Analysis of subsurface microstructure and residual stresses in machined Inconel 718 with PCBN and Al\textsubscript{2}O\textsubscript{3}-SiC\textsubscript{w} tools

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Abstract

Subsurface microstructural alterations and residual stresses caused by machining significantly affect component lifetime and performance by influencing fatigue, creep, and stress corrosion cracking resistance. Assessing the surface quality of a machined part by characterizing subsurface microstructural alterations and residual stresses is essential for ensuring part performance and lifetime in aero-engines and power generators. This comparative study characterizes and analyzes subsurface microstructural alterations and residual stresses in Inconel 718 subjected to high-speed machining with PCBN and whisker-reinforced ceramic cutting tools. Effects of cutting tool materials and microgeometry on subsurface deformation, microstructural alterations, and residual stresses were investigated. Surface and subsurface regions of machined specimens were investigated using X-ray diffraction, electron channeling contrast imaging, and electron back-scatter diffraction to characterize microstructural alterations and measure deformation intensity and depth.

Keywords: Surface integrity, Inconel 718, residual stresses, microstructure, PCBN, Ceramics.

1. Introduction

Inconel 718 is used extensively in aero-engines and power generators because it maintains excellent mechanical properties and corrosion resistance at elevated temperatures up to 800°C [1]. However, Inconel 718 is well known as difficult to machine due to its high strength at elevated temperatures, work-hardening nature, low thermal conductivity (11.4 W mK\textsuperscript{-1}), and tendency to adhere to cutting tools [2–6]. The poor machinability of the material leads not only to short cutting-tool life caused by severe flank and notch wear but also to poor surface integrity in terms of severe surface and subsurface damage, such as surface tearing, cavities, cracking, plastic deformation, metallurgical recrystallization, and unfavorable residual stresses [7–10]. Inconel 718 is traditionally machined only at limited to very low cutting speeds (30–80 m min\textsuperscript{-1}) using carbide tools to obtain acceptable surface quality [8,9]. A new production trend is to use advanced cutting tool materials, such as ceramic or polycrystalline cubic boron nitride (PCBN) tools, at much higher cutting speeds (200–350 m min\textsuperscript{-1}) to substantially enhance productivity and obtain better overall product performance [12–15]. However, the surface integrity, especially subsurface quality and residual stresses, achievable by machining with these cutting tools combined with much more aggressive cutting parameters, must be carefully assessed to ensure the performance and lifetime of the machined components [2]. Understanding the effects of advanced tool materials in combination with higher cutting speeds on the formation of residual stresses and the underlying mechanisms of microstructural alteration in the subsurface layer thereby becomes very crucial for predicting product quality and further optimizing the machining conditions [3,6].
This paper presents a comparative study of the characterization and analysis of the subsurface microstructural alterations and residual stresses in Inconel 718 subject to high-speed machining using polycrystalline cubic boron nitride (PCBN) and whisker-reinforced ceramic (Al$_2$O$_3$-SiC$_w$) cutting tools. The effects of the cutting tool materials and tool microgeometry on the formation of subsurface deformation, microstructural alteration mechanisms, and residual stresses were investigated. The surface and subsurface layers of the machined specimens were investigated using electron channeling contrast imaging (ECCI), electron back-scatter diffraction (EBSD), and X-ray diffraction to characterize the microstructural alteration and measure the deformation intensity and depth as well as the residual stresses.

2. Experimental

Workpiece material, Inconel 718, was supplied by Siemens Turbomachinery AB and was used throughout the experiment. The material was in the solution-annealed and aged state with nominal bulk hardness of HRC 45 ± 1. The nominal chemical composition in weight percent was: 53.8% Ni, 18.1% Cr, 5.5% Nb, 2.9% Mo, 1% Ti, 0.55% Al, 0.25% C, and 0.04% Si, the balance being Fe. In the aged condition, the alloy consisted of an equiaxed Ni-solid solution γ strengthened by a dispersed γ’ phase. Elongated δ particles were also observed at the γ-grain boundaries. The work material was received in forged bar shape with dimensions of 70 mm × 200 mm.

