Prediction of machining induced residual stresses in turning of titanium and nickel based alloys with experiments and finite element simulations

T. Özel (T), D. Ulutan
Manufacturing & Automation Research Laboratory, Department of Industrial and Systems Engineering, Rutgers University, NJ, USA

ARTICLE INFO
Keywords:
Turning
Residual stress
Finite element method

ABSTRACT
Titanium and nickel alloys represent a significant metal portion of the aircraft structural and engine components and the residual stresses induced by machining are very critical due to safety and sustainability concerns. This paper presents experimental investigations and finite element simulations on turning of Ti–6Al–4V titanium alloy and IN100 nickel based alloy with uncoated and TiAlN coated tools. Face turning of Ti–6Al–4V and IN100 using uncoated tools with various edge radii and TiAlN coated carbide tools is conducted; and residual stresses are measured in radial and circumferential directions using X-ray diffraction technique. 3-D finite element (FE) modeling is utilized to predict forces and machining induced stress fields. The feasibility and limitations of predicting machining induced residual stresses by using viscoplastic finite element simulations and temperature-dependent flow softening constitutive material modeling are investigated. A friction determination method is utilized to identify friction coefficients in presence of tool edge radius. The predicted stress fields are compared against measured residual stresses. Effect of tool edge radius and coating on the predicted stress profiles is also investigated. The results are found useful in predicting machining induced surface integrity that is critical to determine the fatigue life of nickel and titanium alloy components.

© 2012 CIRP.

1. Introduction
Titanium and nickel alloys are difficult-to-machine materials with considerable manufacturing problems such as machining induced surface integrity and residual stresses [1]. Titanium alloys, specifically Ti–6Al–4V, are used in many industries including aerospace, automotive and medical device and offer favorable mechanical characteristics such as high strength-to-weight ratio, toughness, superb corrosion resistance and bio-compatibility. Nickel-based super alloys are often used in mission critical components such as in aircraft/industrial gas turbine engines. Particularly, IN100 nickel-based alloy manufactured via powder metallurgy route is rated as extremely difficult-to-machine due to the high toughness and work hardening behavior in which a work hardened layer forms in response to the machining induced thermal and plastic deformations on the subsurface [2].

Most such structural components are finish-machined. When the thermo-mechanical load on the workpiece material is released, the residual stresses that remain in the material after unloading, which are considered to be mainly due to machining-induced plastic work at the subsurface and thermal effects at the surface due to friction and tool wear, are revealed [3]. In case of high tensile stress, which is considered detrimental to the fatigue life of the component, the machined component undergoes costly surface treatment operations to create a compressively stressed surface. Therefore, when such components in the industry are manufactured with the objective of reaching high reliability levels, machining-induced surface integrity becomes one of the most relevant parameters for the fatigue life of these components. In general, machining-induced residual stresses are more tensile at the surface of the workpiece and become compressive as the depth in the workpiece increases to around 50 μm [2–4]. In addition, an increase in feed rate makes the residual stresses more tensile at the surface and more compressive in the peak compressive depth, especially at higher cutting speeds, where the peak residual stresses might become less compressive with increasing feed in lower cutting speeds [3–5]. In the presence of tool flank wear, the residual stress profiles change and become more tensile due to increased heat generation and related thermal effects. For example, the effect of flank wear on residual stress (in axial direction) is investigated by Chen et al. [6] for Ti–6Al–4V and Sharman et al. [7] for IN718. Circumferential or hoop stresses (in the direction of cutting velocity vector) are mainly compressive on the machined surface when using a fresh unworn tool. However, circumferential stresses turn tensile when cutting with a worn tool or in presence of tool flank contact. This is consistent with machining both Ti–6Al–4V titanium alloy and IN718 nickel alloy. Tool material also affects residual stress formation. Outeiro et al. [8] reported higher tensile surface residual stress generation when machining with the uncoated tungsten carbide (WC/Co) when compared to TiAlN coated tungsten carbide tool in machining IN718 nickel based alloy. Although some influence of cutting edge geometry on machining has been shown [5], its effect on machining induced residual stresses has not been fully explored.

In this research, uncoated tools with various edge radii and TiAlN coated tungsten carbide inserts (WC/Co) have been tested to explore the effects of tool geometry and coatings on machining
induced residual stress in Ti–6Al–4V titanium and IN100 nickel based alloy. Finite element (FE) simulations are utilized in predicting machining induced stresses with experimental comparisons. Three dimensional FE simulations have been designed and conducted to predict forces, temperatures and stress fields to investigate the effects of tool micro-geometry and coatings in machining of Ti–6Al–4V and IN100.

