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EFFECTS OF CUTTING SPEED IN FORCES, SURFACE TOPOGRAPHY AND RESIDUAL STRESSES IN MILLING OF INCONEL 718

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Abstract. *The heat generated in the cutting zones during milling plays an essential role in the final workpiece quality and power consumption. Surface integrity in the milling process can be influenced by tool geometries and cutting conditions, depending on the field temperature and cutting forces which the workpiece is submitted. Although, these effects in machining of Inconel are crucial as the tool life can be reduced to some seconds and more experimental studies need to be done in milling of Inconel to understand and optimize the machining process. This paper presents an experimental analysis of milling INCONEL 718 using two different cutting conditions, recommended by the tool manufacturer. Machining forces are measured during the cutting process and roughness, burr height and residual stresses are taken in the identified channels. Analysis of variance is used to compare the experimental results and calculate the effects of the factors. The results show that the lenght of cutting is the main factor that influence all the results. The two cutting speeds used (30 and 40 m/min) present no influence, compared to the lenght of cutting effect and the variance of data.*

Keywords: *Inconel Machinability, Residual Stress and Cutting Force*

1. INTRODUCTION

Milling is one of the most fundamental processes of machining materials used in the metal industry. Due to thermal and mechanical loads during machining, the main problems identified on the surface of the workpiece are overheating and burning, surface irregularities, Build-Up-Edges or deposits of debris, macro and micro cracks, cavities, micro defects, such as ridges and inclusions, metallurgical alterations including microstructural distortion, phase transformations, heat affected layers and tensile residual stresses (RS) (Devillez *et al.*, 2011).

Most of the mechanical energy used to form the chip becomes heat, that generates high temperatures in the cutting area. Due to the reason that a high tool temperature leads to faster wear, the use of cutting fluids in machining processes has as its main objective the reduction of temperature in the cutting region, which through lubrication, reduces wear and friction. There are numerous cutting fluid application methods, however, the most widely used currently, because of its simplicity, is the low-pressure jet, or by gravity, which is applied in the direction of chip-tool interface or rake face tool. In this method, the cutting fluid removes the chips from chip-tool interface, dispensing special devices or equipments (de Freitas, 2013). How can it be seen, cutting fluids play important roles in machining processes. Proper selection and use of cutting fluids usually results in a best process performance, better workpiece quality and longer tool life (Oliveira and Alves, 2006).

The material machined in this study is Inconel 718, a nickel superalloy, heat resistant superalloys (HRSA), which has excellent strength properties at high temperatures and high resistance to corrosion (Sharman *et al.*, 2015). This material finds many applications, like equipment for heat treatment, chemical and petrochemical industries, turbine power plants steam and applications in the aerospace industry, such as the manufacture of chambers combustion, drives, casings, rings, vanes and supports, components for the hot sections of gas turbine engines. According to Arunachalam *et al.* (2004), nickel-based alloys currently constitute over 50 % of the weight of advanced aircraft engines, and Inconel 718 accounts for between 50 % to 78 % of nickel alloys used by the main aircraft engine producers. Due to the properties presented, Inconel 718 has poor machinability, resulting in high cutting forces and reducing cutting tools performance. Its austenitic matrix promotes rapid hardening during machining, and the low thermal conductivity leading to high temperature in the cutting zone. These characteristics cause high temperature (1000 °C) and stresses (3450 MPa) in the cutting zone leading to accelerated flank wear, cratering and notching, with damage to the integrity of the machined surface (Choudhury and El-Baradie, 1998).

Researches on machining Inconel 718 had significant increase of interest in the last ten years. Machining high performance materials presents technical problems such as high tool wear, low efficiency machining and high cost production. Optimization of cutting parameters, in order to provide a beneficial RS state to the material, can reduce the use of cutting fluids and revels an opportunity to improve process performance. Cutting forces, residual stresses, microstructure, hardness, surface finish and tool life are evaluated in studies related to machining of Inconel 718 or other materials. The variation of the cutting parameters, such as feed and cutting speed, the condition of lubricating / cooling, the cutting tool geometry and material, are considered determinants in these work results.