Table 1. Specifications of cutting tools

<table>
<thead>
<tr>
<th>Details of cutting tools</th>
<th>Units</th>
<th>Al$_2$O$_3$-SiC$_w$</th>
<th>PCBN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inserts</td>
<td></td>
<td>CC670</td>
<td>CBN100</td>
</tr>
<tr>
<td>Composition</td>
<td></td>
<td>Al$_2$O$_3$ 80%</td>
<td>CBN 50%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SiC$_w$ 20%</td>
<td>TiC 50%</td>
</tr>
<tr>
<td>Edge radius ($r_5$)</td>
<td>μm</td>
<td>20–25</td>
<td>10–15</td>
</tr>
<tr>
<td>Chamfer</td>
<td></td>
<td>0.1 × 20°</td>
<td>0.1 × 20°</td>
</tr>
<tr>
<td>Density</td>
<td>g m$^{-3}$</td>
<td>3.74</td>
<td>4.2</td>
</tr>
<tr>
<td>Hardness</td>
<td></td>
<td>HV 18</td>
<td>28</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>GPA</td>
<td>390</td>
<td>595</td>
</tr>
<tr>
<td>Rupture strength</td>
<td>MPa</td>
<td>900</td>
<td>1000</td>
</tr>
</tbody>
</table>

Two types of cutting tools, made of polycrystalline cubic boron nitride (PCBN) and whisker-reinforced ceramic (Al$_2$O$_3$-SiC$_w$), were employed throughout the experiment. Table 1 shows the geometric specifications and mechanical properties of the used tools. The insert was mounted in a CRSNL3225P12 tool holder (ISO) at a 6° inclination and –6° rake angle. The coolant used throughout all cutting tests was Sitala D 201-03 (Shell) containing 5% semi-synthetic emulsion in solution and provided at 5 bars at 40 L min$^{-1}$ through an orifice 5 mm in diameter. Two cutting speeds, $v_c = 200$ m min$^{-1}$ and 350 m min$^{-1}$, were selected, as recommended by the tool manufacturer. A constant feed rate ($f = 0.1$ mm rev$^{-1}$) and depth of cut ($a_p = 0.3$ mm) were used for all tests. Three cutting forces were measured by the Kistler 9121 force dynamometer. Cutting tests were carried out on a SMT500 CNC machine.

Electron channeling contrast imaging (ECCI) and electron back-scatter diffraction (EBSD) were used to characterize the microstructure and measure the deformation intensity and depth on cross-sections prepared from the machined bar. ECCI is based on variations in the collected backscattered electron intensity, and observed channeling contrast is attributed to lattice misorientations introduced during fabrication or deformation processes. EBSD can be used to quantitatively measure the extent of plastic deformation beneath the machined surface by determining grain orientations and obtaining information about intragranular misorientations [2,14]. All these studies were conducted on a Hitachi SU-70 FEG electron scanning microscope equipped with an EBSD setup and annular solid-state backscatter detectors. The density of low-angle grain boundaries was determined using Channel-5 software from HKL Technology. Samples were cut from the machined bars; a surface parallel to each of the cut and feed directions was then mechanically ground and polished to study microstructural changes in the machining-affected depth.

The state of residual stress in the machined surface was measured using X-ray diffraction (XRD). XRD analysis was conducted using Co Kα source on a DRON-3M diffractometer with a diffraction angle of 111° in plane [311]. A Sin$^2$Ψ method with Ψ = 30, –20, –10, 0, 10, 20, 30° was used for stress estimation. Material removal by electropolishing with a step of 20 μm was applied to measure the profiles of residual stresses [19].

3. Results and discussions

3.1 Cutting forces

Cutting forces fundamentally affect the formation of surface deformations and residual stresses [2,3]. Three cutting forces, $F_c$, $F_p$, and $F_f$, were measured under different cutting conditions in this investigation. Fig. 1 presents the cutting force magnitudes for two cutting tools at two cutting speeds. All three force components decrease slightly as the cutting speed changes from 200 m min$^{-1}$ to 350 m min$^{-1}$, as the work material tends to be soft due to the increased cutting temperature when the higher cutting speed is used. With the ceramic cutting tool, the force...
magnitudes are higher at both cutting speeds than with the PCBN cutting tool. The difference becomes more pronounced at the lower cutting speed (200 m min⁻¹) due to the lower temperature, especially in the passive force ($F_p$), which is up to 40% higher with the ceramic than the PCBN tool. The higher force generated by the ceramic tool is primarily attributable to its larger edge radius ($r_E$) than that of the PCBN tool. The variation in the edge radius along the active cutting edge is presented in Fig. 2. For the ceramic cutting tool, at the trailing edge where the surface is formed, the edge radius changes from the original value of 20 μm to approximately 50 μm and this is much larger than that of the PCBN tool, which is approximately 20 μm at the trailing edge.