2. Experimental work

Titanium alloy material, annealed Ti–6Al–4V, has been obtained as cylindrical billets with 100 mm diameter in annealed conditions with 36 HRC hardness. Nickel based alloy material used in this study, IN100, is manufactured via powder metallurgy route with a chemical composition of 18.3% Co, 12.3% Cr, 4.9% Al, 4.3% Ti, 3.3% Mo, 0.7% V, 0.1% Fe, 0.06% C, 0.02% B, 0.02% Zr and Ni balance. This material was isostatically pressed and cylindrical billets were formed. Disks with 113 mm diameter were cut from the billet with wire electrical discharge machining (WEDM) process. Face turning of annealed Ti–6Al–4V titanium alloy and IN100 nickel based alloy disks was performed using TPG432 type insert geometry (insert nose radius of $r = 0.8$ mm and relief angle of $\alpha = 11^\circ$) in a rigid CNC turning lathe under dry machining conditions as shown in Fig. 1.

Tool edge radii were measured as $r_f = 5 \pm 0.5 \mu m$ for sharp uncoated tungsten carbide (WC/Co) and $r_f = 10.0 \pm 0.7 \mu m$ for TiAlN coated WC/Co respectively. In addition, uncoated sharp tools were edge prepared using abrasive brushing technique to have edge radii of $r_f = 10.0 \pm 0.7 \mu m$ and $r_f = 25 \pm 1.0 \mu m$. The inserts were mounted in a CTFFPR-164C right hand tool holder that provided 0° lead, 0° side rake, and –5° back rake angles. Two or three tracks have been machined on the face using different cutting conditions. After each face turning test, disks with approximately 3 mm thickness have been sliced out of the cylindrical workpiece.

In the experiments, WC/Co inserts with three different edge radii of $r_f \approx 5$, 10, and 25 $\mu m$, and TiAlN coated WC/Co inserts with edge radius of $r_f \geq 10$ $\mu m$ have been tested in face turning of Ti–6Al–4V and IN100 disks. Two cutting speeds of $v_c = 12$ m/min and 24 m/min, a depth of cut of $a_p = 1$ mm and a constant feed of $f = 0.05$ mm/rev for IN100 nickel based alloy and a depth of cut of $a_p = 2$ mm, two cutting speeds of 55 m/min and 90 m/min and two feeds of $f = 0.05$ mm/rev and 0.1 mm/rev for Ti–6Al–4V were selected as cutting conditions. The cutting forces were measured with a force dynamometer mounted on the turret disc of the CNC lathe. The averages of the measured forces for each insert are shown in Fig. 2. In face turning of IN100, lowest forces are obtained using TiAlN coated WC/Co tool at the lower cutting speed ($v_c = 12$ m/min). But the performance of uncoated WC/Co ($r_f \geq 25$ $\mu m$) tool became the same as TiAlN coated at the higher cutting speed ($v_c = 24$ m/min). In machining Ti–6Al–4V at both cutting speeds, uncoated WC/Co ($r_f \geq 25$ $\mu m$) tool resulted in lower forces regardless of the feed rate.

3. Residual stress measurements

After all the machining process was completed in Ti–6Al–4V alloy disks, residual stresses were measured using X-ray diffraction technique on Bruker HiStar unit using Cu-Kα radiation ($\lambda = 1.54$ Å) at 20 kV, 2 mA to acquire [1 1 4] and [2 1 3] diffraction peaks or lines at 29 angles of about 115° and 140° respectively using a spot size of 1 mm collimated from 2 mm beam by using a tungsten filament. In order to prevent the detection of banding created due to presence of Cu within the disks, a nickel foil was used to filter the detected radiation beams. This banding, when not filtered, hinders the accuracy of measurements. The residual stresses through the depth profiles of the disks were measured by chemically etching successive layers of material to a depth in excess of 100 $\mu m$ using a titanium etchant reagent (8–30% HFI and 70–92% H2O). Residual stresses on IN100 disks were measured using X-ray diffraction technique on Proto iXRD unit Mn–Cu-Kα radiation ($\lambda = 2.1$ Å) at 17 kV, 4 mA to acquire [1 1 1] diffraction peaks or lines at 29 angles of about 155° using a spot size of 1 mm × 2 mm beam. Similarly, residual stresses and depth profiles were measured by removing successive layers of material to a depth in excess of 100 $\mu m$ by electropolishing. In-plane surface stress measurements were performed at selective positions from inner and outer radial positions along the tracks on the disks that were machined with face turning.

