



COB-2021-0129 INFLUENCE OF DEBURRING METHODS IN MICRO SLOTS OF INCONEL 718

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Abstract. *In view of the increasing trends towards miniaturization of components, machining processes have been trying to attain higher levels of dimensional and geometric quality. Micromilling cannot be analyzed with the same theories applied in the macro-scale process, because the cutting edge radius of the tool is greater than the minimum chip thickness, characterizing the size effect. One of the main issues associated with the quality of surfaces obtained by micromilling is the presence of burrs. Inconel 718 is a nickel super-alloy commonly used in aggressive conditions, such as nuclear and aerospace industries, due to its outstanding mechanical properties. This material is well known for its low machinability and it is frequently reported to exhibit burrs when micromilled. Deburring techniques often performed in traditional milling cannot always be performed in micromilled surfaces, since they might affect the dimensional accuracy and possibly damage the piece. Therefore, this work aims to investigate the effectiveness of deburring operations on slots obtained by micromilling of Inconel 718. In order to reduce potential damage on the surface, the abrasive deburring method was selected. Four different abrasive grit sizes were employed so that their abilities of removing the burrs could be analyzed. It was possible to notice that the abrasive size did not had high influence in the deburring. The selected method was able to reduce the burr heights from 350 μm to 8 μm , approximately. The analysis of the deburred surfaces indicates that despite the high burr removal, there was no damage in the slot geometry nor in the sample surface. Therefore, the selected methodology proved to be suitable for deburring slots in flat surfaces.*

Keywords: *Micromilling, Deburring Methods, Inconel 718, Surface Quality.*

1. INTRODUCTION

In the last few decades, micromanufacturing technologies have gained prominence. Research works in these fields have increased significantly because of the necessity of creation of highly compact components, with high levels of dimensional and geometric precision, especially in the biochemical, biotechnological, aerospace and electronics industries. There are high demands in the market for the creation of micro-components and for the addition of complex microscopic features in pre-existent pieces, in order to improve their functionalities.

The design of cutting tools used in traditional machining has been passing through continuous improvements in order to remove smaller and smaller chips. One of the principal micromachining processes is micromilling. According to Camara *et al.* (2012), the definition of micromilling is based on the dimensions of the cutting tool, which should range from 1 μm to 1000 μm . This process is highly versatile and is well suited, for instance, for the fabrication of microinjection molds (Takács *et al.*, 2003 and Chae *et al.*, 2006).

Inconel 718 is one of the most often used nickel super-alloys (Veiga *et al.*, 2012). Owing to its excellent mechanical properties, it is commonly expected to withstand high temperatures and stresses. However, it is known as a material of low machinability. Burrs of relatively large size are frequently observed in surfaces obtained by micromilling, especially in hard-to-cut materials such as Inconel 718. In some cases, the burr height can be even larger than the depth of cut (de Oliveira, 2019).

An important parameter when analyzing micromilling is the cutting tool wear. Considering the difficulties in directly measuring the wear of micromills, some authors recommend it to be evaluated indirectly by means of the dimensions of the microslot. According to Alhadeff *et al.* (2019), considering that the width of the micro slot decreases with the

micromill diameter, its measurement is a simple and efficient way to quantify the tool wear. Nevertheless, the presence of burrs may lead to imprecise measurements (Figure 1). It is desirable, thus, to use some deburring or edge finishing technique to properly remove the burrs, even though burr removal may be particularly difficult in microscale.