3.2. Subsurface plastic deformation and microstructural alterations

High-speed machining is characterized by increased strain, strain rate, and temperature in the cutting area. Consequently, metallurgical changes are expected in the material [13,14]. The micrographs shown in Fig. 3 reveal typical microstructures observed below the machined surface parallel to the cutting direction. Fig. 3(a) clearly shows the plastic deformation, the gradient of which varies from the surface to depth, and the microstructural changes in the region. A very thin layer of structure (less than 1 μm thick) was observed in the very near surface, which is distinguished from the rest of the material structure. This thin layer covers almost all the investigated surfaces and was observed in the specimens produced under all machining conditions. Close examination of this layer with high-resolution ECCI, as shown in Fig. 3(b), further indicates that the microstructure of this layer is highly refined with nano-sized grains (50–100 nm) much smaller than those of the bulk material (5–20 μm) (Fig. 4). This suggests that grain refinement occurred in this layer of material during surface formation under the plastic deformation caused by the mechanical and thermal loading during the high-speed machining. The grain-refinement process originates from the high density of dislocation in the original grains during plastic deformation in this region [11]. Dislocation interactions or interactions between dislocations and mechanical twins can lead to the formation of sub-grain boundaries, which results in the subdivision of the original grains with the further increase of strain under the severe plastic deformation during the machining. Grain refinement in the near-surface layer has also been confirmed by several other investigations [14,19].

Although atomic-force microscopy (AFM) and high-resolution transmission electron microscopy (HRTEM) provide evidence of a γ phase in this layer, which suggests that phase change does not happen in this layer during grain refinement [17], further investigation is necessary to confirm the metallurgical structures in this layer. In addition, the mechanical properties of the grain-refinement layer and their effect on the fatigue strength, especially at elevated temperatures, are still unclear. Grain refinement in the near-surface layer was also observed in the white layer after high-speed cutting [19, 20]. In this case, the refined grain layer is generally attributed to a high cutting temperature followed by rapid cooling or severe plastic deformation [14,17].

The severe deformation area, represented by the
presence of plastic slip bands, lies beneath the near-surface layer. Grains in the severe deformation layer are characterized by grain bending and elongation, grain boundaries, and intense slip bands towards the cutting direction. In this area, grain distortion was visible as varied grey shades at a depth of up to 40 μm, as shown in Fig. 3. The grain distortion varies as the depth increases. In the slight deformation area, only some slip bands can be observed. The intensity of the plastic deformation declines following the temperature and mechanical load gradient from the surface to the bulk material.

Fig. 4 shows the morphology of the subsurface layers generated by PCBN and ceramic cutting tools at cutting speeds of 200 m min⁻¹ and 350 m min⁻¹. The presence of microstructural alterations was obvious in all cases, although the alteration varied with depth from the surface depending on the cutting tool material and cutting speed. In general, the specimens produced by both PCBN and ceramic tools, when increasing the cutting speed from 200 m min⁻¹ to 350 m min⁻¹, the plastic deformation beneath the machined surface became more pronounced in terms of both intensity and area or depth. More distinguishable bending, deformation twin bands, and slip bands were observed and the whole deformation area in the subsurface layer became more marked than when the lower cutting speed was employed. The larger subsurface deformation area is clearly associated with increasing cutting temperature at the higher cutting speed.

Besides cutting speed, the cutting tool material and edge radius are also essential factors affecting the plastic deformation in the machined subsurface. Fig. 4(a) and (b) show the subsurface layers produced by ceramic tools at different cutting speeds. At a cutting speed of 350 m min⁻¹, the most severe and deeper plastic deformation was found in the subsurface machined with ceramic tools (Fig. 4b) due to their larger edge radius at the trailing edge (Fig. 2a). A shallower plastic deformation depth in the subsurface region was observed when PCBN cutting tools were employed (Fig. 4c and 4d). The near-surface layer with a nano-crystalline microstructure, however, differs little between the PCBN and ceramic tool machining, as shown in Fig. 5(a) and (b). This suggests that the cutting tool material has little effect on the depth of the nano-structured layer in the high-speed range (νc > 200 m min⁻¹), while the plastic deformation depths in the subsurface layer are affected by tool material and geometry.

The extent of plastic deformation in the machined subsurface layers can be qualitatively visualized by electron backscatter diffraction (EBSD) scanning, as shown in Fig. 6. Misorientations (i.e. the orientation difference between two adjacent measurement points), induced mainly by plastic deformation, are indicated by green (between 1° and 5°) and red (between 5° and 10°) lines.

![Fig. 6: EBSD maps (pixel size, 0.5 μm) of near-subsurface layers produced by (a) PCBN and (b) Al₂O₃-SiC₆ cutting tools.](image)

Fig. 7: Average misorientation profile obtained using EBSD.
Obviously, grain misorientations from $1^\circ$ to $5^\circ$ are dominant in the near-surface layer. With the use of ceramic tools, they are concentrated at a depth of ~10 μm from the surface and then gradually decline in concentration down to a depth of ~25 μm. A higher concentration of misorientations induced by PCBN tools was observed in the near surface but only down to a depth of ~5 μm, the concentration decreasing to zero at a depth of ~10 μm. The high concentration of misorientations in the near-surface layer suggests that PCBN tools generate much higher surface plastic deformation than do ceramic tools, possibly attributable to a higher cutting temperature, whereas the deeper plastic deformation produced by the ceramic tools results from higher cutting forces.

