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Influence of tool wear on residual stresses when turning Inconel 718

A.Madariaga*, A. Kortabarria, E. Hormaetxe, A. Garay, P.J. Arrazola

Mondragon Uniberstitatea, Faculty of Engineering, Loramendi 4, Arrasate-Mondragón, 20500, Spain

* Corresponding author. Tel.: +34 943 71 22 74; fax: +34 943 71 19 21. *E-mail address:* amadariaga@mondragon.edu

Abstract

This paper analyzes the effect of tool wear on residual stresses when turning. Inconel 718 discs were machined for prolonged periods at several cutting speeds, feed-rates and depth of cut. Tests were interrupted to measure and relate tool wear with the subsequent residual stress measurements. The discussion of experimental results is supported by orthogonal cutting simulations. It was found a critical tool wear where tensile surface residual stresses were maximum, decreasing for lower and higher values of tool wear. Nevertheless, it was observed that the compressive residual stress layer increased with increasing tool wear.

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Keywords: Residual Stress, Turning, Wear

1. Introduction

Titanium and nickel based alloys are extensively used to manufacture aero-engine components as they possess excellent mechanical and chemical properties at high temperatures. Nevertheless, they are very difficult to machine and if appropriate machining conditions are not used the surface integrity can be negatively affected and therefore the final behavior of the component.

The level of tensile residual stress generated during cutting is one of the most important characteristic of the surface integrity of the machined component [1]. Together with cutting conditions, tool geometry and wear are major variables in residual stress generation [2]. For this reason, many researchers have focused their studies on analyzing the effect of tool wear on machining induced residual stresses.

In general, surface tensile residual stresses increase as well as the depth of the compressive residual stress layer when machining with worn tools [3]. For instance, Liu *et al.* [4] observed higher tensile residual stresses and deeper compressive layers when hard turning JIS SUJ2 bearing steel with worn tools than with new tools for different nose radius. El-Wardany and co-workers [5] also reported more tensile residual stresses in the near surface when hard turning D2 tool steel with slightly worn tools (0.15 mm flank wear). More recently, Sharman *et al.* [6] also found higher surface residual stresses in Inconel 718 with increased tool wear.

However, some authors have reported contradictory trends when machining with worn tools. For instance, in an earlier study Sharman *et al.* [7] found that surface residual stresses in the cutting direction increased when turning Inconel 718 with worn coated cemented carbide tools at cutting speeds of 40 $m \cdot min^{-1}$ and 80 $m \cdot min^{-1}$, but they decreased when machining at 120 $m \cdot min^{-1}$. In each of the cases, the feed-rate was of 0.25 $mm \cdot rev^{-1}$ and the depth of cut of 0.25 mm. Recently, Muñoz-Sanchez *et al.* [1] analyzed experimentally and numerically the effect of flank and crater wear on surface residual stresses induced when machining Inconel 718 at constant cutting speed, feed rate and depth of cut. They found that surface residual stresses were higher when flank wear was increased. By contrast, surface residual stresses with the largest crater wear were lower than with the smallest crater wear used in their tests.

Although there is a general agreement in the literature about the effect of tool wear on residual stress generation some contradictory trends have also been reported. As tensile surface residual stress can play an important role in the fatigue behavior of the machined component, it is important to

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understand the influence of tool wear on machining induced residual stresses. This paper is aimed at understanding the effect of flank wear on residual stresses. For that purpose, Inconel 718 discs were machined for prolonged periods at several cutting speeds, feed-rates and depth of cuts, and residual stresses were measured by the fine hole-drilling technique [8]. In order to explain qualitatively the thermal and mechanical effects on the residual stresses induced by worn tools, orthogonal cutting simulations were also carried out.

2. Methodology

2.1. Materials and experiments

Aged hardened Inconel 718 rolled plates were selected for this study. First, these plates were cut by waterjet to obtain ring shaped parts. Fig. 1 shows the geometry of these parts. Then, the ring shaped parts were placed in a Danobat TV700 vertical lathe. The upper and lower intermediate surface of the rings were face turned initially to obtain a 0.01-0.05 mm flatness tolerance. After that, finish face turning trials were carried out at two cutting speeds (30; 80 m·min^{-1}), two feed-rates (0.1; 0.4 mm·rev^{-1}) and two depth of cuts (0.1; 0.5 mm). All the rings were machined with coolant using a 4 mm nose radius fresh cemented carbide tool for each cutting condition.