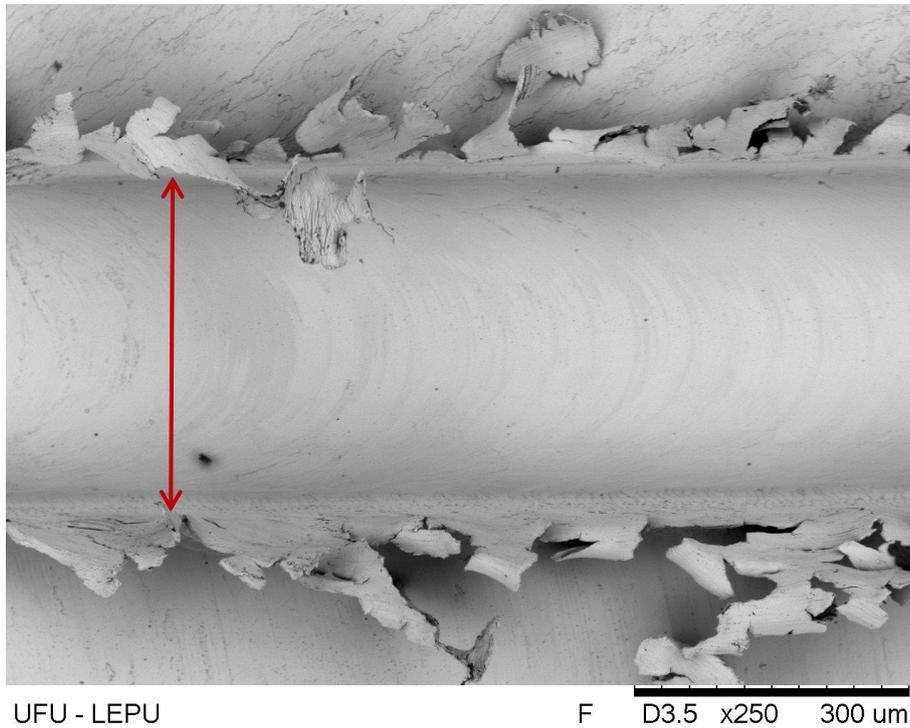


Figure 1. Large burrs hindering the precise measurement of the width of a slot obtained by micromilling.

Thus, considering the difficulties caused by the presence of burrs in micromilling, the objective of this work is to deburr micro slots on workpieces of Inconel 718 in order to evaluate the effectiveness of the chosen deburring method. For this purpose, the burr heights of the micro slots were measured before and after the deburring experiment. The surface quality of the slots was also evaluated qualitatively by means of microscopy images.

2. MATERIALS AND METHODS

In order to study the deburring process, two methodologies were employed: a literature analysis and experimental trials.

2.1 Literature analysis

For the literature analysis, an empirical research was conducted according to the methodology proposed by Flynn *et al.* (1990). The following terms were used for the research: micromachining, micromilling, Inconel 718, burr, burrs, deburring, abrasive deburring. This analysis was conducted to define the best procedures for the deburring method.

2.2 Micromilling trials

Micromilling was performed to obtain slots in Inconel 718 workpieces, whose chemical composition is presented in Table 1. Four different workpieces with dimensions 15 mm×10 mm×15 mm were used. The material was cast, and age hardened, and it has the properties presented in Table 2.

Table 1. Mechanical properties of Inconel 718 (de Oliveira *et al.*, 2019).

Tensile strength (MPa)	Yield strength (MPa)	Young's Modulus (GPa)	Hardness (HRC)	Density at room temperature (g/cm ³)	Melting Range (C)	Thermal Conductivity (W/mK)
1275	1034	200	40	8.22	1260 – 1336	11.4

Table 2: Chemical composition of Inconel 718 (de Oliveira *et al.*, 2019).

Element (wt.%)	C	Al	Ti	Cr	Fe	Ni	Nb	Mo
	0.04	0.50	0.90	19.00	18.50	50.66	5.10	5.30

The tool is a micro end mill from Mitsubishi, its material is ultra-refined cemented carbide, and it is coated with (Al, Ti)N. The micromill has a 400 μm diameter and 2 flutes. The machine tool was a Mini-mill / GX CNC, that has a maximum spindle speed (n) of 60000 rpm and 3 axes with position resolution of 0.1 μm , manufactured by Minitech Machinery Corporation.

