Surface integrity in finishing turning of Inconel 718

J. Díaz, A. Díaz-Álvarez, X. Soldani, J.L. Cantero, H. Miguélez

(1) Department of Mechanical Engineering, Universidad Carlos III de Madrid, Avda. Universidad 30, 28911, Leganés, Madrid (jodiaz@ing.uc3m.es)

ABSTRACT
Ni alloys are used in high responsibility applications in different industrial sectors. Their excellent mechanical properties give advantages during service life of the component but also implies low machinability because of the severe thermo-mechanical loads at the tool-chip interface resulting in significant wear of the tool and machined surface damage. Tool life should be defined accounting not only for tool durability but also for surface integrity of the component. In this paper surface integrity of the workpiece and tool wear are analyzed in finishing turning of Inconel 718. On the other hand, numerical modeling gives qualitative information about difficult to measure variables related with tool wear and surface state.

Keywords: Inconel 718, turning, tool wear, surface integrity, numerical modeling

1. Introduction
Nickel-based superalloys are widely used in aerospace applications due to their excellent mechanical properties at high temperature and elevated corrosion resistance. Machining of these alloys is still a challenge since characteristics of superalloys induce severe thermo-mechanical loads at the tool-chip interface resulting in significant wear of the tool [1] and could also affect surface integrity of the component [2]. Surface integrity is critical for the components submitted to high thermal and mechanical loads during their use in high responsibility applications [3].

Strong work hardening induced during machining of Ni alloys influences both surface integrity and tool wear. Highly deformed material at the machined surface is related with elevated hardness and residual stress affecting service life of the component [4,5]. Tool wear mechanisms also depend on the elevated stresses and temperatures at the cutting edge. Notch formation, commonly observed when machining Ni alloys, is due to work-hardened layer. Flank wear, chipping, BUE and catastrophic failure also cause tool rejection during machining of Ni alloys [6].

Surface integrity is also affected by tool wear evolution [7], thus tool life criteria should be established avoiding machining induced damage in the workpiece [8].

Valuable experimental work concerning surface integrity and tool wear when machining Ni alloys can be found in the literature, see recent advances in a recent review [9]. On the other hand numerical modeling, commonly based on finite elements (FE), offers a useful tool for machining analysis of difficult to cut materials such as Inconel 718, giving information about difficult to measure variables during cutting.

FE simulation of tool wear and surface state of the workpiece requires the use of three dimensional (3D) models able to reproduce the complex geometry of the tool [10-12]. Main drawback of the 3D modeling is the elevated computational cost especially when small elements are required. Although different authors have developed 3D models of cutting of advanced materials [10-13], most studies are focused on two dimensional (2D) approaches giving valuable information about residual stresses [7], contact phenomena [14,15] or damage at the machined surface [16]. For instance a two dimensional (2D) finite element tool wear model able to predict the worn geometry quantitatively in cemented carbide tool machining nickel-based alloys was presented in [17]. The influence of different wear and friction models on parameters affecting the wear progression was investigated.

Residual stresses induced during machining of Inconel 718 have been analyzed in different works in the literature, see for instance [18,19]. Despite the dispersion in results inherent to the different configurations of machining adopted in each work, high levels of tensile residual stresses are commonly observed when machining Inconel 718, being detrimental to component service life. Parallel analysis of
tool wear evolution and surface integrity indicators should be done, since the tool life criterion should take into account surface integrity indicators.

This work focuses on the analysis of surface integrity in finishing turning of Inconel 718. Experimental analysis and numerical modeling have been carried out. The aim of the experimental work is showing the relation between tool wear and surface integrity. Numerical modeling based on a 2D approach has been carried out with the objective of analyzing the influence of cutting speed in predicted residual stresses.

2. Experimental work

Finishing turning tests were carried out in a lathe Pinacho Smart turn 6/165, and cutting forces were measured with a dynamometer Kistler 9257B for model validation. The workpiece was Inconel Alloy 718 annealed 968ºC held for 50 minutes, water cooled, shaped as a disc with diameter 150 mm and thickness 20 mm. Tool positioning, at constant cutting speed, is indicated in Fig. 1, the longitudinal tool axis was parallel to the lathe axis.