The face turning tests were conducted for long cutting periods through successive passes. When cutting a new pass, the last 5 mm of the preceding pass (measured in the radial direction) were not machined. Consequently, the cross section of the ring showed a step corresponding to each cutting pass as shown in Fig. 2. Residual stress profiles were measured employing the fine increment hole-drilling technique [8] in the hoop direction (cutting direction) and radial direction (feed direction) at the surface of these steps. The uncertainty of residual stress measurements was evaluated based on the procedure described in [9]. In fact, these steps allowed identification of the cutting conditions and machining time or degree of tool wear.

Flank wear was measured during machining trials. For that purpose, after finishing a pass the tool holder was moved to a determined position in the lathe and an image of the tool edge was captured with a camera.

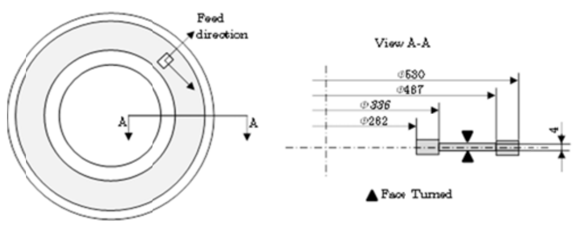

Fig. 1. Geometry of the ring shape parts

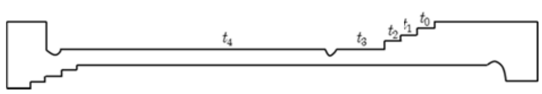

Fig. 2. Example of a cross section after machining the upper surface

2.2. Finite element model

A 2D orthogonal cutting model was developed to analyze qualitatively the influence of flank wear on the residual stresses generated during machining. The chip formation was modelled with Deform v10.2, which is a finite element program specific for metal forming. Based on lagrangian formulation, a coupled thermo-mechanical model was used, and aimed at solving the problems associated with the chip formation process. A continuous remeshing strategy was adopted.

Inconel 718 input data were defined according to the NASA Military Handbook [10]. Based on the work of Mitrofanov *et al.* [11], a Johnson Cook constitutive model was employed, and 0.23 constant Coulomb friction coefficient was employed as previously reported by Salio *et al.* [12].

All tests were carried out at 30 m·min^{-1} cutting speed and 0.15 mm·rev^{-1} feed-rate, which is within the range of experimental tests. In order to study the effect of tool wear on residual stresses, three different tool geometries were analyzed: i) a new tool, ii) a tool with 0.1 mm flank wear and iii) a tool with 0.3 mm flank wear.

3. Results and discussion

3.1. Experimental results

Residual stress profiles measured in the cutting and feed direction showed the typical hook shape generated by the turning process in nickel based alloys: tensile residual stresses at the near surface (σ_{surf}) that drop to compressive residual stresses within a shallow layer until a maximum compressive peak value (σ_{peak}) is reached, and after that residual stresses are relaxed and stabilized around 0 MPa values. As this work is aimed at understanding the influence of tool wear on residual stresses, the following analysis is focused on the surface tensile surface residual stress (σ_{surf}) and the maximum compressive peak value (σ_{peak}) and its depth (d_{peak}) in the cutting direction, which is the principal direction affected by the machining process.

Fig. 3 shows normalized surface residual stress values for different cutting conditions and degree of flank wear. It should be clarified that for this study residual stresses have been normalized with respect to the maximum surface residual stress measured in the experiments. As can be seen in Fig. 3 surface residual stresses in the cutting direction were tensile for all tested conditions, which means that the thermal effect was more significant that the mechanical effect associated with machining forces. Surface residual stresses increased with small-medium flank wear (V_B < 0.25 mm), however in most studied cutting conditions they decreased when using heavily worn tools.

In general, the maximum compressive residual stress and its depth increased in the cutting direction when flank wear was increased, as can be seen in Fig. 4 and Fig. 5. It should be noted that changes in maximum compressive residual stresses with tool wear were lower than the variations observed in surface residual stresses.