The trials consisted in micromilling 12 slots, with 15 mm, in each workpiece, with the cutting parameters shown in Table 3. To perform the trials, cutting fluid was applied following the methodology proposed by de Oliveira *et al.* (2020), using the Coolube 2210EP, by UNIST, applied at a flow rate of 270.0 ml/h at 200 pulses per minute and an air pressure of 33 psi (0.23 MPa). The nozzle was positioned in the feed direction, and the distance between the nozzle and the cutting tool was kept constant.

Table 3. Cutting parameters.

Parameter	Sample 1	Sample 2	Sample 3	Sample 4
Spindle speed n (rpm)	11 000	20 000	11 000	20 000
Cutting speed v_c (m/min)	13.8	25.1	13.8	25.1
Feed rate v_f (mm/min)	110	200	110	200
Feed per tooth f_z ($\mu\text{m}/\text{tooth}$)	5			
Axial depth of cut a_p (μm)	40			
Radial depth of cut a_e (μm)	400			

2.3 Deburring trials

As mentioned, the abrasive method was selected due to its characteristics that lead to less damage in the workpiece surface and the high industrial application. To perform the deburring tests, silicon carbide sandpaper sheets, with mesh sizes 800, 1200, 2000 and 3000, were selected. The deburring operation was carried out with a Pantec metallurgical polishing machine Polipan-U, with a constant rotation of 120 rpm. Each sample was polished for 30 s with different mesh sizes. Table 4 shows the combination between deburring and cutting parameters.

Table 4. Deburring parameters.

Sample	Mesh	Sanding time
1	800	30 s
2	1200	30 s
3	2000	30 s
4	3000	30 s

2.4 Burr heights measurement

The equipment used to measure the burr heights was a Confocal Laser Scanning Microscope Olympus Lext OLS4100. For each individual slot, the burr heights were measured three times so that the mean values with standard deviations could be obtained. For comparison reasons, the microscopy operations were conducted twice, once before and once after the deburring procedure. The equipment was also used to obtain the images of the slots in order to complement the study with a qualitative analysis.

3. RESULTS AND DISCUSSION

Theoretic and experimental results were obtained. The theoretic results were based on a literature review, in order to understand the processes and nuances involved in the formation and removal of burrs in micromilling and on Inconel 718. The experimental results are based on the machining and deburring operations that were carried out.

3.1 Theoretic Results

3.1.1 Burrs in micromilling

The most important aspect that differs micromilling from macroscale milling is the size effect. This phenomenon is due to the fact that the edge of the microtool cannot be considered perfectly sharp as in traditional milling. Chip thickness in microscale can be typically comparable in size to the cutting edge radius of the tool and to the microstructure of the workpiece material. The rake angle is negative, with an intense plowing effect. It provokes a non-linear increase in the specific cutting energy, because a high amount of material needs to be in the plastic regime so that a small amount can be sheared in the form of chip. So, the size effect directly influences fundamental mechanisms in the cutting process, such as cutting force, chip formation, burr formation and quality of the machined surface (Aramcharoen and Mativenga, 2009).

The most frequent type of burrs in micromilling is Poisson burrs (Gillespie, 1973). These burrs are formed when the workpiece is extruded in the cutting direction by the straight rake face and the cutting edge arc of the tool. According to Wu *et al.* (2017), there is considerable interacting stress on the contact area between the workpiece and the tool, which causes the material to begin plastic deformation and flow along the minimum resistance direction. Since the effective rake angle in micromilling is negative, the flow of material in front of the tool is separated into two directions: some up the rake face - forming a chip - and some through the flank face to the machined surface - resulting in Poisson burrs. Wu *et al.* (2017) investigated the burr formation mechanism in micro cutting for burr minimization. The authors observed that the burr formation decreases to a minimum value when the uncut chip thickness reduces to the same size as the cutting edge radius, and then increases with further reduction of the uncut chip thickness due to the change of the maximum stress distribution.

