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EXPERIMENTAL INVESTIGATION ON MACHINABILITY OF INCONEL 751

Anderson Clayton Alves de Melo, anderson@ufrnet.br[1]
Júlio César Giubilei Milan, milan@joinville.udesc.br[2]

[1]Universidade Federal do Rio Grande do Norte, Centro de Tecnologia, Departamento de Engenharia Mecânica, Campus universitário, S/N, Lagoa Nova, Natal/RN, CEP 59072-970
[2]Universidade do Estado de Santa Catarina, Departamento de Engenharia Mecânica, Campus Universitário Prof. Avelino Marcante, S/N, Bom Retiro, Joinville/SC, CEP 89223-100

Abstract: *Inconel represents a family of nickel-based super alloys with an wide range of application including components that work at high temperatures. In despite of this, nickel-based super alloys are generally known to be one of the most difficult materials to machine. In this paper, attention is focused on the machinability of Inconel 751 which is a nickel-based super alloy normally used to manufacture exhaust valves of internal-combustion engines. In this case, an experimental investigation where a series of dry and wet rapid facing trials (turning) using coated carbide tools were performed. Metal removing process was carried out for two different feed rates and two different tool geometries. For indirectly quantify the tool wear, the machined surface profile has been measured using a centesimal dial gauge. The results provide important practical information about the machinability of Inconel 751.*

Keywords: *Machinability, Inconel 751,Tool wear, Tool geometry.*

1. INTRODUCTION

Inconel 751 is a nickel-based super alloy containing at least 70% of nickel and others chemical elements such as Cr, Ti, Al, Fe, etc., which together with adequate heat treatment provide excellent properties such as high mechanical strength and corrosion resistance at elevated temperatures. These properties are very important in parts that work under intense thermo-mechanical stresses, like exhaust valves of internal-combustion engines. However, as normally happens for the most nickel-based superalloys, Inconel 751 is classified as difficult-to-machine material, that is, it presents poor machinability.

Unfortunately, literature about machinability of Inconel 751 is not common. In this case, the nickel-based super alloy most frequently studied is Inconel 718, because it stands out as the most dominant alloy in production, accounting for as much as 45% of wrought nickel-based alloy production and 25% of cast nickel-based products (Choudhury et al, 1998 and Loria, 1992). However, the problems concerning to machining of these two super alloys are so similar, which will be described in the next paragraphs.

According to Ezugwu et al (1999), the difficulty of machining nickel-based super alloy resumes itself into two basic problems: short tool life and severe surface abuse of machined workpiece, which are caused directly or indirectly by one or more of the following properties of them or by some phenomena correlated to these properties (Devillez et al, 2007; Dudzinski et al, 2004; Li et al, 2002; Jawaid et al, 2001; Sharman et al, 2001; Ezugwu et al, 1999; Choudhury and El-Baradie, 1998 and Rahman et al, 1997):

- ✓ A major part of their strength is maintained during machining due to their high-temperature properties;
- ✓ They are very strain rate sensitive and readily work harden, causing further tool wear;
- ✓ The highly abrasive carbide particles contained in the microstructure cause abrasive wear;
- ✓ The poor thermal conductivity leads to high cutting temperatures up to 1200^{o}C at the rake face (Kitagawa et al, 1997);
- ✓ Nickel-based super alloys have high chemical affinity for many tool materials leading to diffusion wear;
- ✓ Welding and adhesion of nickel alloys onto the cutting tool frequently occur during machining causing severe notching as well as alteration of the tool materials;
- ✓ Due to their high strength, the cutting forces attain high values, excite the machine tool system and may generate vibrations which compromise the surface quality;
- ✓ The heat generation and the plastic deformation induced during machining affect the machined surface, inducing to residual stresses, generation of cracks and microstructural changes, as well as large microhardness variations (Dudzinski et al, 2004; Ezugwu and Tang, 1995).

Thus, most of the major cutting parameters including, tool geometry, lubrication, cutting speed and feed rate, must be controlled in order to achieve adequate tool lives and surface integrity of the machined surface (Dudzinski et al, 2004; Ezugwu and Tang, 1995; Guerville and Vigneau, 2002).