Three commercial carbide diamond shaped cutting inserts, were used for finishing turning of Inconel 718 using coolant. All inserts presented tip angle equal to 80º and tip radius equal to 0.4 mm. two different substrates, recommended by the tool manufacturer for Ni alloys, were CP500 and TS2000 with the same multilayer coating (inner layer TiAlN and external layer TiN).

Two different configurations of the cutting edge (E1 and E2) suitable for finishing turning of superalloys, were considered for the inserts based on substrate TS2000. E1 was a sharp cutting edge that gives easy-cutting properties and E2 was robust and proper for finishing operations. The inserts based on CP500 substrate had the configuration E1, while both E1 and E2 were used for substrate TS2000. The inserts were positioned with two different values of the side cutting edge angle ($\kappa_r = 0^\circ$ and 45\(^\circ\)). Thus four different insert configurations denoted T1, T2, T3 and T4 were tested (see table 1).

<table>
<thead>
<tr>
<th>Table 1. Tools used in turning tests</th>
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<td>Tool</td>
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<tr>
<td>T1</td>
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<td>T2</td>
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<td>T3</td>
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<td>T4</td>
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Turning tests were carried out at 50 and 70 m/min those are in the range recommended by the tool manufacturer for finishing turning of Inconel. Tool wear evolution was analyzed for the velocities 50 and 70 m/min and the details can be found in a previous work of the authors [1].

Cutting forces were measured in each test. Turning tests were systematically stopped in order to analyze wear evolution using optical microscope and SEM-EDS technique was used to verify the initial geometry of the fresh cutting edge and to analyze the final state of wear at the end of tool life.
2.1 Cutting forces and tool wear evolution

The components of the cutting force in directions of cutting speed, feed and depth of cut are denoted cutting force $F_c$, thrust force $F_t$, and axial force $F_a$, respectively, and presented in Fig. 2. Similar values of the components of cutting force were observed for fresh tools $T_1$ and $T_2$. The component $F_c$ was also similar for tools $T_3$ and $T_4$. However increased values of $F_t$ and $F_a$ (10-25%) were measured for the tool $T_3$ (cutting edge $E_2$ with decreased effective rake angle) when compared with $T_1$ and $T_2$. The tool $T_4$ presented a significant increment (70-120%) in the component $F_t$ because of the inclination of the cutting edge and the enhanced specific cutting force due to the change of edge position ($45^\circ$).

Combination of different wear mechanisms was observed: notch wear, flank wear, workpiece material adhesion (built up edge, BUE) and chipping at the cutting edge. The end of tool life criterion corresponds in each case to different geometrical configuration of the worn tool. Thus it is difficult to observe clear trends concerning cutting forces at the final wear stages of the tools. As is commonly observed, cutting forces were higher for worn tools when compared with those obtained for new inserts. Cutting force $F_c$ was larger for worn tool than for fresh tool (between 50-115%). Radial and axial components ($F_t$ and $F_a$) showed much larger increments (between 40-400%). Forces for worn $T_4$ insert were more elevated than those observed for $T_2$, especially the axial component of the force. These observations are related to the lower uncut chip thickness with $\kappa_r 45^\circ$ causing an enhanced influence of the damaged cutting edge on the cutting forces.

![Figure 2: Components of cutting force measured with fresh and worn tool](attachment:fig2.png)

Wear analysis showed dominant notching in the case of $T_1$, leading to reduced tool life, lower than 5 min. Significant level of BUE, chipping and notch wear were found in the case of $T_2$; tool lives were 15 and 5 min for low and high velocity respectively, breakage of the tool was due to chipping. The same wear patterns as those reported for edge configuration $E_1$ were observed for $T_3$: BUE, chipping and notch wear, and tool lives are comparable. However, the use of the robust edge configuration $E_2$ increases edge resistance to chipping, while notch wear was dominant leading to tool lives lower than 10 min.

The increment of $\kappa_r$ in the case $T_4$ diminished the undeformed chip thickness and pressure at the cutting edge decreased; flank wear was dominant. In consequence, tool life increased significantly up to 30.5 min and 6.5 min in the tests at low and high velocity respectively. $T_4$ demonstrated the best behavior under the point of view of insert durability.