Wan *et al.* (2013) and Kou *et al.* (2015) presented an innovative method to prevent burrs which consists in using a kind of support material to be deposited on the workpiece surface. This material provides auxiliary support force and increases the stiffness of the original edge of the workpiece, preventing plastic deformations further increasing at the edge of the piece. When the tool radius slides over the edge of the workpiece, the primary shear zone, the plastic zone and the elastic zone are extended to the supporting material. Therefore, the burrs are generated on the support material instead of the workpiece. The material used as support should be carefully selected: it needs to be easy to be deposited and removed from the workpiece; it must not pollute the workpiece; it should have enough strength so as to prevent burr generation; and it should be recycled for cost reduction. Wan *et al.* (2013) conducted experiments in aluminum alloy 7050-T7451 with two different support materials, namely a wax and a low melting point alloy (LMPA). The authors observed that the wax provided undesirable results, seeing that its low strength doesn't prevent the occurrence of burrs on the aluminum. The LMPA was able to avoid burrs formation, even though the proposed method is difficult to be applied in micromanufacturing industry since there is no automatic controlled LMPA deposition or coating system that is able to provide a more accurate coating layer on the workpiece and the consequent highly productive burrs-free micromachining process. Kou *et al.* (2015), on the other hand, used an instant adhesive composed of α -ethyl cyanoacrylate as support material and conducted experiments in a beryllium bronze workpiece. The authors' results showed that burrs did not appear on the workpiece surface after the instant adhesive was removed and EDS analysis revealed that there was no contamination on the workpiece surface.

3.1.2 Micromilling of Inconel 718

Inconel 718 is one of the most used nickel-based super-alloys. It has been often used in applications that involve exposure to high temperatures and stresses, because it has excellent mechanical resistance, high strength and good corrosion resistance. These desirable properties of Inconel 718, however, result in low machinability. Since it is widely known as a hard-to-cut material, this super-alloy has been the subject of several recent research works seeking to improve its machinability under different machining conditions. In general, it has been observed that burrs of large dimensions are frequent in micromilling of Inconel 718 and they are usually difficult to avoid.

FANG *et al.* (2020) conducted a comparative study of two different machining methods on Inconel 718: traditional micromilling (TMM) and ultrasonic vibration assisted micromilling (UVAMM). This latter technique consists in applying ultrasonic vibrations periodically on the workpiece or on the cutting tool in order to avoid tool wear and improve finished surface quality. The authors' results show that UVAMM is more efficient in reducing burrs and improving the surface quality compared with TMM, in which pits, bumps and gullies are often formed.

Other factors that affect machinability in micro scale include lubrication techniques and coating of the cutting tool. Aslantas and Çiçek (2018) investigated the effects of different cooling conditions when micromilling Inconel 718. It was

observed that ethanol is an inefficient lubricant for this material, because it causes intense reduction of the tool diameter and large burr size. In addition, the burrs formed under dry cutting condition adhered to the sides of the slots, as a result of excessive growth of the cutting edge radius. Minimal Quantity Lubricant (MQL) was considered the most efficient lubrication method in micromilling Inconel 718 because it caused minimal tool wear and better surface quality.

Ucun *et al.* (2013) conducted an experimental investigation on the effects of the coating material on tool wear in micromilling of Inconel 718. Flank wear was observed due to the abrasive wear mechanism, which is the most frequent wear type. Because of fatigue, the formation of built-up edges and local fractures on the cutting edges and sides of the cutting tools were observed. The authors noticed that lower levels of wear and lower diameter changes occur in the coated tools compared to the uncoated ones, which is attributed to the high hardness values and low friction coefficients of the coated materials. It can be noticed that the cutting edge radius in micro tools is strongly dependent on wear and the lubricating technique contributes significantly to the cutting performance. Moreover, the authors showed strong evidence that the MQL process significantly enhances tool life and prevents chip adherence.