Rahman et al (1997) presented a work which discusses the machinability of Inconel 718 subjected to various machining parameters including tool geometry, cutting speed and feed rate. Turning experiments were conducted under wet conditions. Multi Al_2O_3 CVD coated cemented carbide inserts were used. They studied the effect of the side cutting angle (SCEA) on the tool life for three feed rates (0.2, 0.3 and 0.4 mm/rev) and three cutting speeds (30, 40 and 50 m/min), the depth of cut was fixed to 2mm. Based on this work, Dudzinski et al (2004) presented a graph which shows the effect of SCEA on tool life for a cutting speed of 30 m/min and for the three feeds. It was verified that tool life increases when the SCEA increases from -5 to 45^o and when the feed rate reduces from 0.4 to 0.2 mm/rev.

In the present paper, results about an experimental investigation on the machinability of Inconel 751 are presented. Dry and wet rapid facing trials based on Bradsmann's test using coated carbide inserts have been carried out on a conventional lathe. Cutting speed, feed rate and tool geometry (rake and relief angle) were modified during the trials. Tool tip wear has been indirectly quantified by measuring the machined surface profile (flatness deviation) using a dial gauge.

In the following item the materials and the experimental procedure used in this work are presented.

2. MATERIAL AND METHODS

For this experimental investigation the workpiece was a cylindrical bar of Inconel 751 with length equal to 570mm, diameter equal to 96mm and with the following chemical composition: 0,06C; 0,13Si; 0,27Mn; 16,7Cr; 2,34Ti; 0,88Nb; 1,33Al; 6,97Fe; 0,001P; 0,001S; 0,04Co; 0,08Mo; 0,01V; 0,02W; 0,04Cu; rest Ni (% mass) and average hardness of 33.4 HRC.

TiN-TiCN-TiC coated carbide inserts, manufactured by Sandvik-Coromant was used as cutting tools. These inserts were set on two different toolholders specifically manufactured for this work (Fig. 1).

When the inserts were set on these toolholders and then on the lathe, the following tool geometries were defined (Fig. 2):

- Geometry 1 (G1): $\gamma_o = +2^o$; $\alpha_o = 23^o$; $\lambda_s = 0^o$; $\chi_r = 45^o$; $\varepsilon_r = 90^o$; r = 2mm.
- Geometry 2 (G2): $\gamma_o = +12^o$; $\alpha_o = 13^o$; $\lambda_s = 0^o$; $\chi_r = 45^o$; $\varepsilon_r = 90^o$; r = 2mm.

Where: γ_o – rake angle; α_o – relief angle; λ_s – back angle; χ_r – approach angle; ε_r – tip angle; r – tool-tip radius.

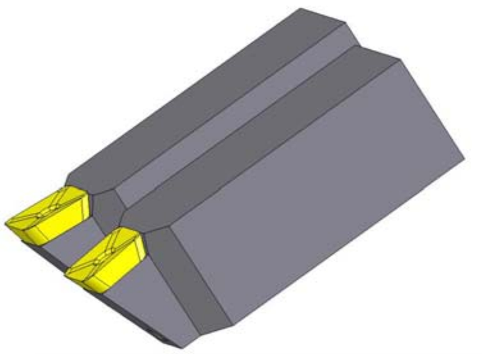

Figure 1. Drawing of toolholders used in the trials.

Figure 2. (a) Tool geometry G1 ($\gamma_o = +2^o$; $\alpha_o = 23^o$; $\lambda_s = 0^o$; $\chi_r = 45^o$; $\varepsilon_r = 90^o$; r = 2mm); (b) Tool geometry G2 ($\gamma_o = +12^o$; $\alpha_o = 13^o$; $\lambda_s = 0^o$; $\chi_r = 45^o$; $\varepsilon_r = 90^o$; r = 2mm).

The machining trials were carried out on an AMERICAN/Cincinnati conventional lathe with an available power of 15cv. The spindle rotation (n) of 256 rpm and depth of cut (a_p) of 1.0mm were kept constant during the trials.

For measuring the machined surface profile, a dial gauge with a resolution of 0.01mm was used.

Table 1 summarizes all the trials carried out.

Table 1. Summary of rapid facing tests carried out.

n = 256 rpm / a_p = 1.0 mm			
Condition	Feed (mm/rev)	Tool geometry	Cutting condition
1	0.038	G1	Dry
2	0.038	G2	Dry
3	0.155	G2	Dry
4	0.155	G1	Dry
5	0.038	G1	Wet
6	0.038	G2	Wet
7	0.155	G2	Wet
8	0.155	G1	Wet

For each condition showed in Tab. 1, 3 replicas using new cutting edges were performed.

