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Influence of tool wear on residual stresses when turning Inconel 718

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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

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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·min^{-1} and 80 m·min^{-1}, but they decreased when machining at 120 m·min^{-1}. In each of the cases, the feed-rate was of 0.25 mm·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.

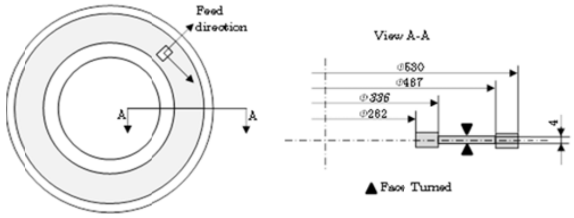

Fig. 1. Geometry of the ring shape parts

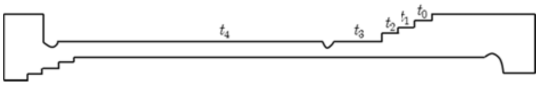

Fig. 2. Example of a cross section after machining the upper surface

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.