3.1.3 Deburring in Micromilling

In general, the removal of burrs originated from machining processes is desirable because these burrs may directly influence the performance, safety, cost and appearance of the manufactured product. There is a wide variety of deburring methods available, the most common of which being manual and abrasive methods, according to Gillespie (1999). However, the deburring techniques used in macromilling cannot always be used in micromilling since they may cause dimensional errors and residual stresses in the components, in such a way that the removal of burrs in microscale is particularly difficult (Khan *et al.*, 2019).

Mathai and Melkote (2012) performed an experimental characterization of the deburring rate in slots obtained by micromilling. The deburring method used by the authors consists in using a rotating nylon brush over the part in the presence of an abrasive slurry, which is a simple and inexpensive technique. The parameters considered by the authors were the abrasive grit type, grit size and spindle speed. It was concluded that the deburring rate is proportional to the initial burr height, with an almost constant proportionality for the conditions of the studied carried out. No clear trend was evident for the influence of grit size. In general, this study showed that abrasive brushing can efficiently remove large burrs and enhance surface quality in slots obtained by micromilling in copper alloys.

It can be observed that abrasive deburring methods are efficient in removing burrs. Besides, these methods are highly versatile, being present in the majority of industries. These facts, associated with the low cost of abrasive methods and its easy handling by the operator, justify their use in this work.

3.2 Experimental results

The mean values of burr heights of the slots before and after the deburring process are presented in Figs. 2, 3, 4 and 5, with their respective standard deviations.

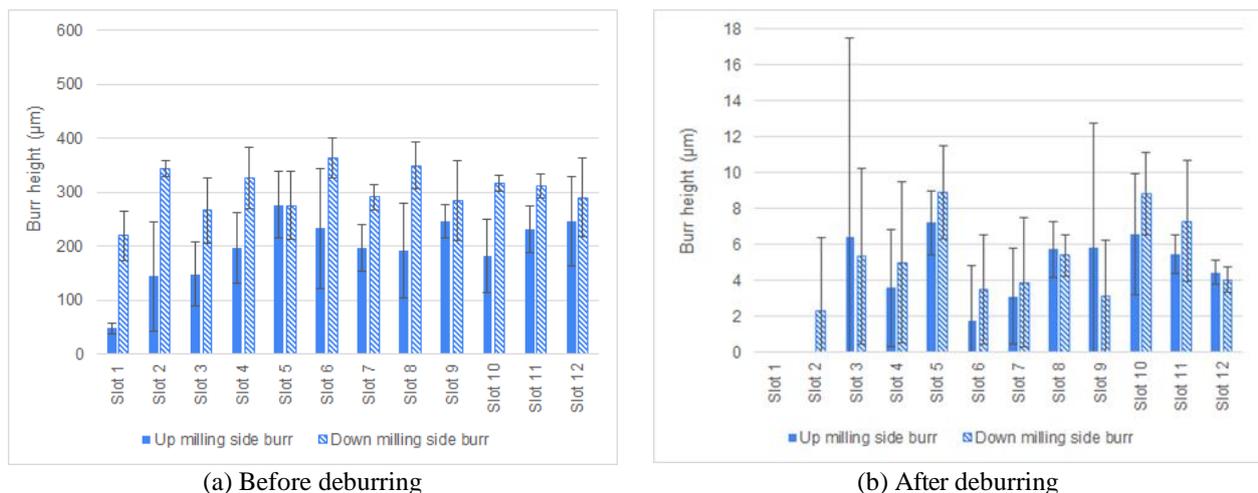
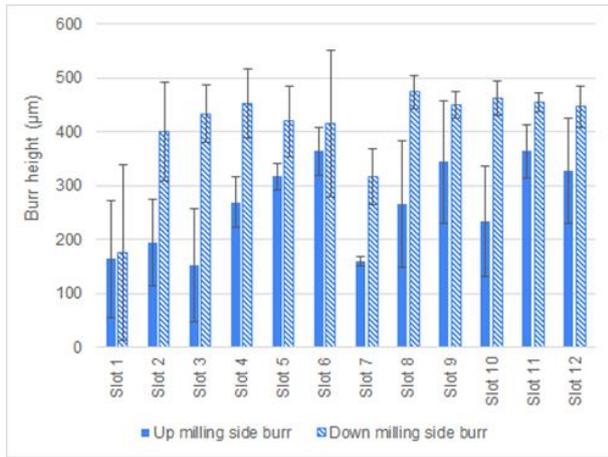
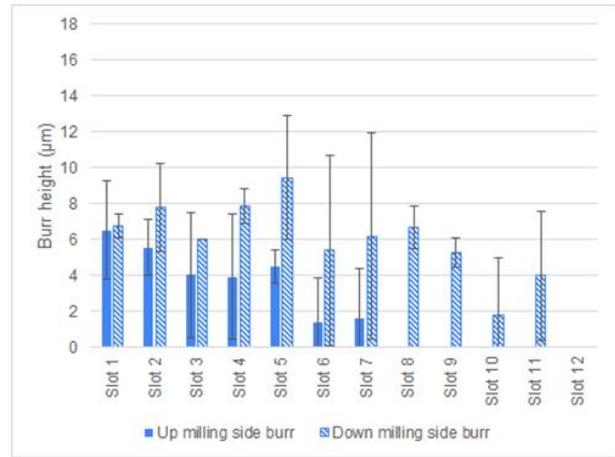