Dudzinski et al. presented a review of several works about progress made in high speed and dry machining of Inconel 718. For high cutting speeds (more than 50 m/min for nickel based alloys), the lubricating effect of cutting fluid in the cutting zone was not effective. This explains why the high speed machining is often associated with dry machining. High speed machining leads to a reduction in cutting forces, increase removal rates, and hence reduce energy consumption. Alternatives to enhancing the machining performance of hard-to-cut materials were addressed, such as hot and cold machining. In the first, located heat sources, with laser or plasma, are used to achieve high temperatures, above (750 °C), reducing significantly the yield strength of the material. In the second, the temperature in the cutting zone is reduced with the coolant property of the cutting fluid as the application of high pressure water jet, compressed air or liquid nitrogen (Dudzinski *et al.*, 2004). Although the high cost of liquid nitrogen, it provides a cryogenic machining process with improvement of all major surface integrity features: increases the hardness and the compression RS, and reduces the roughness of the workpiece (Pusavec *et al.*, 2011).

The surface integrity and cutting forces for Inconel 718 turning were evaluated by Devillez et al. Experiments were performed with coated tool of 4 μm thickness (TiCN-Al2O3-TiN), with and without cutting fluid, and variable cutting speeds. The use of cutting fluid limited the tensile RS. However, the lubricating effect of cutting fluid was reduced with increasing cutting speed. To a cutting speed of 80 m/min the tensile RS values were equivalent to the dry machining condition. On these conditions, when the cutting speed was increased, the peak tensile RS was reduced because much of the heat generated during machining was dissipated with the chip. Finally, in dry machining conditions using insert coated, the cutting speed of 60 m/min was considered ideal for the surface quality finish by limiting RS and depths affected by tensile RS. At this cutting speed the missing of cutting fluid has less influence on the microstructure deformation and hardness variation of the machined surface in comparison with machining in presence of cutting fluid (Devillez *et al.*, 2011).

The tool life and cutting forces were evaluated for end milling Inconel 718 associating dry cutting and with MQCL (Minimum Quantity Lubrication Cooling). About tool cutting, the insert had a cemented carbide substrate, with an inner coated layer of TiAlN and an outer coated layer of TiN. Based on conclusions of Zhang *et al.* (2012) the tool wear topographies under dry cutting condition are similar to that under MQCL cutting condition, but the tool life is 1.57 times greater and cutting forces lower in MQCL condition. In this study the milling process was carried out with cutting speed of 55 m/min.

Using coated tungsten carbide inserts with a multilayer TiCN/Al2O3/TiN coating, Sharman *et al.* (2015) used a range of tool nose radius from 2 mm to 6 mm at various feed rates and chip thickness, to evaluated the cutting forces, microstuctural changes and RS levels when turning Inconel 718. In this work was used cutting speed of 40 m/min and the tool wear had the greatest influence on the level of microstructural alteration and magnitude of RS. Increased friction caused by the rubbing of the worn tool flank, combined with the effective increase in edge rounding resulted in higher cutting forces and potentially cutting temperature. This lead to higher levels of near surface tensile RS and a deeper depth of compressive RS. For a fixed tool nose radius, an increase in feed rate produced greater levels of near surface tensile stress and increased the depth of the tensile layer. And an increase in tool nose radius from 2 to 6 mm resulted in greater levels of plastic deformation and thermal input into the near surface layer as evidenced by the large increase in near surface tensile stress levels (up to 1550 MPa) and depths (up 100 μm).

The present study is an experimental work that aims to evaluate the influence of cutting speed on forces, roughness, burr height and RS levels generated in milling of Inconel 718. The tool (and tool nose radius) is fixed in this work, although two new tools are used to generate two replicates. The cutting conditions used were recommended by the tool manufacturer and cutting fluid is present in the machining process.

2. EXPERIMENTAL PROCEDURE

The experimental procedure is divided in two parts: data taken during machining tests and measurements done in the workpiece after milling.

2.1 Workpiece Material

The Inconel 718 workpiece material was machined in the milling experiments. The chemical requirements and mechanical properties of Inconel 718 are listed in Tables 1 and 2, respectively. This sample was supplied in bar form with 95 mm of diameter, 106 mm of length and welded to a plate for fixing to the dynamometer. The surface of the workpiece was flatted before the experiments.