Figure 3 shows the Inconel 751 bar positioned on the AMERICAN/Cincinnati lathe. It can be seen that the workpiece was fixed at one side using a three-jaw chuck and rested at the other by a center rest. The face of this last side was used for carrying out the rapid facing trials.

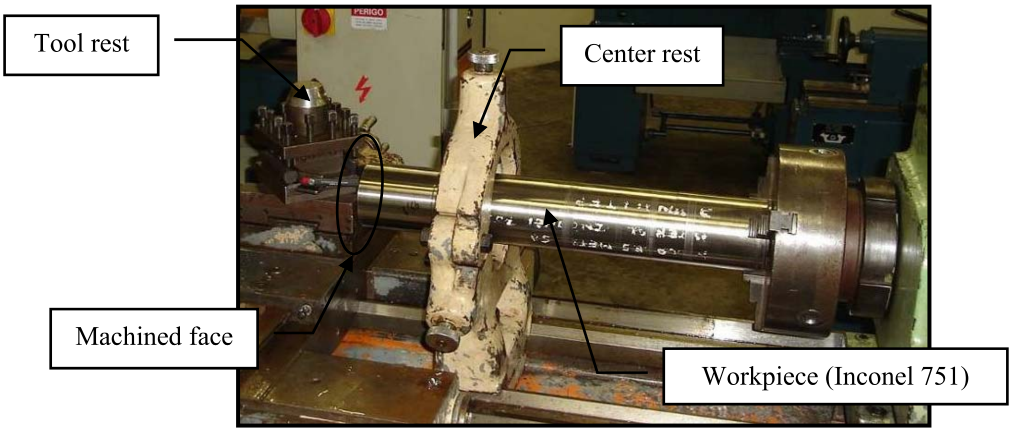

Figure 3. Workpiece set on the conventional lathe.

Each test listed in Tab. 1 was carried out throughout workpiece's face, always from the center towards the periphery. It is important to highlight that before each trial, a 10mm center hole was drilled on the workpiece's face to adjust previously the depth of cut of 1.0mm. Thus, the feed length (L_f) for all tests was 43 mm (Fig. 4). Then the cutting speed was modified from 8 to 77 m/min.

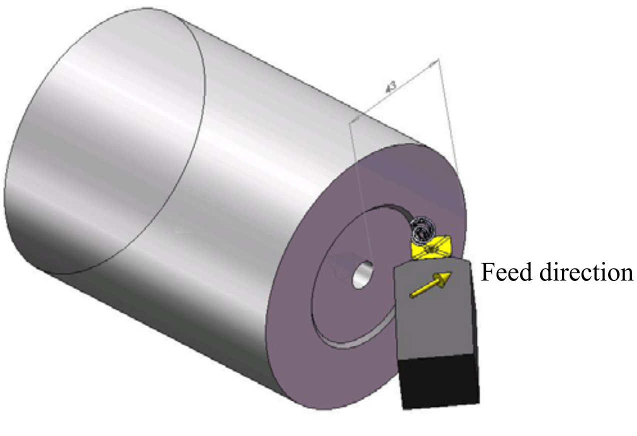

Figure 4. Cutting geometry configuration during face turning.

After each test (after L_f equal to 43 mm), the machined surface profile was measured with a dial gauge with resolution of 0.01 mm (Fig. 5). In this case, measurements along of the feed length (43mm) distanced of 0.508mm were performed. It is important to emphasize that these measurements were carried out three times on the same face on lines angularly distanced of 120° for obtaining an average value of flatness deviation at each point.

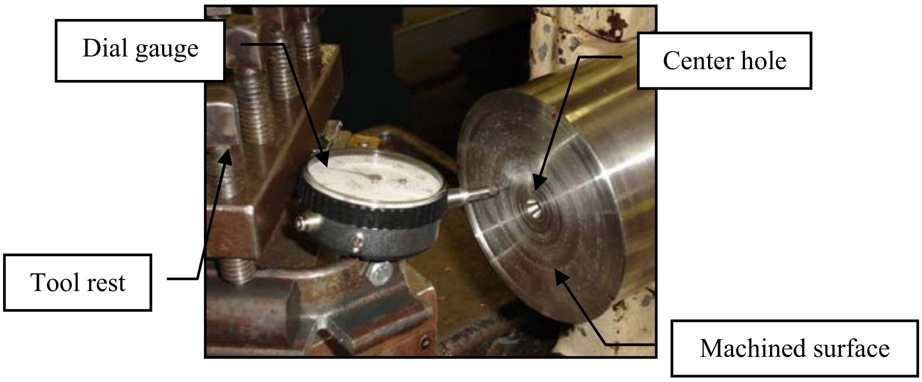

Figure 5. Measurement of the machined surface profile using a dial gauge.

