1st CIRP Conference on Surface Integrity (CSI)

Experimental and computational investigation of machining processes for functionally graded materials

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Abstract

Experiments on dry face turning of functionally graded heat treatable steel are conducted. The workpieces have a hardened zone of approx. 60 HRC and a non-hardened zone of approx. 30 HRC. PCBN tools are used with different feeds, cutting speeds and depths of cut. Measurements of residual stresses in the surface layer reveal compressive stresses in the hardened zone and tensile stresses in the non-hardened zone. These experimental observations are compared with the results of representative simulations of the cutting process. A large-deformation thermo-elasto-viscoplastic material model is used and the geometry of the cutting tool is precisely reflected by the finite element discretisation. To predict the overall response, an adaptive remeshing scheme and full thermo-mechanical coupling is accounted for. Moreover, measured residual stresses are incorporated as initial conditions within the simulation.

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Selection and peer review under responsibility of Prof. E. Brinksmeier

Keywords: Finite element method (FEM), Turning, Residual stresses, Functionally graded materials, Remeshing

1. Introduction

Workpieces featuring a functional gradation of material properties can be manufactured by thermo-mechanical forming processes. The functional gradation of these steel-made workpieces allows their adaption in applications with varying requirements concerning physical properties like hardness and ductility. This poses a great challenge to the machining process due to the combination of different material properties within one workpiece. The treated workpieces are made of steel AISI 6150 and are produced by a thermo-mechanical forming process. Figure 1 shows a cross-section of the stub shaft and the associated phases in the shaft and the flange. The result is a martensitic and hardened flange as well as a non-hardened shaft. Experimental investigations are carried out in combination with finite element
based simulations to develop strategies for efficient machining and to analyze and predict the material properties sought. In order to obtain a realistic model for the simulation of turning processes, chip formation and the surface integrity have to be considered. In this regard, the commercial finite element program ABAQUS in combination with an in-house adaptive remeshing scheme is used to simulate the machining process and to determine residual stresses in the surface layer. [2]

2. Experimental investigations and measurements

Experimental investigations are carried out, in order to detect the influence of the material hardness on resulting surface residual stresses. While a wide variation of process parameter values has been investigated in this work, the paper at hand focuses on a fixed feed in order to compare experiment and simulation.

Turning processes are carried out for hardened (65 HRC) and non-hardened steel (30 HRC). Table 1 shows the parameter value sets using solid carbide inserts HC-P15 (CNMG 120408) forming a positive rake angle of \( \gamma = 4^\circ \) and a cutting edge rounding of \( r_\beta = 60 \, \mu m \) (Experiment 74, 82 and 70) and the parameter value sets using CBN inserts (CNGA 120408) with a chamfer forming a negative rake angle of \( \gamma = -31^\circ \) (Experiment 5 and 20). Different cutting speed values are studied for machining the hardened and non-hardened material in order to increase tool life, as investigated in former research activities at the Institute of Machining Technology. [1] As the current investigations concentrates on safe and efficient manufacturing of graded materials, low cutting speeds are chosen for hardened material. Parameter sets 74 and 82 represent the same attempt, parameter sets 70, 5 and 20 are a variation of the cutting depth \( a_p \) and the cutting speed in the hardened material.
Table 1. Used parameter value sets for turning processes

<table>
<thead>
<tr>
<th>Experiment</th>
<th>f in mm</th>
<th>a_p in mm</th>
<th>v_c,h (hardened material) in m/min</th>
<th>v_c,nh (non-hardened material) in m/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>74</td>
<td>0.1</td>
<td>0.1</td>
<td>50</td>
<td>250</td>
</tr>
<tr>
<td>82</td>
<td>0.1</td>
<td>0.1</td>
<td>50</td>
<td>250</td>
</tr>
<tr>
<td>70</td>
<td>0.1</td>
<td>0.22</td>
<td>70</td>
<td>250</td>
</tr>
<tr>
<td>5</td>
<td>0.1</td>
<td>0.15</td>
<td>100</td>
<td>250</td>
</tr>
<tr>
<td>20</td>
<td>0.1</td>
<td>0.15</td>
<td>150</td>
<td>250</td>
</tr>
</tbody>
</table>