Table 1. Chemical Requirements of Inconel 718 (ASTM B637, 2012).

Element		Ni	Cr	Nb + Ta	Mo	Ti	Al	Co	Si
Composition Limits, %	Min	50.0	17.0	4.75	2.80	0.65	0.20	$\leq 1.0^A$	≤ 0.35
	Max	55.0	21.0	5.50	3.30	1.15	0.80		
Element		Mn	Cu	P	S	Fe	C	B	
Composition Limits, %	Min Max	≤ 0.35	≤ 0.30	≤ 0.015	≤ 0.015	remainder^B	≤ 0.08	≤ 0.006	

^{A} If determined.
^{B} The element shall be determined arithmetically by difference.

Table 2. Mechanical Properties of Inconel 718 (ASTM A1014/A1014M, 2006).

Tensile and Hardness	
Tensile strength, min, ksi [MPa]	185 [1275]
Yield Strength, min, ksi [MPa] 0.2 % offset	150 [1035]
Elongation in 2 in., or 50 mm (or 4D), min %	12
Reduction of area, min, %	15
Hardness, Brinell	331 - 444

2.2 Milling Experiments

The workpiece was fixed into a dynamometer (Fig. 1(a)), a three-component piezoelectric dynamometer Kistler 9257 BA table associated to a 5070 multichannel charge amplifier connected to a NI USB-6551 National Instruments data acquisition system. The tests were conducted on a machining center CNC Romi Polaris V400.

(a) Dynamometer and workpiece.

(b) Surface roughness measurement.

Figure 1. Experimental Set-up for Forces and Roughness

The cutting tools were coated inserts R390-11 T3 08M-PM 1030 supplied by Sandvik-Coromant. The R390-11 T3 08M-PM 1030 insert grade is a PVD TiAlN coated and tool radius of 0.8 mm. The used tool holder was R390-16 supplied by Sandvik-Coromant.

Machining experiments were performed with two cutting speeds (Vc) referenced in Table 3. First column shows the experiment and the replica for each machining experiment. The depth of cut is 1.0 mm, full immersion tool is milled producing channels with 16 mm and 28 mm of length. Feed per tooth is defined to be 0.04 mm/tooth. The choice for radial distribution of channels was found to ensure an alternative of machining the same area in all channels, as shown in the third column.

The cutting fluid was a soluble vegetable-based fluid with ethanol and soy oil in the composition, diluted in 1:40 ratio with potable water using the CNC milling coolant system at 7 bar and 10 l/min.

Table 3. Design of Experiments (f_z = 0.04 mm/tooth).

Experiment (Replica)	Length of cutting (mm)	Channel Position (radial channels)	Cutting Speed (m/min)	Cutting Fluid (Cutting Tool)
1 (1)	10	ϕ_2	30	Water Soluble Fluid 1:40 (New Tool)
2 (1)	38	ϕ_6	40	
3 (1)	66	ϕ_{10}	40	
4 (1)	94	ϕ_4	30	
5 (1)	122	ϕ_8	40	
1 (2)	10	ϕ_7	30	Water Soluble Fluid 1:40 (New Tool)
2 (2)	38	ϕ_1	40	
3 (2)	66	ϕ_5	40	
4 (2)	94	ϕ_9	30	
6 (1)	122	ϕ_3	30	

2.3 Surface Quality measurements

After milling, workpiece was taken to examine the machined surface. The surface roughness and burr height were measured using a profiling device 112-2062-02 Taylor Hobson and stylus 112-2011. The transversal measuring length was 15 mm, speed measuring of 0.5 mm/s and cutoff used to calculate the average roughness was 0.08 mm. For average surface roughness (Ra) were taken three readings on the same direction along the channel length, and the average was considered (Fig. 1(b)).

The burr height is measured in each channel using three different transversal sections readings along the channel length, as shown in the scheme presented in Fig. 2.

