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Geometric distortion analysis using a combination of the contour method and machining simulation

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Abstract

During machining the material removal releases residual stresses introduced by previous process steps. This causes geometric machining distortions and thereby high rejection rates and costs. By simulating the process chain it is possible to predict this type of distortions. However, this requires advanced material models and accurate process- and material data for the individual processes. In order to simplify the modelling efforts a methodology that combines the contour method with machining simulation is proposed. The methodology is validated for an aerospace component using deep layer removal X-ray diffraction and CMM measurements. The methodology will improve possibilities to reduce machining distortions.

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1. Introduction

The problem of geometric distortions after machining is well known and causes high costs and rejection rates. Several factors influence distortions such as clamping forces, residual stresses induced from the tooltip and residual stresses induced from previous process steps. The latter will be released during machining and thereby influence machining distortions. This paper focuses on how to model and simulate the effects on machining distortions based on bulk residual stresses induced from previous process steps such as forging and heat treatment.

One approach is to simulate the complete process chain, and thereby predict the aggregated influence from the individual process steps on the final residual stresses. The most established numerical method is the Finite Element Method (FEM) where a continuum is divided into finite elements connected with nodes. Since the nodal and element data constitute both input and output data it is possible to establish a sequence of simulations of e.g. continuous casting, shape rolling, hot forging, heat treatment and machining.

The simulation of individual process steps are industrially established and e.g. forging simulation may be used in order to study how variations in press kinematics, forging tools and temperature of the workpiece influence the shape of the workpiece, the material filling in the tools and residual stresses after cooling [1]. Heat treatment processes, like case hardening and induction hardening can be simulated in order to study how variations in temperature, cooling time and cooling rate influence the residual stresses, hardness and phase distribution [2]. Simulation of machining processes, like drilling, turning and milling, may be used in order to study...
how variations in machining parameters and fixture design influence the workpiece shape, temperature and residual stresses. The chip removal can be simulated as a continuous material separation procedure where the finite elements close to the cutting tool are separated using a separation criteria [3]. Also instantaneous material removal is possible where the finite elements on the cutting side of the machining path are deleted using the level set method [4] or Boolean operations [5]. A simplified machining simulation approach is utilized in this paper and is described in section 2 and 3.

The establishment of a complete virtual sequence for prediction of aggregated properties is complex and requires several nonlinear material models, mapping methodologies as well as accurate material- and process data through the sequence [6]. This paper proposes a simplified procedure using the contour method [7] in combination with machining simulation. Here the contour method is used in order to acquire the aggregated residual stresses from process steps previous to machining. This information is used as input data to the final machining simulation. This will reduce the process simulation efforts, see Figure 1.

Figure 2, namely prediction of:

2.1 Out of plane stresses in cut sections  
2.2 Workpiece stresses  
2.3 Deformations after machining

The contour method uses the fact that a body that contains residual stresses will deform when cutting the body into sections. The tractions required to restore the deformed section to its original shape are equivalent to the residual stress released by sectioning. An alternative method is the slitting method [8] using strain gauges. However the contour method, using geometric optical measurement (GOM), may be beneficial for analysis of complex geometries.

One limitation, using the contour method, is that the calculated stresses are limited to the out of plane stresses from the cut sections. The method may be expanded to a 3-dimensional stress state using multiple cuts at 90 degrees [9] or 45 degrees from the first direction [10]. This paper proposes a numerical iterative approach for prediction of 3-dimensional stresses based on single cut measurements.

An overall methodology for prediction and adjustment of machining distortions is presented in section 2. The methodology is demonstrated in section 3, using an aerospace component and validated in section 4. The methodology includes a numerical iterative approach, using FEM, for prediction of 3-dimensional stresses and a simplified approach for machining simulation. The conclusions are summarized in section 5.

2. Methodology

The methodology includes three main activities according to Figure 2, namely prediction of:

Fig 1. Simplified method for analysing aggregated bulk stresses

Fig 2. Methodology
2.1. Prediction of out of plane stresses in cut sections

The first step is to cut the workpiece in planar sections at positions where the distortions are to be measured. In order to accomplish this, without imposing residual stresses from the cutting procedure, it is recommended to use an electric discharge machine (EDM). The sectioning of the workpiece leads to out of plane distortions that are recorded using GOM and stored as STL-meshes, see Figure 3.

The out of plane distortions are directly related to the out of plane stresses before sectioning and are applied as boundary conditions to a finite element model of one of the parts after sectioning. The displacement surfaces from opposite sides of the cut are averaged in order to improve the accuracy of the results [10]. Solving for equilibrium in the presence of the specified displacements provides the stresses acting normal to the plane of the cut in the original part.