Average intragrain misorientation can also be used to characterize the plastic deformation [13,15]. Low-angle grain boundaries (LAGBs) are defined here as misorientation angles between 1$^\circ$ and 10$^\circ$. Their density at a particular sample depth was then calculated from EBSD maps, such as those shown in Fig. 6, by dividing the measured number of LAGBs by the total number of measurement points at the same depth. The step size for mapping was 0.5 μm. Fig. 7 presents the LAGB density profile extending from the machined surface down into the bulk material, and the average misorientation generally decreases with increased depth, which further confirms the depth of subsurface plastic deformation.

### 3.2 Residual stresses

Both tensile and compressive residual stresses were observed from the X-ray diffraction measurements. The tensile residual stresses are from plastic deformation generated by the advancing tool and the local thermal effect generated by friction between the tool flank face and the machined surface. The stresses generated by both types of cutting tools display the property of anisotropy, in which more compressive stresses occur in the feed direction than in the cutting direction, as shown in Fig. 8.

![Fig. 8: (a) and (b) Residual stresses in the subsurface layer produced by Al$_2$O$_3$-SiC$_w$ cutting tools at cutting speeds of 200 m min$^{-1}$ and 350 m min$^{-1}$, respectively; (c) and (d) Residual stresses in the subsurface layer produced by PCBN cutting tools at cutting speeds of 200 m min$^{-1}$ and 350 m min$^{-1}$, respectively.](image)

The influence of PCBN and whisker-reinforced ceramic cutting tools on the residual stresses has been investigated, and Fig. 8 compares the residual stresses generated under the recommended cutting conditions by both types of tools. Much higher tensile residual stresses were observed to be generated by whisker-reinforced ceramic tools than by PCBN tools. High tensile stresses are attributed to the dominant thermal effect during machining, which is primarily due to the poor thermal conductivity of the whisker-reinforced ceramic inserts. In the case of PCBN tools, surface residual stresses were found to be compressive, in contrast to the undesired tensile stresses generated by whisker-reinforced ceramic tools and even by cemented carbide tools. Tool geometry and multiple deformation of the machined surface could account for this [19].

In addition, high thermal conductivity may also be associated with surface compressive residual stress, in which generated thermal energy is dissipated faster during machining, resulting in lower tensile stress values. In addition to different material properties, different cutting edge geometries also contribute to the difference in residual stress values. The cutting edge radius of a whisker-reinforced ceramic tool is slightly larger than that of a PCBN tool (see Table 1). Since both cutting tool inserts were round in shape, a small difference in the edge radius will greatly affect the contact area between the tool and workpiece formed, which is expected to generate more friction heat in the cut zone [21,22]. This, together with the poor thermal conductivity of the work material, results in the domination of the thermal effect.

Fig. 8 also reveals the effect of cutting speed on the residual stresses generated by both types of cutting tools. The trend is for increased cutting speed to shift the residual stress from compressive to tensile stress due to increased temperature in the cutting zones. At the higher cutting speed, the heat generated in the cutting zones can hardly be dissipated in the very short time available, leading to higher temperatures. Similar results have also been reported by Schlauer and Oden [11] and Sharman [7].

### 4. Conclusions

Microstructural alterations of Inconel 718 machined with PCBN and ceramic cutting tools at two different cutting speeds were investigated using ECCI, EBSD, and XRD.

In all studied cases, plastic deformation and heat generated in the cutting process induced pronounced microstructural changes. The results indicate an obvious alteration of subsurface microstructure associated with the gradient of mechanical forces and
temperature in the depth direction under all studied cutting conditions. Under all the cutting conditions, a near-surface layer of refined grains was observed, formed due to severe plastic deformation and affected by the elevated local temperature during machining. Both PCBN and ceramic tools produced grain-refinement zones of similar depths regardless of the cutting speed employed. The layer below was the plastic-deformed area characterized by severely distorted grains and grain boundaries, deformation twin bands, and crossed slip bands. Compared with the PCBN tool, the ceramic tool produced a deeper severe deformation zone due to its larger edge radius at cutting speeds of both 200 m min⁻¹ and 350 m min⁻¹. Further investigations are necessary to characterize the mechanical properties of the grain-refinement layer and its effect on fatigue strength.

The investigated samples have depth profiles displaying residual stresses, with surface tension and subsurface compression generated due to localized plastic deformation and heating. Both cutting tool material and cutting speed noticeably affected the magnitude of residual stresses. Only compressive residual stresses in both the speed and feed directions were produced by the PCBN tool at a lower cutting speed, while the ceramic tool generated fairly high tensile residual stresses in the subsurface region.

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