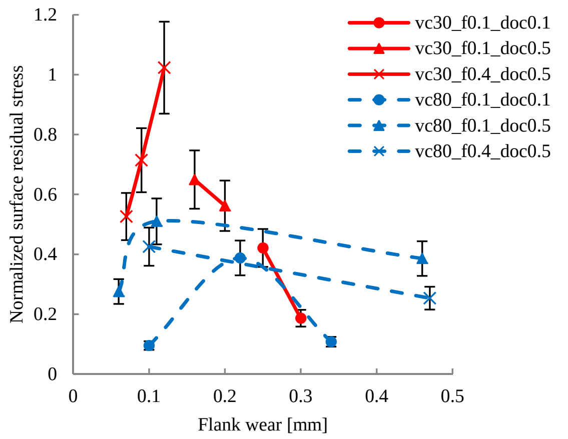

Fig. 3. Normalized surface residual stresses in the cutting direction vs. flank wear for different working conditions

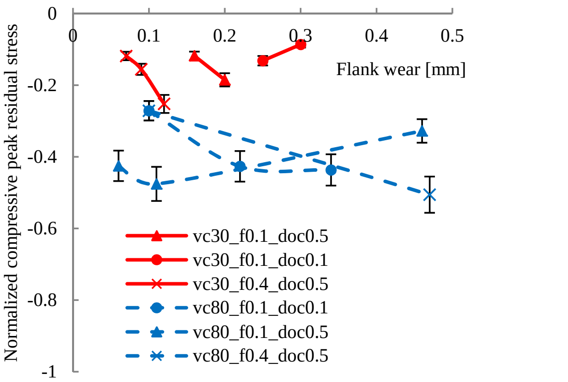

Fig. 4. Normalized maximum compressive residual stresses in the cutting direction vs. flank wear for different working conditions

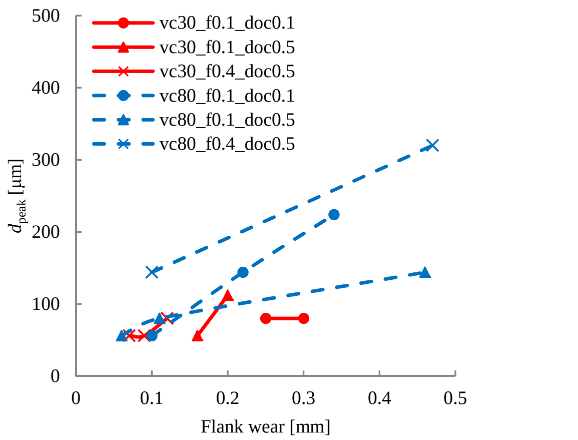

Fig. 5. Depth of the maximum compressive residual stress peak in the cutting direction vs. flank wear for different working conditions

3.2. Finite element simulation: Thermal and mechanical effect

Finite element simulations and experimental tests showed a similar trend in residual stresses with regard to flank wear for the analyzed cutting conditions. Finite element simulations obtained the highest tensile surface residual stresses (595 MPa in the cutting direction) when a 0.1 mm flank wear was used. However, similar surface stresses were obtained with the new tool (198 MPa in the cutting direction) and the tool with the highest flank wear (245 MPa in the cutting direction).

In order to explain the increase or decrease in surface residual stresses with tool wear observed in experiments and simulations, it is worth analyzing the temperature and stress fields during machining. Fig. 6 shows the temperature and stress fields of the final machined surface for the three simulated cases.

Tool wear causes an increment in the maximum tool temperature as can be seen in Fig. 6a, 6b and 6c. In addition, the hottest area of the tool moves from the rake face to the worn clearance face, which is in contact with the final machined surface, when the tool wear is increased. Therefore, the temperature in the workpiece surface was 200 ºC higher when the worn tool was used compared to the new tool as a consequence of both the increase in temperature and localization of the hottest area in the worn clearance face.