Residual stresses in the surface layer depend on the machining parameters applied and they are a consequence of temperature and deformation resulting from machining processes. In the current context, tensile residual stresses mainly result from thermal effects, while compressive residual stresses are primarily induced by mechanical loads. Both are measured on the plane surface of the shaft (cf. Fig. 1b) by using a conventional X-ray diffraction technique applying the sin^2Ψ-method with CrKα-radiation. [5]

3. Analysis of experimentally measured residual stresses

Figure 2 shows the measured surface residual stresses and the location of the surface residual stresses at the stub shaft flange. These values are taken to validate the simulative investigations described in Sections 4 and 5. As known from the literature, positive tensile residual stresses are created when turning non-hardened material and compressive residual stresses are induced by turning hardened material. [4, 7]

The analysis of the measured residual stresses in the surface layer for experiment 74 and 82 compared with experiment 70, 5 and 20 shows that different cutting depths have no influence on the residual stress values. Here, the considered surface layer has a thickness of about 0.8 millimeter. The chain lines in Figs. 2a and 2b show the residual stresses present in the surface layer of the workpiece as induced by the thermo-mechanical forming process. They are present before the turning process takes place, and therefore have to be considered as inhomogeneous initial conditions in the later finite element model (see Section 4). The figure shows that the martensitically transformed phase of the flange possesses compressive residual stresses. Furthermore, at the transition from non-hardened to hardened material in the zone between 23 and 26 mm from the symmetry axis (within the ferritic and perlitic phase) the residual stresses turn to negative values which means that thermal influences no longer predominate when machining the hardened steel. This effect is observed for radial as well as for tangential residual stresses in the surface layer, as shown in Figs. 2a and 2b.

![Fig. 2. Experimentally measured radial (a) and tangential (b) residual stresses in the surface layer for carbide metal and CBN insert, respectively](image)
4. Finite element based modeling

For the simulation of the turning process, a thermo-elasto-viscoplastic material model with full thermo-mechanical coupling is used. [2, 3] The yield stress $Y$ is determined using the Johnson-Cook equations

$$Y_{\text{nh}} = \left[900 + 341 \alpha^{0.203}\right] \left[1 + 0.01 \ln\left(\dot{\varepsilon}/\dot{\varepsilon}_0\right)\right] \left[1 - \left(T - 300\,\text{K}\right)/\left(1270\,\text{K}\right)\right]$$

and

$$Y_{\text{h}} = \left[1073 + 234 \alpha^{1.235}\right] \left[1 + 0.01 \ln\left(\dot{\varepsilon}/\dot{\varepsilon}_0\right)\right] \left[1 - \left(T - 300\,\text{K}\right)/\left(1270\,\text{K}\right)\right],$$

for non-hardened and hardened workpiece zones, respectively, with $T$ denoting the temperature in K and $\alpha$ the equivalent plastic strain. The elastic response is assumed to be isotropic ($E = 210$ GPa, Poisson’s ratio $\nu = 0.3$) and Fourier’s relation is adopted for the heat flux vector (thermal conductivity $\lambda = 46.6$ W/mK, heat capacity $c = 475$ J/kgK). Moreover, inhomogeneously distributed residual stresses – particularly in the surface layer as resulting from the thermo-mechanical forming process of the shaft – are considered as an initial condition for the simulation for both tangential and radial stress components.