Wet machining trials were carried out using a synthetic cutting fluid (10% of concentration) overhead applied at a flow rate of 2.5 l/min, see Fig. 6.

Figure 6. Application of the cutting fluid during wet trials.

3. RESULTS AND DISCUSSION

Figures 7 to 14 show the machined surface profile after machining at conditions 1 to 8, respectively. Each point represents the median obtained from 12 values of flatness deviation measured with the dial gauge, that is, as previously described in the experimental procedure, each test was repeated three times (thus, 4 tests with the same cutting condition, the same tool geometry and the same cutting parameters were performed). For each one of the 4 tests, the flatness deviation has been measured on the machined surface along of 3 lines distanced of 120°, at points linearly distanced of 0.508mm (3 x 4 = 12).

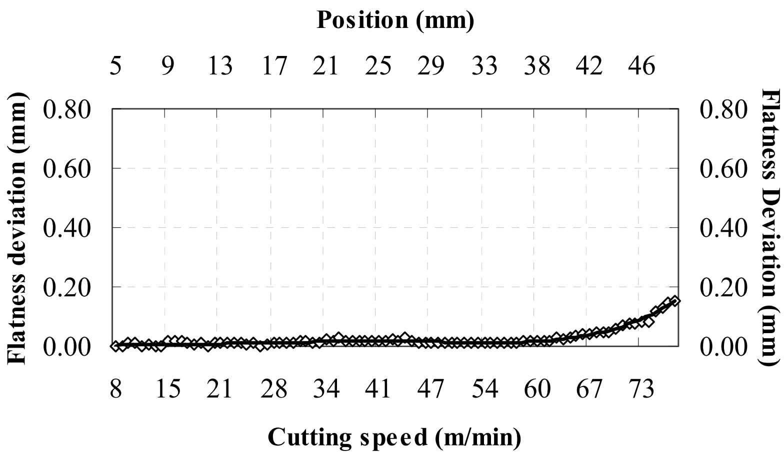

Figure 7 – Machined surface profile after machining at condition 1.

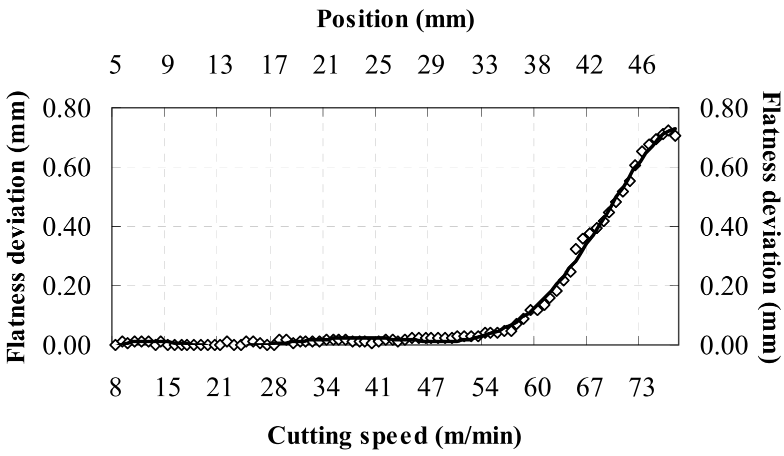

Figure 8 – Machined surface profile after machining at condition 2.