Figure 2. Sample 1.

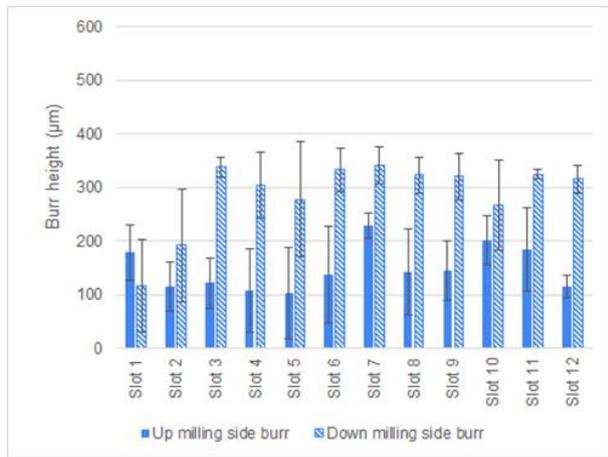


(a) Before deburring

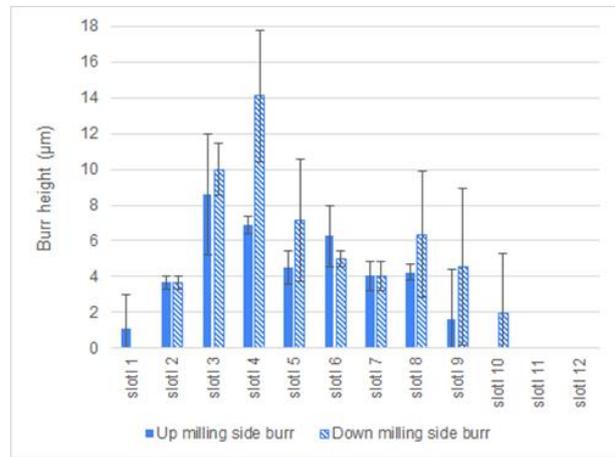


(b) After deburring

Figure 3. Sample 2.