2.2 Surface integrity

Surface integrity was evaluated in terms of roughness, residual stress and microhardness at the machined surface. Surface roughness was obtained from five measurements of the average roughness ($Ra$) at four different points in the surface (total number of measurements equal to 20). The surface roughness at the machined surface was taken as the maximum value of the twenty average roughness ($Ra$) measurements. Maximum standard deviation of the measurements was 0.5 micrometer. According to International Standard Organisation ISO 4287, the evaluation length was set equal to 4 mm and the cut-off length was fixed equal to 0.8 mm.
Small variations in Ra were be observed for different tool configurations, probably due to the different edge geometry (chamfered or not) and to the different side cutting edge angle. Comparison between surface roughness obtained with tool T2 and T4 is shown in figure 3.

![Roughness comparison T2 VS T4](image)

**Figure 3. Roughness at the machined surface for T2 and T4**

The residual stresses at the machined surface both in cutting and feed direction (0°, 90°) was measured in the Technological Center IDEKO. Values of residual stresses are shown in figure 4. Small differences between worn and fresh tool are observed in the case of T1, T2 and T3, however significant differences are observed in the case of T4. This insert presented the best durability however the risk for surface integrity of using the tool during a long cutting time should taken into account when defining tool life.

![Residual stresses at the surface obtained after turning with fresh and worn tool.](image)

**Figure 4: Residual stresses at the surface obtained after turning with fresh and worn tool.**

Microhardness was measured with a device ZWICK/ROELL ZHV 2.5. The test consists in forcing a diamond indenter in the form of a right pyramid with a square base and an angle of 136° between the opposite faces at the Vickers pyramid, into the surface of a specimen. Microhardness is shown in figure 5. Maximum differences between worn and fresh tool are observed for T1, however the inserts T2, T3 and T4 presented slight increase of microhardness when machining with worn tool.

![Microhardness at the machined surface for worn and fresh insert](image)

**Figure 5. Microhardness at the machined surface for worn and fresh insert**
3. Numerical model

A plane strain 2D model was developed using the commercial Finite Element code ABAQUS with Lagrangian formulation. Thermo-resistant alloys such as Inconel 718 experience chip segmentation at elevated cutting speed, Lagrangian formulation was preferred over ALE because simulations can reproduce localization phenomena. The objective is analyzing trends concerning residual stresses when the cutting speed is increased up to very high speed.

The analysis was carried out in two steps: first step simulated cutting, using an explicit integration scheme; and second step reproduced cooling and unloading, using an implicit integration scheme proposed in [20]. The residual stress distribution was averaged from different zones of the machined surface.

A thermo-mechanical coupled analysis was developed by using CPE4RT element type in ABAQUS/explicit those are plane strain, quadrilateral, linearly interpolated, and thermally coupled elements with reduced integration and automatic hourglass control.

The basic geometry and dimensions of the numerical model are shown in Fig.6. The workpiece is fixed at the lowest contour and the cutting speed is applied to the tool. Cutting develops under plane strain conditions. Tool geometry reproduces cutting edge geometry of E1.

**Figure 6: a) Scheme of the numerical model; b) Equivalent plastic strain fields at cutting speed xx, chip segmentation is observed**

Feed was equal to 0.1 mm/rev. The feed rate was stated during the experimental tests (previously described) equal to 0.1 mm/rev, however the geometry of the edge lead to a chip with a variable feed from the nominal value ($\kappa_0$) to small values at the tool tip. This fact is a limitation of the model, giving just qualitative information when compared with oblique cutting developed in the experiments.

A wide range of cutting speed values are analyzed (50 - 2400 m/min), turning test are performed at conventional velocity, however it is interesting to know the evolution of predicted surface integrity indicators with cutting speed. Validation was performed comparing specific cutting forces with experimental tests and residual stresses with values presented in the literature [18].

Erosion criterion was stated as the maximum level of the equivalent plastic strain above which mesh elements are erased. The level of was equal to 4 in the chip (this value is stated in order to remove just few highly distorted elements, most elements remained active in the model). The geometrical and numerical characteristics of the model allowed the simulation of orthogonal cutting in the range of velocities studied avoiding excessive mesh distortion that would lead to the end of calculation.

