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The effect of tool nose radius on surface integrity and residual stresses when turning Inconel 718™

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ABSTRACT

This paper investigates the influence of tool nose radius on the residual stress distribution developed in Inconel 718 by finish turning. Although previous studies have shown that changes in rake angle, cutting edge geometry and nose radius can affect the tool performance and resulting workpiece surface integrity, no systematic study examining nose radius has been performed. Cutting force, microstructural alteration and residual stress distribution have been analysed for machining trials examining 2, 3, 4 and 6 mm radius tools at various feed rates and in both the new and worn tool condition. In general the results show that an increase in tool nose radius results in; increased radial cutting forces, increased microstructural deformation depth, higher near surface tensile stresses (up to 1550 MPa with a worn tool), and deeper tensile and compressive residual stress distribution.

1. Introduction

Inconel 718 is a high strength, heat resistant superalloy (HRSA) that is used extensively in the aerospace industry for the hot sections of gas turbine engines. It is typically used for components such as, turbine disks, blades, combustors, casings, etc. Moll (2008) reported that Inconel 718 accounts for between 50% and 78% of nickel alloys used by the main aircraft engine producers. Donachie and Donachie (2002) state that Inconel 718 became the world standard nickel based superalloy for gas turbine engines because it is cheaper and more readily available (than competing alloys) and has excellent strength properties up to 650 °C.

The properties that make Inconel 718 an important engineering material are also responsible for its generally poor machinability. Low thermal conductivity (11.4 W/mK) leads to high cutting temperatures being developed in the cutting zone. Kitagawa et al. (1997) reported that when machining Inconel 718 with CBN tools at a cutting speed of 30 m/min the temperature measured was around 900 °C, with over 1300 °C being found at 300 m/min. Conversely, Thakur et al. (2009) reported lower cutting temperatures of 480–510 °C when turning Inconel 718 with tungsten carbide tools at 40 m/min, with temperatures of 580–640 °C being reported at 60 m/min. Smart and Trent (1975) found very steep temperature gradients in the tool (compared to those seen for steels) with the maximum temperature being generated in the tool nose region. The cutting forces generated were also very high, around double that found when cutting medium carbon alloy steels. This, in combination with the relatively short chip tool contact length, means that stress is concentrated on the area of maximum tool temperature leading to plastic deformation of the cutting edge. Nickel based superalloys also have a high chemical affinity for many tool materials and as such form an adhering layer leading to diffusion and attrition wear. Liao and Shiue (1996) stated that workpiece material elements (e.g. nickel and iron) diffuse into the tool along the Co grain boundaries, weakening the bond between carbide particles and the binder phase. This leads to a removal of carbide particles and exposure of the low wear resistant cobalt phase to the machining process. Nickel based superalloys are also sensitive to strain rate and rapidly work harden causing abrasive wear, particularly at the depth of cut and leading edge positions. The presence of hard phases in the microstructure, such as carbides, nitrides, oxides, etc., further exacerbates tool abrasion. All of these factors together with the materials ability to retain its mechanical properties to elevated temperatures make it one of the most difficult materials to machine.

Studies on machining Inconel 718 have shown that the residual stress profile produced when turning is generally tensile at the workpiece surface followed by a gradual reduction with increasing depth beneath it. Sadat and Reddy (1992, 1993) found that an increase in cutting speed from 6 to 60 m/min reduced workpiece surface damage, in the form of microstructural deformation, surface tearing, etc., by reducing the cutting forces generated (by ~400 N) due to an increase in cutting temperature and corresponding drop

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in workpiece mechanical strength. However, at the higher cutting speed the maximum tensile residual stress value was increased. Sharman et al. (2006) compared the effect of coated and uncoated WC tools at various cutting speeds and feed rates and found the opposite effect, in that higher cutting speeds produced lower peak surface tensile stresses. It was stated that the higher chip flow rate associated with increasing cutting speed reduced the length of time available for the heat generated in the shear zone to diffuse into the workpiece surface and consequently increased the amount of thermal energy evacuated in the chip.

Gorsler (1985) stated that turning nickel-based superalloys without the use of a cutting fluid produced a higher and deeper tensile residual stress profile than was seen when cutting wet due to the higher temperatures generated. In contrast, Sadat and Reddy (1992, 1993) found that machining dry actually reduced the peak residual stress measured when compared to machining wet. However, the workpiece surfaces produced in the study were highly cracked and it is expected that this would correspond to some stress relief. Sharman et al. (2008) showed that the use of ultra high pressure coolant (UHPC) at 450 bar reduced the level of tensile stress produced, and by directing coolant at the flank face of the tool, compressive residual stresses could be obtained under conditions that produce tensile stresses with flood coolant (5 bar), this was attributed to the increased cooling ability of the directed UHPC jet.