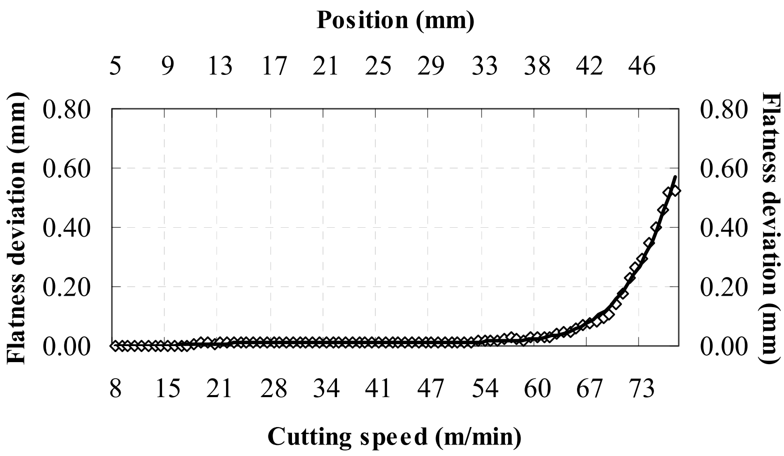

Figure 9 – Machined surface profile after machining at condition 3.

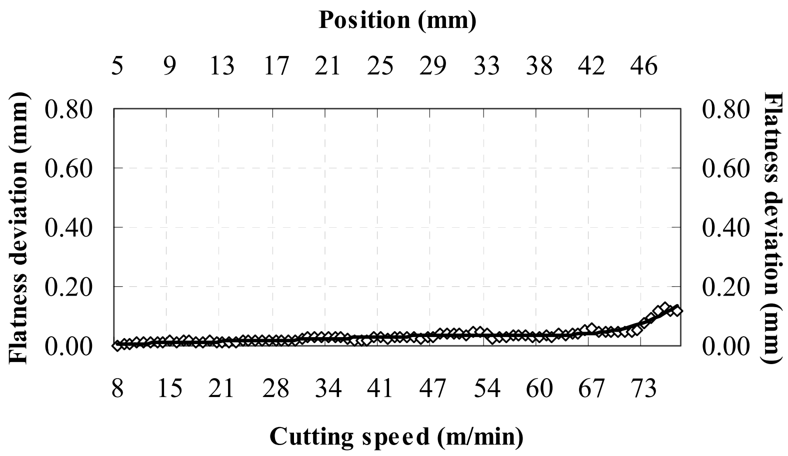

Figure 10 – Machined surface profile after machining at condition 4.

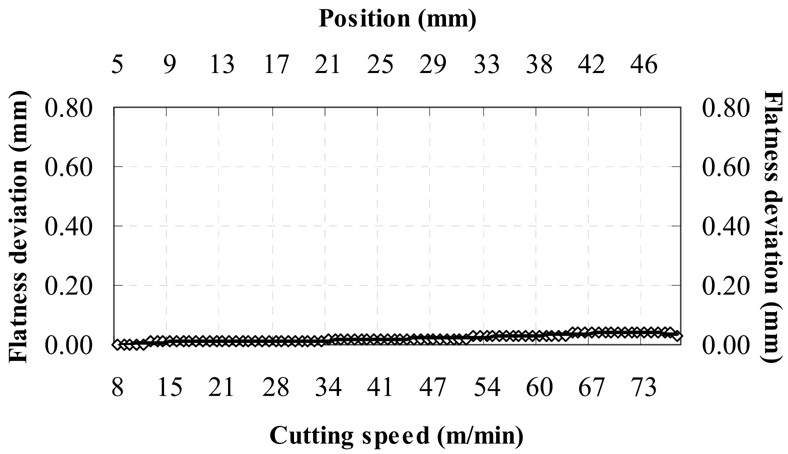

Figure 11 – Machined surface profile after machining at condition 5.

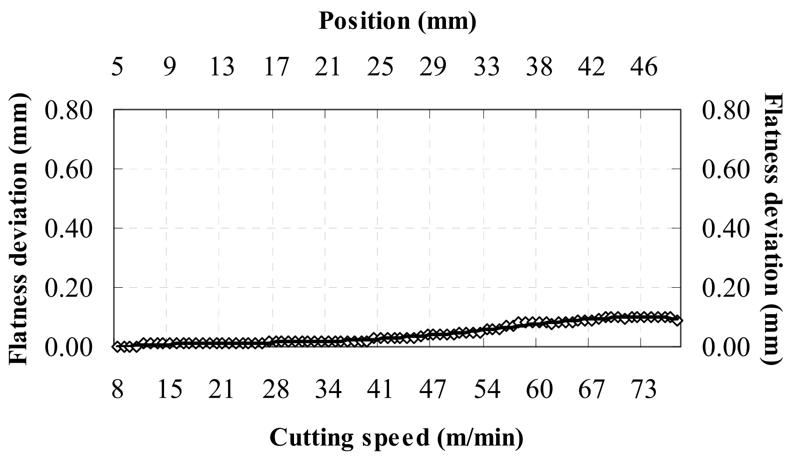

Figure 12 – Machined surface profile after machining at condition 6.