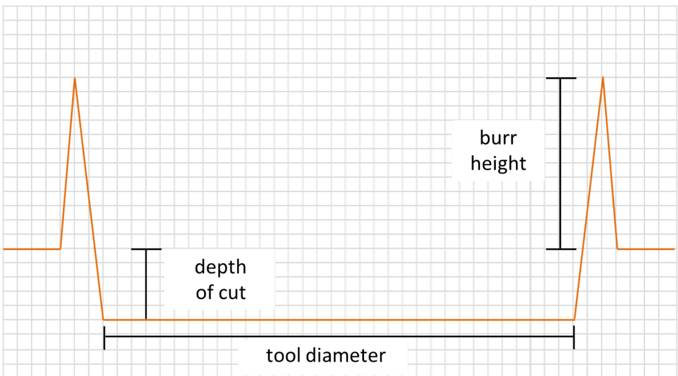


Figure 2. Burr height scheme - front view of the channels

Residual stresses in the workpiece surface were measured and analyzed by X-ray diffraction technique using the sen$^2\Psi$ method. Analysis was performed with the Xstress3000 analyzer, manufactured by Stresstech (Fig. 3), using radiation (λCr$\kappa\beta$ = 2.0848 Å), diffracting the {311} plane of nickel with angle 2θ = 157.73°. The measurements were performed on the surface of each channel, in the cutting direction. Parameters used for residual stress measurements in Table 4.

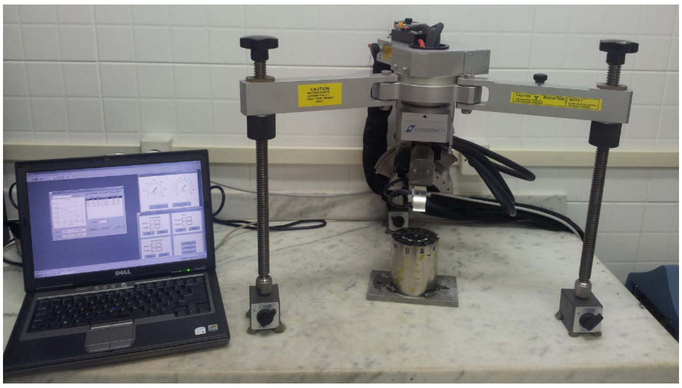


Figure 3. X-ray residual stress analyzer.

Table 4. Residual stresses measurements parameters.

Parameter	Standardized value
Collimator diameter (mm)	2
Incidence angle 2θ (degree)	157.73
Diffraction plane {hkl}	{311}
Radiation	Cr$\kappa\beta$
Wave length λCr$\kappa\beta$ (Å)	2.0848
X-ray tube current (mA)	6.7
X-ray tube voltage (kV)	30
Inclination angles Ψ (degree)	0; 20.7; 30; 37.7; 45
Exposition time (s)	20

3. RESULTS AND DISCUSSION

This section presents the separate results from the experiments: machining resultant forces F_{res}, average roughness R_a, burr height and residual stresses.

3.1 Machining Forces

The machining force results presented in this section, F_{res}, were calculated from the components taken from the dynamometer, as an example in Fig. 4, where F_z was negleted.

$$F_{res} = (F_x^2 + F_y^2 + F_z^2)^{0.5} \tag{1}$$

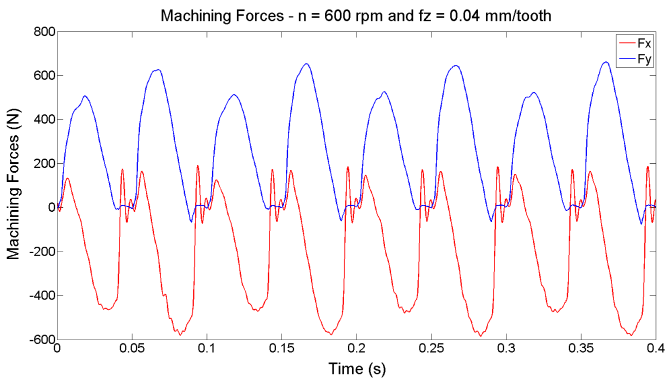
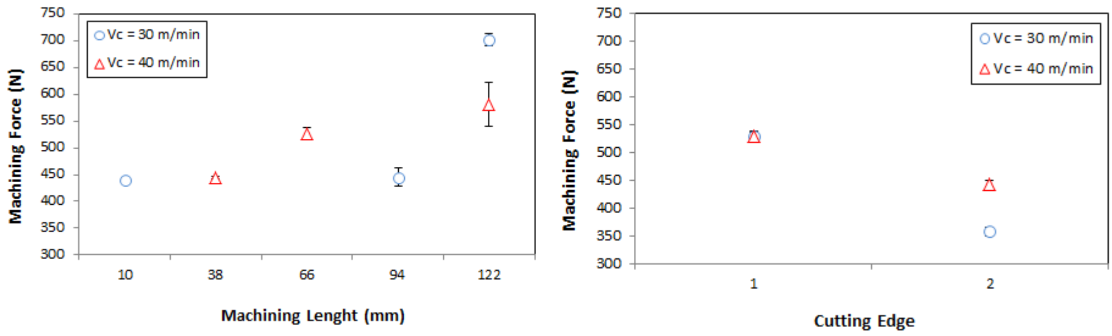