3.1. 3D finite element simulations

Recently, finite element simulation models of chip formation begin to enable prediction of machining-induced residual stresses and optimization of tool micro-geometry and machining parameters without running costly experimentation [9]. However, 3D FE simulation models still suffer from not only numerical convergence problems (elastic–viscoplastic deformations), but also uncertainty associated with calculated output variables. For the purpose of identifying prediction accuracy, 3D finite element models are developed using updated Lagrangian software (DEFORM-3D) in which chip separation from workpiece is achieved with continuous remeshing. The simulations included a workpiece as viscoplastic with a mesh containing $1.5 \times 10^5$ quadrilateral elements. Tool is modelled as rigid with a mesh containing into $1.0 \times 10^6$ elements. The workpiece is represented by a curved model, a 4° segment of disk surface, with the disk diameter used in experimental conditions. The bottom surface of this workpiece is fixed in all directions. A small segment around the corner radius area of the cutting insert ($r = 0.8$ mm with 11° relief angle) is modelled as a rigid body which moves at the specified cutting speed [9]. A very fine mesh density is defined at
Table 1

<table>
<thead>
<tr>
<th>Alloy</th>
<th>A (MPa)</th>
<th>B (MPa)</th>
<th>n</th>
<th>C</th>
<th>m</th>
<th>D</th>
<th>p</th>
<th>r</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti–6Al–4V</td>
<td>1000</td>
<td>625</td>
<td>0.55</td>
<td>0.029</td>
<td>0.955</td>
<td>0.48</td>
<td>0</td>
<td>1.2</td>
<td>2.7</td>
</tr>
<tr>
<td>IN100</td>
<td>1350</td>
<td>1750</td>
<td>0.65</td>
<td>0.017</td>
<td>1.3</td>
<td>0.6</td>
<td>0</td>
<td>1.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Tool type</th>
<th>Fc, Fp (N)</th>
<th>Fc, Fp (N)</th>
<th>Fc, Fp (N)</th>
<th>Fc, Fp (N)</th>
<th>Temp Tool (°C)</th>
<th>Temp Chip (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC/Co</td>
<td>592 ± 38</td>
<td>562 ± 35</td>
<td>302 ± 21</td>
<td>321 ± 31</td>
<td>196 ± 24</td>
<td>181 ± 10</td>
</tr>
<tr>
<td>r&lt;sub&gt;p&lt;/sub&gt; = 5 μm</td>
<td>511 ± 44</td>
<td>530 ± 37</td>
<td>248 ± 36</td>
<td>237 ± 31</td>
<td>182 ± 22</td>
<td>200 ± 9</td>
</tr>
<tr>
<td>WC/Co</td>
<td>513 ± 49</td>
<td>481 ± 24</td>
<td>203 ± 33</td>
<td>176 ± 26</td>
<td>242 ± 24</td>
<td>216 ± 9</td>
</tr>
<tr>
<td>r&lt;sub&gt;p&lt;/sub&gt; = 10 μm</td>
<td>506 ± 41</td>
<td>511 ± 27</td>
<td>187 ± 18</td>
<td>187 ± 38</td>
<td>232 ± 31</td>
<td>229 ± 24</td>
</tr>
<tr>
<td>WC/Co</td>
<td>579 ± 33</td>
<td>780 ± 24</td>
<td>307 ± 32</td>
<td>356 ± 48</td>
<td>188 ± 19</td>
<td>167 ± 24</td>
</tr>
<tr>
<td>r&lt;sub&gt;p&lt;/sub&gt; = 25 μm</td>
<td>759 ± 33</td>
<td>780 ± 24</td>
<td>307 ± 32</td>
<td>356 ± 48</td>
<td>188 ± 19</td>
<td>167 ± 24</td>
</tr>
</tbody>
</table>

4. Prediction of machining induced residual stress

FE simulation predictions in machining Ti–6Al–4V alloy indicated that circumferential residual stresses at the surface increased with increasing cutting speed, while the tool coating/edge radius change did not affect these values. (Fig. 3). Compressive peak residual stresses in circumferential direction were not significant for all tests, but they all showed this peak around 80 μm at approximately 100 MPa. This peak was slightly more compressive with the coated tool compared to the uncoated tool. In the radial direction, all tests showed compressive residual stresses both at the surface and deep into the material. They all occurred at
approximately \(-250 \text{ to } -400\) MPa. The prediction accuracy for the simulations was found better for the circumferential residual stresses rather than the radial direction which was found inferior. In IN100, prediction accuracy of the simulations was better in both circumferential and radial directions (Fig. 4). For both circumferential and radial directions, surface tensile residual stresses showed an increase with increasing cutting edge radius, and the coated tool showed a slightly less tensile residual stress at the surface than the 25 \(\mu\)m edge radius tool. Compressive peak residual stresses varied from \(-400\) to \(-600\) MPa for the uncoated tools and were not significant for the TiAlN coated tool. Measurement and prediction uncertainty in residual stress findings are indicated with standard deviation bars in both Figs. 3 and 4.

5. Conclusions

In this study, 3D FE simulations to predict machining induced residual stresses in Ti–6Al–4V and IN100 alloys are utilized. Results are compared with experiments. It is concluded that predicted residual stresses are influenced by the tool micro-geometry as they become more compressive with increased edge radius but more tensile at the surface when coated.

Acknowledgment

The authors gratefully acknowledge the support by the National Science Foundation (grant number CMMI-1130780).