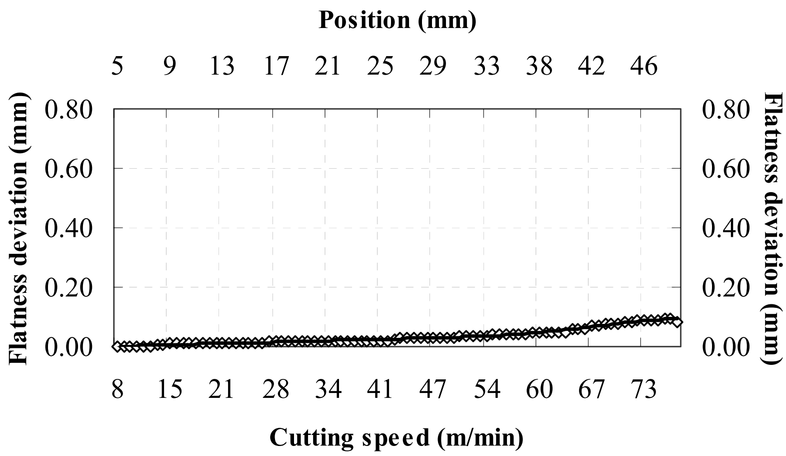

Figure 13 – Machined surface profile after machining at condition 7.

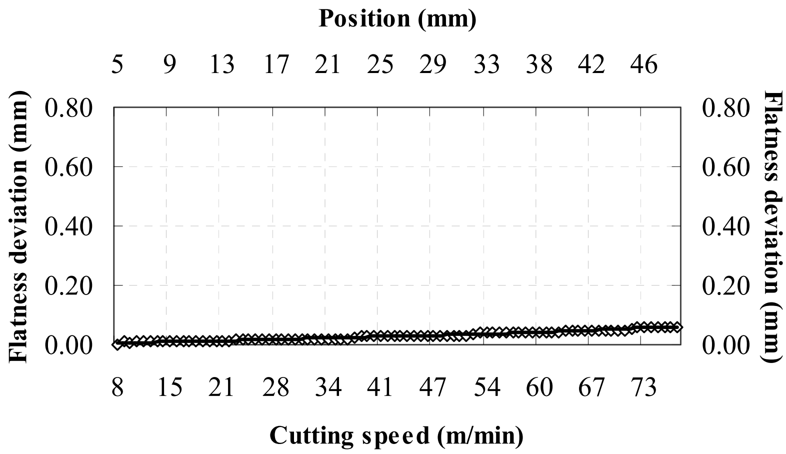

Figure 14 – Machined surface profile after machining at condition 8.

It can be seen in Fig. 7 that the flatness deviation underwent a little variation up to the position 39.04mm approximately (v_c=62.7 m/min). After this point, the deviation increases up to it attains the maximum value of 0.16mm.

Flatness deviation provides an estimate of the tool tip wear, which may be used for quantifying the machinability of the workpiece material for a particular cutting condition. In the case of figure 7, insignificant tool wear was verified up to the cutting speed reaches approximately 62.7 m/min. Some authors (Dudzinski et al, 2004; Choudhury and El-Baradie, 1998) have reported that the cutting speeds employed for machining nickel-based super alloys using cemented carbide tools under dry conditions, are in the range of 20-30 m/min and up to 50 m/min for coated tools. Thus, when the cutting tool attained the position 39.04mm (approximately) the cutting speed was already higher than the limit recommended of 50 m/min. At the cutting speed of 62.7 m/min it is believed that the chip-tool interface temperature is very high when machining Inconel 751 which motivates the development of thermally activated wear mechanisms. A work by Itakura et al (1999) has demonstrated that the cutting temperature at 30 m/min was 717^{o}C, when dry turning Inconel 718 with cemented carbide tools (P20, TiN/TiC multilayered coating).

