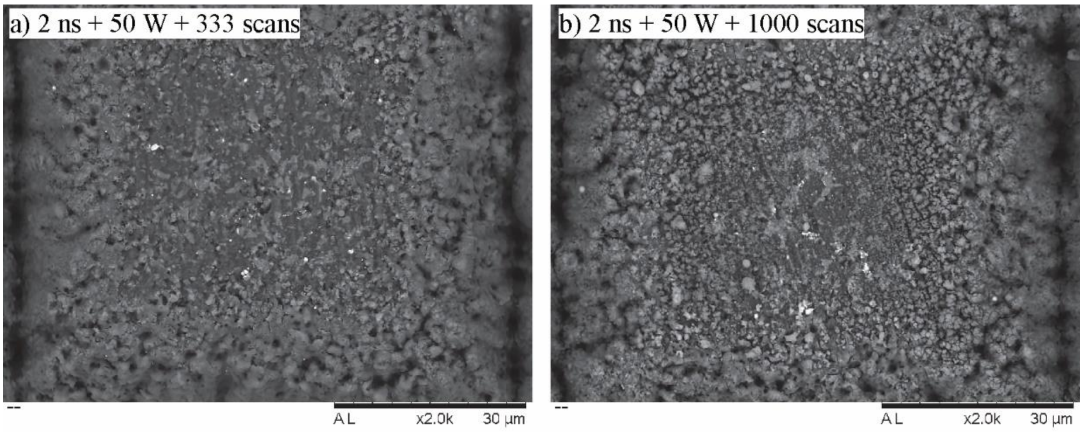

Figure 4 – Topography of the textured cutting tools with 2 ns + 50 W + a) 333 scans and b) 1000 scans.

Therefore, based on the tested laser texturing parameters, the best tool performance in turning was found in tools manufactured with 2 ns, 50 W, and 333 scans.

4. CONCLUSIONS

The laser texturing process has a great impact on the performance of textured ceramic tools applied in turning, since the laser texturing parameters cause different levels of thermal damage to the tool material. Textured tools manufactured with pulse duration = 8 ns and laser power = 30 W (number of scans = 333) presented premature failure (machining time ≤ 0.9 min), while textured tools with 2 ns and 50 W (333 scans) presented regular wear in the machining time evaluated (3.6 min). Although both texturing conditions generated microcracks on the cutting tool, the thermal damage on the tool manufactured with 8 ns + 30 W was substantially greater than when used 2 ns + 50 W.

In addition to pulse duration and laser power, the number of scans is also an important parameter in laser texturing of ceramic tools. In textured tools manufactured with 2 ns + 50 W, the increase in the number of scans from 333 to 1000 increased the heat affected zone on the tools, leading to higher tool wear in turning. On the other hand, the decrease in the number of scans from 333 to 11 did not impact the flank wear. However, in the textured tool manufactured with 11 scans (consequently, with shallower textures), the abrasive wear caused the removal of the textures in the chamfer and rake face. Thus, the tool manufactured with 2 ns, 50 W and 333 scans showed the best performance among the turning experiments performed.

Whereas there are several laser texturing parameters and surface texturing techniques available nowadays, the results obtained in this research indicate that it is essential to evaluate the texturing process for the development of textured cutting tools, combined with the evaluation of these tools in the machining process.

5. ACKNOWLEDGEMENTS

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