Figure 4. Example of Machining Force Measurement.

The data taken is the maximum of F_{res} on every tooth passage, for all tests, 20 revolutions after the full immersion were taken for analysis. As the tool has two teeth, it is possible to compare the results using separate cutting edges. The effect of cutting speed, machining length and tooth number on machining forces was first studied; the experimental results are shown, respectively, in Figs. 5(a) and 5(b).



(a) Effect of machining length.

(b) Effect of cutting edge.

Figure 5. Effect of machining length, cutting edge and cutting speed on machining forces.

In Fig. 5(a) it can be seen that machining forces increases from the first test to the last test, concluding that the wear is constantly increasing. For the machining length of 122 mm, cutting speed of 40 m/min provide lower cutting force than cutting speed of 30 m/min. The relative sharp tools at the initial stages of machining produce lower cutting forces. With the increase of cutting time (machining length, Lu), the tool edges become dull, higher friction coefficient and more contact area at the tool/chip and tool/workpiece interfaces are generated. As a result, the high cutting forces are obtained at the end of machining (Zhang *et al.*, 2012).

To plot the graph of Fig. 5(b) was took in account an information from Table3, in wich there is no replica for machining lenght of $122mm$, so data from experiments 5 and 6 was not considered. This way, the Fig. 5(b) shows that the cutting edge had great influence in the machining forces, and the cutting speed had influence on edge 2. This is in agreement with ANOVA analysis for machining forces shown in Table 5. Besides cutting edge and the cutting speed, the machining length is a factor with good influence in machining forces. For the same reason presented before, the experiments 5 and 6 were not considered for ANOVA analysis either.

Table 5. ANOVA analysis for machining force.

	Df	Sum Sq	Mean Sq	F Value	Pr(>F)	
dados$Tool	1	15084	15084	3.254	0.07222	.
dados$Edge	1	1328830	1328830	286.637	< 2e-16	***
dados$Lu	1	36186	36186	7.805	0.00553	**
dados$Vc	1	146590	146590	31.620	4.14e-08	***
Residuals	315	1460320	4636			