For cutting speeds lower than 62.7 m/min, the flatness deviation was very close to zero, indicating insignificant tool tip wear. It is believed that for lower cutting speeds, it is possible to verify the presence of Built-up-edge (BUE) which protects the cutting wedge against the development of wear mechanisms. This phenomenon was observed by Liao and Shiue (1996) when they dry turned Inconel 718 with K20 and P20 cemented carbide tools at a cutting speed of 35 m/min.

Figure 8 shows the machined surface profile after machining at condition 2. It is important to highlight that the only difference between conditions 1 and 2 is the tool geometry, that is, for condition 2 the cutting tool has a relief and rake angles equal to 13^o and +12^o, respectively, against +23^o and 2^o for condition 1.

It is possible to observe in Fig. 8 an insignificant variation (around zero) of the flatness deviation up to approximately the position 30.91mm (v_c=49.7 m/min). Beyond this point, the deviation increases exponentially up to the maximum value of 0.73mm. A small drop is observed at the extremity of the workpiece due to the negative displacement of the feeler gage in this region.

Two observations can be made when comparing the behavior of flatness deviation for conditions 1 and 2:

- **First:** when condition 2 was used, the beginning of the exponential curve has occurred earlier than when machining under condition 1;
- **Second:** The rate of tool wear evolution under condition 2 has been faster than when the condition 1 was used, which has contributed to increase the value of maximum deviation at that condition.

In general the observations aforementioned indicate best machinability of Inconel 751 when condition 1 was used (in comparison with condition 2), that is, the use of the tool geometry G1 was more favorable than geometry G2, considering dry cut and feed rate of 0.038 mm/rev. A smaller relief angle of condition 2 increases the contact area between flank surface and the new fresh workpiece surface, intensifying friction and cutting temperature, which promotes tool wear acceleration.

Figure 9 shows the machined surface profile after machining at condition 3. It can be seen a slight variation (around zero) of the flatness deviation up to the position 34.46mm (v_c=55.4 m/min). From this point, the flatness deviation undergoes an exponential increase up to the maximum value of 0.53mm.

It is possible to verify a similar behavior when comparing the results obtained from conditions 2 and 3 (the same tool geometries, but different feed rates). A little advantage for condition 3 is observed, because the beginning of the exponential behavior occurs approximately at the position 34.46mm, while for condition 2, this one occurs at the position 30.91mm. Moreover, the maximum flatness deviation verified for condition 2 (0.73mm) was larger than that one measured at condition 3 (0.53mm).

Another interesting observation comparing conditions 2 and 3 it is that the exponential curve at condition 2 rises slightly faster than for condition 3, as can be verified through the values of flatness deviation for the positions 40.05mm e 45.13mm (See Tab. 3).

Table 3. Flatness deviation measured at different points after machining at conditions 2 and 3.

	Position 1 (mm)	Deviation 1 (mm)	Position 2 (mm)	Deviation 2 (mm)	Variation of the flatness deviation (mm/mm)
Condition 2	40.05	0.25	45.13	0.61	0.071
Condition 3	40.05	0.05	45.13	0.27	0.043

The behavior depicted in Tab. 3 can be explained by analyzing the times of machining and the trybological situation at each cutting condition. At condition 2 (feed rate of 0.038 mm/rev) the time for the cutting tool to traverse all length of feed is equal to 4.42 min, while this time is 1.08 min at the condition 3 (feed rate of 0.155 mm/rev). That is, when machining at condition 2, the time of contact between tool and workpiece is about 4 times higher than when machining at condition 3, for a same length of feed. Thus, despite the heat generation and cutting temperatures to be higher at condition 3, due to the higher feed rate at this condition, the cutting time is shorter, reducing the time of trybological interaction among tool, workpiece and chip and, consequently, the rate of tool tip wear.

When the results obtained at conditions 3 and 1 are compared, it is clearly that condition 1 was the best, certainly due to its larger relief angle.

Figure 10 shows the machined surface profile after machining at the condition 4. It is possible to observe a slight and continuous increase in the flatness deviation up to approximately the position 44.62mm (v_c=71.7 m/min), when the interpolation curve undergoes a change of inclination, that is, the tool undergoes an increase of its wear rate. In this case, the maximum value observed was 0.13mm at the position 47.16mm. When the results for this condition are compared with that one obtained for the condition 3, where the only difference between both conditions is the cutting tool geometry (condition 3 – G2 and condition 4 – G1), it is clear that the best performance was obtained at condition 4. This result reinforces the negative influence of a small relief angle for machining Inconel 751.