The tool was assumed to be rigid. The workpiece material was taken to be elastic-viscoplastic, isotropic, and to obey to the J2 flow theory (based on the von Mises yield function). The viscoplastic constitutive response was described by the Johnson-Cook law (Johnson and Cook, 1983):

$$\sigma = \left(A + B\varepsilon^p\right) \left[1 + C \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right] \left[1 - \left(\frac{T - T_0}{T_h - T_0}\right)^n\right]$$  \hspace{1cm} (1)
where $\sigma_T$ is the tensile flow stress, $\varepsilon_p$ is the cumulated plastic strain, $\dot{\varepsilon}_p$ is the equivalent Mises plastic strain rate and $T$ is the absolute temperature. For Inconel 718 alloy, the parameters of the constitutive equation were obtained from [21] and are shown in table 1.

<table>
<thead>
<tr>
<th>A (MPa)</th>
<th>B (MPa)</th>
<th>n</th>
<th>C</th>
<th>m</th>
<th>$\dot{\varepsilon}_0$ (s$^{-1}$)</th>
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<tr>
<td>980</td>
<td>1370</td>
<td>0.164</td>
<td>0.02</td>
<td>1.03</td>
<td>1.0 E-3</td>
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</table>

Concerning heat generation due to plastic work the value of the Quinney-Taylor coefficient was taken as $\beta=0.9$. The initial temperature $T_0$ for both the tool and the workpiece was equal to 293 K, the melting temperature was 1900 K. Thermal conductivity and other physical constants of tool and workpiece materials were obtained from literature.

The contact at the tool-chip interface was simulated with the simple law of Coulomb: constant value of the friction coefficient is assumed (0.4). It has been shown in previous works of the authors the ability of this formulation to reproduce complex phenomena including thermal softening and sticking at the interface chip-tool [14,15]. The model was validated in terms of cutting forces showing reasonably accuracy.

The limitations of the model should be noted. Firstly the model is 2D while the tests presented previously have been obtained during machining with an insert with a tool nose radius comparable to feed and depth of cut. Secondly the effect of successive passes lead to a significant work hardening of the machined surface increasing resultant residual stress. Thus the numerical results give qualitative information concerning the trends observed with cutting speed.

3.1 Residual stresses

The profiles of the in depth distribution of residual stresses beneath the machined surface are presented in figure 7 for a wide range of cutting speed. The level of tensile residual stress at the machined surface increases with cutting speed at low velocities, however it remains almost constant for values higher than 5 m/s. This result agrees with a previous work of the authors where similar behavior was found for other materials such as stainless steel and Ti alloy [21].

Tensile residual stresses increases in the vicinity of the machined surface when the cutting speed is augmented due to two main physical mechanisms. The first one is related to the transition to adiabatic conditions and the associated thermal softening of the workpiece material. Adiabatic conditions are reached for a critical value of the cutting velocity which depends on the material considered. The second mechanism contributing to the increasing of residual stresses is friction softening. At high cutting speeds, the friction coefficient at the tool-chip interface is reduced. In turns, higher residual stresses are generated. At high enough cutting velocities adiabatic conditions are reached and the friction coefficient is stabilized; therefore residual stresses are no more dependent upon the cutting speed.

4. Conclusions

In this paper experimental analysis of finishing turning of Inconel 718 is presented. Four different inserts configuration have been tested at conventional cutting speeds. Tool wear evolution showed combined tool wear mechanisms. The best durability was found for the insert $T_4$ having a side cutting edge angle equal to 45°.

Residual stresses at the surface, roughness and microhardness were measured. Although roughness and microharness did not show significant differences for the insert $T_4$, it was found that the level of residual stress was the highest in this case. The origin of residual stresses is related with deformation and also with thermal phenomena at the interface. The competition between these factors resulted in high values of residual stresses, higher than 1GPa; for the insert $T_4$. On the other hand this tool presented the best durability, thus tool life should be stated from the compromise between both aspects.

Numerical modeling was developed with the aim of analyzing the influence of cutting speed on residual stresses. The model simulated orthogonal cutting of Inconel 718. It was found that the increase of cutting speed raises tensile residual stresses however a stabilization of these stresses is observed at high cutting speeds. This result could be important for practical applications at high speed machining.
5. Acknowledgements

The authors are indebted for the financial support of this work, to the Ministry of Economy and Competitiveness of Spain (project DPI2008-06746)

6. References

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