Relatively, few studies have directly examined the influence of tool nose radius when machining nickel-based superalloys. Ezugwu and Tang (1995) found that rhomboid-shaped inserts (1.2 mm nose radius) induced greater near surface microhardness increases than 12 mm round inserts (in Inconel 718). Arunachalam et al. (2004) reported that inserts with 1.2 and 1.6 mm nose radius produced tensile residual stresses on the workpiece surface at 60 m/min cutting speed, 0.1 mm/rev feed rate and 0.5 mm depth of cut. In contrast, 0.8 mm nose radius and 12 mm round inserts produced compressive residual stresses under the same conditions. Coelho et al. (2004) also showed that a round ceramic insert produced a compressive layer when machining Inconel 718 at 500 m/min cutting speed, 0.1 mm/rev feed rate and 0.35 mm depth of cut. In contrast Li et al. (2009) showed that when turning a powder metallurgy nickel based superalloy (RR1000) the use of a 12 mm round insert produced a tensile surface stress of 1520 MPa (hoop direction) compared to ∼1000 MPa for a 0.8 mm nose radius insert. In addition the 0.8 mm nose radius insert produced a deeper compressive stress beneath the tensile surface layer when compared to the 12 mm round insert.

It is possible that larger radius tools can cause surface integrity problems due to insufficient chip thickness at the trailing edge. Chip thickness can be increased by the use of an increased feed rate or depth of cut, but increases in both of these parameters will lead to increased cutting forces, which can lead to surface integrity problems.

None of the previously published studies have specifically and systematically studied the effect of varying tool nose radius and chip thickness conditions on the residual stress distribution in Inconel 718. Therefore, this work will focus on a range of tool nose radii from 2 mm to 6 mm at various feed rates and chip thickness to evaluate the cutting forces, microstuctural changes and residual stress levels obtained.

2. Experimental procedure

2.1. Workpiece materials and equipment

The workpiece material used was a bar of Haynes 718 with a chemical composition of 53.8% Ni, 18.1% Cr, 5.5% Nb, 2.9% Mo, 1% Ti, 0.55% Al, 0.25% C, 0.04% Si, 0.06% Mn, and balance Fe (weight percent). This material was solution treated and aged to a nominal bulk hardness of 44 HRC.

All machining trials were conducted on a Cincinnati Hawk 300 turning centre employing a continuously variable spindle speed up to a maximum of 3000 rpm and a drive motor rated up to 42 kW.

Cutting force was measured with a Kistler 9121 three-component piezoelectric dynamometer and associated 5070 multichannel charge amplifier connected to a PC employing Kistler Dynoware force measurement software. The sampling rate was set at 1000 Hz and force data was captured in the *x*-axis (axial direction), *y*-axis (tangential direction) and *z*-axis (radial direction). For the cutting force trials inserts where held in a DCLNL shank tool holder. Unfortunately, the 4 mm radius tools could not be assessed as a tool holder compatible with the Dynamometer was not available for this size of insert.

During the cutting tests the Dynoware software was set to record immediately prior to the tool engaging the workpiece and stopped a short time (approximately 10 s) after the forces had stabilised. This results in a short lead in on the force graphs as the cutting forces ramp up from zero to a brief spike as the tool engages before settling to a steady state. To obtain the cutting force values, the lead in and engagement spike where ignored and the overall value was taken from a mean of the steady state region. Maximum and minimum values were obtained from the peaks and troughs within the steady state region. See Fig. 1 for a typical example of the force graph obtained from the Dynoware software.

Sections of the machined workpiece were cut out of the bar using wire electrodischarge machining (wEDM). These samples were used for microstructural evaluation. Sections were hot mounted in Bakelite, ground using SiC paper and polished with diamond grit. After polishing, they were immersion etched in Kallings No. 2 reagent for around 10 s. Subsurface microstructural analysis was conducted with a Leica optical microscope up to a maximum of 1500× magnification. The depth of microstructural alteration was examined at multiple points along the examined length and an average value obtained for each set of parameters investigated. Residual stress measurements were made using the blind hole drilling technique. Due to the cost, timescale and complexity of residual stress measurements each set of parameters was evaluated once. To minimise the influence of the preparation process on the residual stresses, the samples were prepared by sectioning the machined bar using wEDM along its axis to form a single semicircular piece with a minimum thickness of 10 mm. Strain gauges were installed along the centreline of the sample and in the centre of the each of the machined areas (minimum of 20 mm width for each condition, which corresponded to around 1 min in cut time). Target sites were first subjected to a degreasing process using acetone, followed by swab etching using acidic ferric chloride to provide a suitable gauge bonding surface and finally neutralisation using dilute ammonia. No abrasion was applied to the target sites. Each site was further subjected to a secondary degreasing using acetone. The gauges were then installed using glue. Gauge installation and drilling was conducted in accordance with the National Physics Laboratory good practice guide by Grant et al. (2002).

The samples were then cemented to an angled plate and the target surface was levelled for each gauge in turn. A miniature, PC controlled, three-axis drilling machine was aligned with the centre of the gauge and the datum depth detected using an iterative command in the drill control software which advanced the drill bit in 2 μm increments, see Fig. 2 for typical experimental setup.

Between each advance, intervening orbit and withdrawal movements were carried out so that the target site could be inspected for penetration through the gauge backing material and adhesive layer. Relaxed strains were recorded at 16 drill depth increments:

4 × 16 μm from 0 μm to 64 μm, 4 × 32 μm from 64 μm to 192 μm and 8 × 64 μm from 192 μm to 704 μm