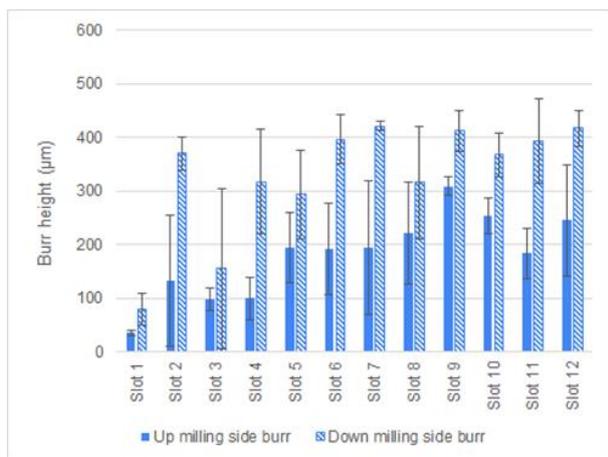


(a) Before deburring

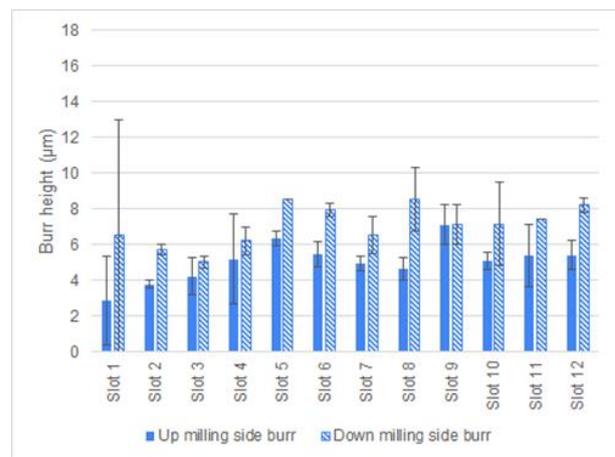


(b) After deburring

Figure 4. Sample 3.



(a) Before deburring



(b) After deburring

Figure 5. Sample 4.

By the figures 2 (a), 3 (a), 4 (a) and 5 (a), it can be noticed that the cutting velocity did not had influence in the burrs height, once the values for the Tests 1, 3 and 4 presented values close to 350 µm regardless of the fact that the first test was performed with the lower cutting velocity. It is also possible to notice that there were differences in the up milling and down milling burrs height, with the burrs in the up milling side being smaller than the burrs in the down milling side.

This was also observed by dos Santos *et al.* (2018), in micromilling duplex stainless steel UNS 32205, with a 381 μm diameter micromill, TiN coated, with different processes of cooling lubrication. The authors verified that the burrs in the down milling side are higher, regardless of the cooling lubricant used. However, for dry cutting, the authors mentioned that both sides presented bigger burrs, with the down milling side presenting burrs up to four times higher when compared to the lubricated condition.

When comparing the burr height values before and after the deburring, it is possible to notice that for all the samples the reduction was significant. The burr heights reduced from 350 μm to 8 μm , approximately, which means an approximate reduction of 98% in the burrs height, with a 30 s process. All the different meshes applied were able to remove the burrs, the one that presented the worse results was the mesh 2000, in which the slot 4 presented the highest burr height after deburring (14 μm).

Another characteristic that stands out in the figures 2 (a), 3 (a), 4 (a) and 5 is the high standard deviation that can be seen, in the same order of magnitude of the mean values. The high standard deviation was also observed by Aramcharoen and Mativenga (2009) when micromilling tool steel. The authors verified differences up to 80 μm . It occurs due to the burr characteristic in micromilling. To exemplify the burr characteristic that lead to the high standard, figure 6 (a) contains a representative slot of a sample before deburring.

In figure 6 (b), it is also possible to notice that the deburring method did not compromise the slot geometry. In a qualitative analysis (by the images), there were no significant variation neither in the bottom of the slot nor in the part surface, which indicates that for deburring slots in flat surfaces, the abrasive methods can be applied. It is worth mentioning that for figure 6, slot 12 of sample 2 is used to represent the average effect of the sanding trial on the removal of burrs, regardless of the sample and the slot number.