Fig. 3. Finite element results obtained from turning simulation with carbid metal insert (cutting edge rounding $r_{\beta} = 60$ $\mu$m, rake angle $\gamma = 5^\circ$). Shown are tangential (a, b), and radial stresses (c, d) in MPa, cf. Fig. 1, as well as the temperature distribution (e, f) in K. The results on the left (a, c, e) are obtained based on the non-hardened material model ($Y_{\text{nh}}$), while (b, d, f) reflect the hardened material model ($Y_{\text{h}}$).
The surface-like stress components obtained from measurements of the polished workpiece (cf. Fig. 2) are assumed to decrease linearly within the distance from the surface layer, reaching zero value in a depth of 0.8 mm from the surface. These relations are represented by
\[
\sigma_{\text{initial}}(d) = \sigma_{0.8} + \frac{\sigma_{\text{surf}} - \sigma_{0.8}}{0.8 \text{mm}} \cdot d
\]
with \(d\) (in mm) the distance from the surface, \(\sigma_{\text{surf}}\) the measured surface stress component, and \(\sigma_{0.8}\) the stress 0.8 mm below surface, which is here assumed to be zero. The obtained finite element results are evaluated in terms of tangential and radial stresses (cf. Fig. 1b) and temperature distributions, see Section 5.

5. Finite element based simulation

The finite element simulations considering the carbide metal insert (Fig. 3) are in good agreement with the experimental data. The obtained radial stresses in the surface layer for both experiment (Fig. 2a) and simulation (Fig. 3d) are in a compressive range of \(\sigma_{33} = -400\ldots-200\ \text{MPa}\). However, in the non-hardened zone (Fig. 3c), the experimentally observed tensile stresses (Fig. 2a) are not predicted as clearly. The temperature distribution (Figs. 3e and f) shows a more intense heat generation for the hardened zone, as also suggested by experimental observations. For the CBN insert, the finite element simulations (Fig. 4) show a zone of compressive tangential stresses, see Fig. 4b.

Fig. 4. Finite element results obtained from turning simulation with CBN insert (cutting edge rounding \(r_\beta = 25 \ \mu\text{m}, \) rake angle \(\gamma = -15^\circ\)). Shown are tangential (a, b), and radial stresses (c, d) in MPa, cf. Fig. 1, as well as the temperature distribution (e, f) in K. The results on the left (a, c, e) are obtained based on the non-hardened material model \((Y_{nh})\), while (b, d, f) reflect the hardened material model \((Y_h)\).
This zone of compressive stresses is also observed in the experiments (Fig. 2b). [6] The distinct compressive stresses in the surface layer have a magnitude of $\sigma_{11} = -700\ldots-600$ MPa. As in the case of the metal carbide insert, the experimentally observed tensile stresses in the non-hardened zone (Fig. 4a) are not predicted as precise. The temperature distribution (Figs. 4e and f) again predicts a more intense heat generation when turning hardened material zones.

6. Conclusions

Turning steel workpieces with a functional gradation in the form of different hardness values and consequent phases induced by the forming process led to tensile residual surface stresses in the non-hardened material and compressive surface residual stresses in the hardened material. The presented results show that the thermomechanically fully coupled two-dimensional elasto-viscoplastic model with inhomogeneously distributed initial stress is capable of capturing fundamental thermomechanical effects that are observed in experiments. In the hardened zones, high compressive stresses in the surface layer are precisely reflected (Figs. 3d and 4b), and the obtained temperature distributions (Figs. 3e, f and 4e, f) are in agreement with experimental observations. However, the distinct tensile stresses occurring in the non-hardened material zones are not captured precisely by the model at hand. Further research activities have to be carried out to investigate the influence of non-linearly graded initial stress distributions as well as temperature- and strain-induced phase-transformation. From a physical point of view, the loading conditions the material is subjected to are expected to induce phase-transformation in the surface layers – a physical effect inducing further complex stress-strain interactions. Apart from this, developing a 3D-extension of the model is of high priority in order to overcome restrictions inherent to the current 2D model.

Acknowledgements

This paper is based on investigations within the scope of the Transregional Collaborative Research Center/TRR30, research projects A3/B6/D2, and is kindly founded by the German Research Foundation (DFG).

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