Now, when comparing condition 1 with the condition 4, it can be seen a discrete advantage for the last one, considering that the larger flatness deviation measured at this condition was of 0.13mm against 0.16mm for condition 1.

Some partial conclusions can be given based in the results presented for the dry trials:

- Tool geometry G1 gave better results than tool geometry G2. It is believed that the relief angle has influenced strongly in this result;
- Higher feed rate gave better results than smaller feed rate. It is believed that the time of contact tool-workpiece (with intense friction) at this last condition was determinant in this result.

Figure 11 shows the machined surface profile after machining at condition 5. It can be seen a significant improvement on the evolution of the wear behavior, comparing to any dry conditions previously presented.

Comparing the results obtained at conditions 1 (dry) and 5 (wet), which have the same tool geometries and the same cutting parameters, it is clear the improvement on the machinability of Inconel 751 caused by introduction of cutting fluid. The maximum value of flatness deviation observed at the condition 5 was of 0.04mm, four times smaller than that one verified at condition 1, equal to 0.16mm.

It is known that the use of water-base cutting fluid in a machining process, causes a drop of the cutting temperature by the cooling action and a reduction of the friction between the contact surfaces (tool-workpiece-chip), by the lubricant action, inhibiting the development of wear mechanisms such as oxidation, abrasion, attrition, etc., which helps to maintain the cutting tool edge for longer periods.

Figure 12 shows the machined surface profile after machining at condition 6. When comparing the graphic shown in Figs. 11 (condition 5) and 12 (condition 6), it can be seen a better performance for the condition 5, which presented a maximum value of flatness deviation of 0.04mm, against 0.1mm obtained for the condition 6. It is important to highlight that the only difference here is the cutting tool geometry (G1 for the condition 5 and G2 for the condition 6, both under wet condition). Again it is believed that the relief angle is the main parameter of influence here.

When the results obtained for the conditions 2 and 6 (same cutting parameters, same tool geometry, however dry cut and wet cut, respectively) are compared it is evident the advantage for condition 6, which proof one more time the improvement on the machinability of the workpiece material when cutting fluid was introduced.

Figure 13 shows the machined surface profile after machining at condition 7. When the graphics of profiles for conditions 6 (Fig. 12) and 7 (Fig. 13) are compared, it can be observed that the maximum flatness deviation for both conditions was of 0.1mm, which indicates insignificant tool wear variation when feed rate was modified from 0.038 mm/rev to 0.155 mm/rev. The same result wasn’t verified for dry machining (when conditions 2 and 3 are compared). It is believed that the cutting fluid has presented a good efficiency during machining even with a smaller relief angle (geometry G2).

Figure 14 shows the machined surface profile after machining at condition 8. It can be seen a behavior so similar to the observed for the condition 5, where the only different parameter between the two conditions is the feed rate. It is possible to verify a maximum flatness deviation of 0.06mm for the condition 8, very close to that one verified for the condition 5 of 0.04mm. This is a result very similar to the described in previous paragraph, but now the tool geometry is G1. Thus, it is possible to conclude that for wet machining, the change of feed rate from 0.038 mm/rev to 0.155 mm/rev has caused little influence on the tool wear. The cutting fluid decreased the cutting temperature and produced a thin film at the chip-tool interface (at the sliding zone) which aid to reduce the tool tip wear.

Some partial conclusions can be given based in the results above presented for the wet trials:

- All wet conditions have presented better results than any dry condition, certainly due to the effect of cooling and lubrication of the cutting fluid which to reduce the cutting temperature and friction, hindering the development of the wear mechanisms on the cutting tools;
- The maximum flatness deviation has undergone little variation when the feed rate was modified from 0.038 mm/rev to 0.155 mm/rev.

4. CONCLUSIONS

- Wet machining provided better results than dry machining;
- Tool geometry with a small relief angle was very harmful to machine inconel 751;
- The cutting condition that provides best machinability of inconel 751 was that one with a slower feed rate, larger relief angle, smaller rake angle and wet, and the cutting conditions that provides worse machinability of inconel 751 was that one with slower feed rate, smaller relief angle, larger rake angle and dry.

5. ACKNOWLEDGEMENTS

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