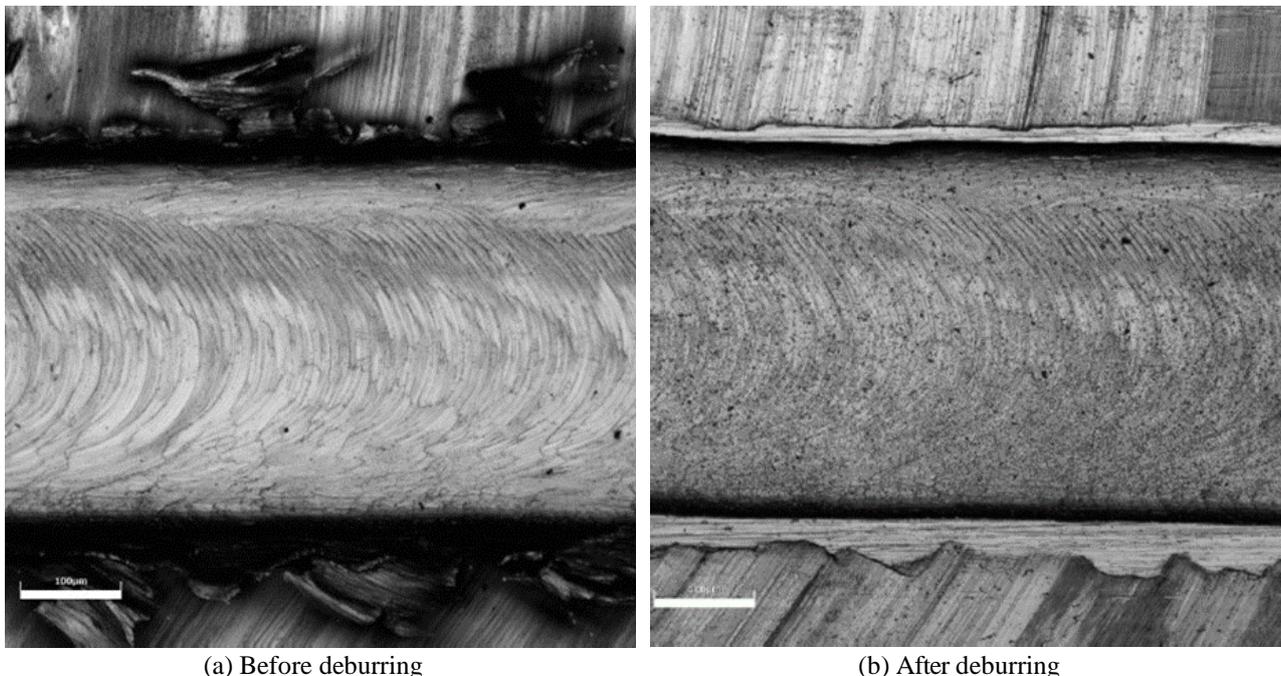


Figure 6. Slot 12 from sample 2.

4. CONCLUSIONS

With the combination of literature review, the experimental results of the machining and the deburring process of Inconel 718 micromilled slots, the following conclusions could be drawn:

- It was possible to notice little interference of the cutting velocity in the burrs height, indicating that other cutting parameters can be studied in order to minimize the burr formation.
- The methodology of measuring the burrs by their heights presented high standard deviation values, due to the burr irregular characteristics, and therefore, it indicates that it should be associated to other information to completely characterize the process.
- According to the literature, the manual and abrasive methods are simple, versatile and have a low cost associated with their handling and operator training.
- The abrasive deburring trials were consistent with what is expected from literature and could promote a reduction in the burrs height of approximately 98% with a deburring time of only 30 s, indicating it is a promising method for deburring slots in flat surfaces.

5. ACKNOWLEDGEMENTS

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