Numerical modeling of residual stresses in turning of a 27MnCr5 steel

Frédéric Valiorgue*, Joël Rech

*Université de Lyon, LITIS, ENISE, 58 rue Jean parot, 42023 Saint Etienne, FRANCE

* Corresponding author. Tel.: +33 4 77 43 75 35; fax: +33 4 77 43 75 39. E-mail address: Frederic.valiorgue@enise.fr

Abstract

Surface residual stresses generated by machining remain a key issue for safety components of mechanical systems. Many simulations technics have been proposed. One of the most promising is to use the hybrid approach, which combines experimental characterizations with numerical computations. The hybrid method simulates equivalent thermomechanical loadings onto the machined surface without modeling the chip removal process. After a preliminary validation of this approach during the machining of an austenitic and a martensitic stainless steel, this paper aims at validating its application on a ferritic-perlitic steel 27MnCr5. This will confirm that the model is capable of predicting residual stresses for a wide variety of alloys.

1. Introduction

Machining and material removal processes in general remain the only way to obtain accurate metallic parts. The dimensional accuracy and the surface roughness are usually easily obtained by manufacturers since they are able to control these parameters on-line. On the contrary, residual stresses is a criteria hardly measurable and understandable by operators. So residual stresses have to be modeled off-line before the cutting operation. However there is currently no click-button software to predict residual stresses. To simulate the residual stresses generation, various strategies were developed by ([1-3]). These methods aim at simulating the cutting process, including the material removal mechanisms (chip formation) which induces long simulation duration and limits the modeling to a single brief cutting operation. On the contrary, in turning, a cutting tool has several revolutions and the surface integrity is a consequence of several passes. In order to overcome this limitation, the hybrid method was developed by ([4-6]). It has been applied successfully on austenitic and martensitic stainless steel and this paper will present its application on a 27MnCr5 steel. This will provide residual stresses profiles for a new steel in order to confirm the model relevance and improve scientist confidence in this approach.

2. Hybrid Method

The hybrid method is a numerical method to simulate residual stresses generated by a machining operation which focuses only on thermomechanical loads applied by the material removal process on the final machined surface (figure 1). It has been developed on SYSWELD®. This ‘chip less’ technic has proven its ability to predict quickly and precisely residuals stress field. It requires an experimental procedure to characterize several input data such as contact length, forces and chip cross section.
Frédéric Valiorgue and Joël Rech / Procedia CIRP 45 (2016) 331 – 334

The shape of the four thermomechnical loadings are detailed in [6].

2.1. Experimentations

The experimental campaign begins with a standard turning operation. The cutting tool is a TiN coated tungsten carbide one (TCMW 16 T3 08). The cutting conditions are the same as the one simulated:

- Cutting speed: 200 m.min\(^{-1}\)
- Feed: 0.23 mm.rev\(^{-1}\)
- Depth of cut: 0.5mm

During the machining operation, the cutting forces are recorded with a Kistler dynamometer. After, the contact length and the chip cross section dimensions are measured with a binocular microscope. The picture 2 and 3 present these results.

The model considers two zones: a direct contact zone and an indirect contact zone. Both are affected by a single cutting pass but in a different way. The width of the direct contact zone corresponds to the feed, whereas the indirect contact zone depends on the depth of cut and on the cutting edge radius. The indirect contact zone will be affected also during the next revolutions (figure 4).

2.2. Friction law

The friction law is a key parameter for the hybrid method. In this article the results obtained by [7] were used. The figure 5 presents the evolution of friction coefficient depending on sliding speed. The results were obtained for a TiN coated tungsten carbide pin against a 27 MnCr5 steel.

2.3. Equivalent thermomechanical loads calculation

One of the key step of the method consists in estimating the thermomechanical equivalent loads. Details are presented in [6]. Figure 6 presents the values ready to be applied onto the numerical model surface.
3. Numerical model

3.1. Model geometry

As described in [6], the simulation model consists of a representative parallelepiped with mechanical and thermal boundaries representing an embedded piece of 27MnCr5. The top surface, exchanging with the air, has a thermal coefficient of $5 \times 10^{-4}$ W·m$^{-2}$·K$^{-1}$ while the other five faces have a coefficient of 0.02 W·m$^{-2}$·K$^{-1}$. The meshes are linear quadrangles and their size is progressive with the smallest ones near the surface so as not to corrupt the thermal and mechanical gradients at the extreme surface [8] (Figure 7).

3.2. 27MnCr5 flow stress model

The material simulated is a 27MnCr5 annealed with a ferritic-perlitic microstructural structure with a 180HB hardness. As no dedicated flow stress is available, the thermo-mechanical behavior of this steel was calculated with the work presented in [9]. It is a Johnson Cook formulation with isotropic hardening. (Eq.1)

$$\sigma_{eq} = \left[ A + BC_{eq}^{n} \right] \left[ 1 + Cln \left( \frac{\dot{e}_{eq}}{0.001} \right) \right] \left[ 1 - \left( \frac{T-T_{amb}}{T_{fus}-T_{amb}} \right)^{m} \right]$$

The table 1 presents the flow stress parameters used to model the annealed 27MnCr5 plastic behavior.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>n</th>
<th>C</th>
<th>$T_{amb}$</th>
<th>$T_{fus}$</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>585</td>
<td>0.33</td>
<td>0.013</td>
<td>20</td>
<td>1460</td>
<td>1.1</td>
</tr>
</tbody>
</table>

4. Results

4.1. Experimental Results

The in-depth residual stress gradients are obtained with an XRD measurement device. These curves are typical residual stress gradient obtained after turning. The extreme surface tensile value is due to high temperature while in-depth compression results from extreme mechanical pressure between the tool and the workpiece. The values for 0.3mm depth are assumed to be pre-stress generated while elaboration process of the bars. In fact there is -100MPa of pre stress axial residual stress value and -180MPa for the tangential one.

4.2. Numerical Results

The residual stress distribution is irregular with a period corresponding to the feed rate of the machining operation. To compare the computed results with the experiments, it is necessary to average the numerical values “layer by layer”. This method is presented in [6]. Figure 8 presents the comparison between measured and calculated residual stress. Tangential direction corresponds to the cutting direction, while axial direction is collinear to feed. The XRD machine uses a 2 mm collimator so the stresses are averaged over several passes of the tool. To compare with numerical results, the calculated values are also averaged over 5 passes of the tool. This value is chosen because it allows to reach the steady state in terms of residual stress generation [6].
5. Discussion

The surface residual stresses values (measured and calculated) are very close. It confirms the interest of this approach and the flow stress model has been accurately identified. The in depth values concerning the compressive peek are also well matching. The calculated deepest values are also in good agreement with measurements and it reveals the importance of taking into account prior pre-stress induced by former process for accurate simulations.

6. Conclusion

In the past the hybrid method has been successfully applied onto martensitic and austenitic stainless steel and this paper presents its successful application to a ferritic-pearlitic steel. The experimental test consists in a standard longitudinal turning operation in order to identify the input data for the simulation. This step can be conducted within 2 hours. The preparation for the computation is reduced because all the programs are developed and ready to be used. The simulation step realized on SYSWELD® was performed within 5 hours by means of a standard computer. This new application of the hybrid method has shown that it is possible to predict a 3D residual stress field for a new tool/material pair within a single day.

7. References