—
Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 . 0.1 1

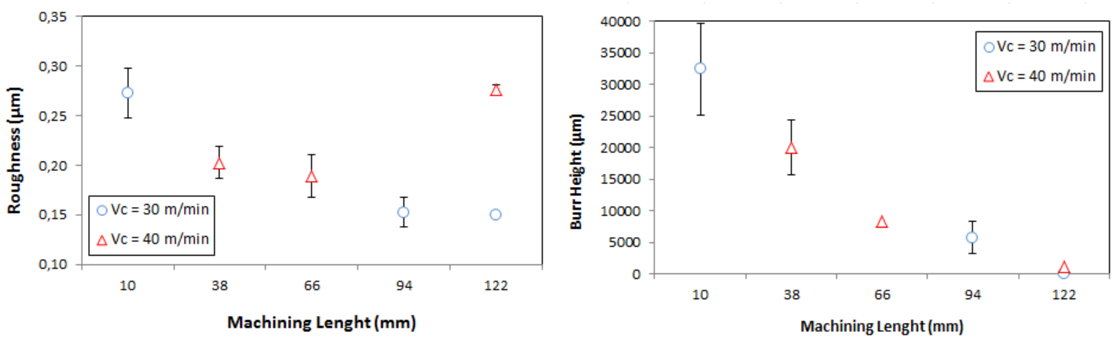
3.2 Surface Roughness

For surface roughness Ra, a comparison between different cutting speeds is presented in Fig. 6 (a). For both cutting speeds, surface roughness Ra has a tendency to decrease with increase machining length, except for the machining length of 122 mm, when better surface roughness result was obtained with cutting speed of 30 m/min. By analogy, this effect can be explicated that increasing the nose radius, the surface finish is improved (Arunachalam *et al.*, 2004). This is expected, since an increase in the nose radius results in an increase in contact length and so the cusp height is reduced as discussed earlier in the section on inserts shape.

The ANOVA analysis for surface roughness was also done and machining length had the main influence, as it can be observed in Fig. 6 (a).

3.3 Burr Height

The depth-of-cut notch is considered as a determinant for tool life when machining Inconel 718. The notching is influenced by the burr formation.This failure mode is mainly due to the hardening of the material during machining (Dudzinski *et al.*, 2004). The workpiece presented side burrs on the channels. The average experimental results are shown in Fig. 6 (b). For both cutting speed, the burr height decrease with increase of machining length, backing to ANOVA analysis for burr height in which between the factors cutting speed, tool and machining length, the last one is the only influence factor.



(a) Effect of machining length on surface roughness.

(b) Effect of machining length and cutting speed on burr height.

Figure 6. Effects on surface quality.

3.4 Residual stresses

The experimental results for residual stress were also analyzed by ANOVA and indicated that the factors of cutting speed and length are of most influence. The Fig. 7 shows the behavior of residual stress in longitudinal (cutting) direction. The residual stress is compressive for the first machining lengths and becomes tensile with the increase of machining length, for both cutting speed. This effect can be related to the relative sharp tool at the initial stages of machining, that produce low cutting forces. As mentioned in previous cited papers, Inconel 718 has high mechanical properties and exhibits severe work hardening, combined with low thermal conductivity, the machining length promotes tool edges dull, higher friction coefficient and more contact area at the tool/chip and tool/workpiece interfaces. As a consequence, high cutting forces are produced with high localized temperatures around the cutting edge, and on the machined surface, thus producing tensile residual stress.

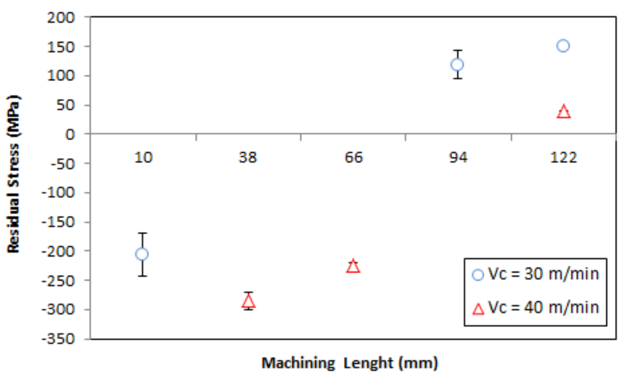


Figure 7. Effect of machining length and cutting speed on residual stress.

4. CONCLUSIONS

This experimental procedure was developed to analyse the effect of cutting speed, machining length and cutting edge on the machining forces, surface roughness, burr height and residual stress during milling of Inconel 718. For all experimental data presented were realized ANOVA analysis and the machining length was identified the factor with more influence:

- the machining forces increased with Lu, reaching maximum values at maximum machining length (around 700 N to Lu = 122 mm);
- the surface quality is better when the tool was horn, reducing R_a with the increase of the machining lengh (Lu). For Lu = 10 mm, were measured maximum values of surface roughness (Ra) and burr height (h), and for Lu = 122 mm, the minimum values;
- for residual stress, the increase of machining length generate tensile residual stress (150 MPa to Lu = 122 mm).

For the choosed range of cutting speed, the ANOVA analysis revealed that tool, cutting edge and machining length have the same level of influence on machining forces, but no influence of cutting speed in the range recommended by the tool manufacturer. It is recommended to investigate the range of cutting speed that provides the high-efficiency range.

5. ACKNOWLEDGEMENTS

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