As it is well known, machining forces also change significantly, especially the thrust force, when tool wear is increased. The increase in machining forces affects the stresses developed in the workpiece during machining. Fig. 6d, 6e and 6f compare stresses in the cutting direction for the three simulated tool geometries. As can be seen in these figures, the magnitude of compressive stress and its depth in the final machined surface increased significantly when using a worn tool.

Higher tensile residual stresses are induced by the thermal effect when the material is cooled down, whilst the mechanical effect leads to more compressive residual stresses [13]. Therefore, the final surface residual stresses will be more tensile or compressive depending on the balance between the mechanical and thermal loads. This balance explains the results observed in this work. For instance, the highest tensile residual stresses were obtained when a 0.1 mm flank wear was used in simulations, because the thermal effect (increase in temperature) was more significant than the increase in machining forces. Nevertheless, when machining with severe wear, temperatures also were higher but compressive stresses in the final surface increased more significantly, which led to lower final surface residual stresses.

By contrast, the maximum compressive residual stress and its depth increased when tool wear was increased. As can be seen in Fig. 6 the layer affected by the thermal load is much thinner than the mechanically stressed layer. Thus, the increase in compressive residual stresses is logical as the mechanical effect increases with flank wear.

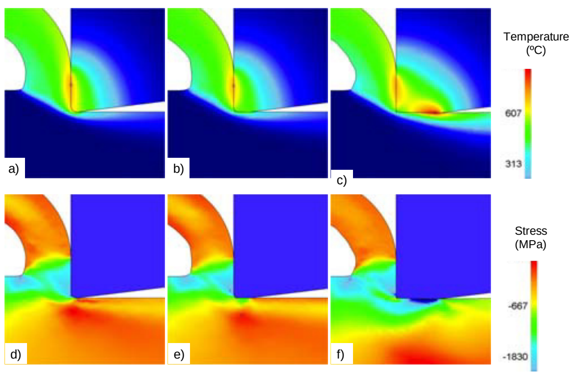

Figure 6: The influence of flank wear in the workpiece temperature and cutting direction stress fields: a) temperature field generated by the new tool, b) temperature field generated by a tool with 0.1 mm flank wear, c) temperature field generated by a tool with 0.3 mm flank wear, d) stress field generated by the new tool, e) stress field generated by a tool with 0.1 mm flank wear and f) stress field generated by a tool with 0.3 mm flank wear.

3.3. Effect of the uncut chip thickness

Results plotted in Fig. 3 suggest that a threshold value of flank wear (V_{BTH}) exists where surface residual stresses are the maximum, and surface residual stresses decrease when flank wear is increased over the threshold value. As discussed in the previous section, higher or lower surface residual stresses are generated depending on the balance between the thermal and mechanical effects for a given flank wear value and cutting conditions. Fig. 7 shows the value of flank wear (V_{BTH}) which produced the most tensile surface residual stress with respect to the maximum uncut chip thickness of each test. Interestingly, this graph shows that the value of flank wear where surface residual stresses are maximum increases considerably when the uncut chip thickness is decreased. This implies that the relevancy of the flank wear increases when the maximum uncut chip thickness is decreased.

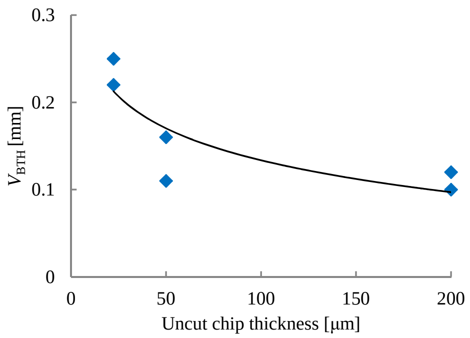

Fig. 7. Flank wear for the maximum surface residual stress vs. uncut chip thickness

4. Conclusions

The main conclusions of this work are the following:

- Surface tensile residual stresses increase in the cutting direction when flank wear is increased up to a threshold value (V_{BTH}). However, surface residual stresses decrease when machining with flank wear values higher than the threshold value. The change in the trend is attributed to the change in the balance between the thermal effect and mechanical effect.
- The value of flank wear where surface residual stresses are maximum increases considerably when the uncut chip thickness is decreased.
- The maximum compressive residual stress and its depth increase when worn tools are used due to the increase in machining forces.

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