2.2. Prediction of workpiece stresses

A simplified machining simulation approach is used where the cutting path is replaced by the CAD-surfaces of the final component. The first step is to position the CAD-model of the component in relation to the CAD-model of the workpiece. The next step is to mesh the CAD-model of the workpiece with a mesh topology including the cut sections and the CAD-surfaces of the component. The previously calculated out of plane stresses in the cut sections are then mapped onto the mesh. The next step is to calculate the out of plane stresses between the cut sections by means of linear interpolation. After mapping and interpolation a springback calculation is performed which, due to equilibrium, establish a 3-dimensional stress condition.

One problem is that this redistribution of stresses will cause the originally mapped out of plane stresses to decrease. To overcome this problem an iterative procedure with remapping of the out of plane stresses on the workpiece with subsequent springback calculation is suggested. This may eventually increase the out of plane stresses to its original level and result in a more correct 3-dimensional stress state.

2.3. Prediction of deformations after machining

The workpiece mesh, at the cutting sides of the CAD-model of the component, representing the removed material, is then deleted and a proceeding springback calculation is performed. The deformations of the component are then determined. If the deformations are out of tolerances, further tests should be performed with variations of geometries and cutting depths until the geometric distortions are within tolerances.

3. Demonstration using an aerospace component

The methodology is demonstrated using a test case, a forged and machined aerospace component in high strength nickel based alloy, see Figure 4.

The workpiece was hot forged in 1100 C with a screw press followed by solution annealing and then machining in several setups to final form. The geometrical shape had a tendency to drift out of tolerance and twist around the axial direction. The twist was max 0.51 mm and min -0.69 mm. The ambition was to set up a model for analysis and adjustments of the drift.

3.1. Prediction of out of plane stresses in cut sections

The workpiece was cut in 5 sections (0, 50, 90, 120, 240 mm) using EDM, according to Figure 5. The cut section displacements were then measured using GOM, see Figure 6, and translated into STL-meshes. Finite element models of the sectioned parts were generated. The displacement surfaces (x-displacement) from opposite sides of the cut were averaged and applied as boundary conditions to the models. The out of plane stresses (x-stresses) were then calculated according to Figure 7.
3.2. Prediction of workpiece stresses

Fig. 6. Cut sections with left and right side x-displacements between -0.2 mm (blue) and +0.2 mm (red).

Fig. 7. FE-models of the sectioned workpieces with applied x-displacements (left) and resulting x-stresses (right).

The workpiece and machined part were discretized with 500,000 tetrahedral elements. The mesh generation was performed with support from CAD-models of the workpiece and the component where the cut sections were integrated in the mesh topology, see Figure 8. The numerical simulations were based on the FE-software LS-Dyna with implicit solution scheme.

The calculated x-stresses in the cut sections were mapped onto the workpiece mesh and interpolated between the sections. For this purpose a mapping- and linear interpolation algorithm was developed in c-program code. The continuous distribution of the mapped and the interpolated x-stresses on the complete workpiece are illustrated in Figure 9.

A springback FE analysis was performed in order to obtain equilibrium and a complete 3-dimensional stress state. After the springback calculation the x-stresses decreased. Due to this fact a number of iterations of x-stress mapping and subsequent springback calculations were performed. This procedure increased the x-stresses and improved the 3-dimensional stress state. The iterative stress mapping procedure also improved the calculated displacements in the cut sections. This improvement was notified using a displacement test at cut section 3 where the differences
between the originally measured x-displacements, using GOM, and calculated x-displacements were noted, see Figure 10. The displacement test indicated good conformity between the displacement results after 5 stress mapping iterations.

Fig. 6. Cut sections with left and right side x-displacements between -0.2 mm (blue) and +0.2 mm (red).

3.3. Predictions of deformations after machining

The mesh of the removed material was deleted and a springback analysis of the remaining component mesh was performed with boundary conditions according to Figure 11.

The resulting deformations were used in order to examine the out of tolerance twist due to different machining setups on upper, lower, left and right side of the workpiece and increased workpiece thickness with 20 mm. Also, a geometry change of the component was tested where a stiffness bar was added at the downside of the component, see Figure 12. A major reduction of the twist was detected when introducing the design change whereas minor reductions were detected for the other options.

Fig. 7. FE-models of the sectioned workpieces with applied x-displacements (left) and resulting x-stresses (right).

Fig. 10. Comparison between measured (experiments using GOM) and calculated x-displacements in section 3 after 0 and 5 x-stress mapping iterations.

3.2. Prediction of workpiece stresses

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Fig. 8. FE-mesh of the workpiece with cut sections and with integrated mesh of the machined geometry.

The calculated x-stresses in the cut sections were mapped onto the workpiece mesh and interpolated between the sections. For this purpose a mapping- and linear interpolation algorithm was developed in c-program code. The continuous distribution of the mapped and the interpolated x-stresses on the complete workpiece are illustrated in Figure 9.

Fig. 9. Workpiece mesh with mapped and linearly interpolated x-stresses between the sections.

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Fig. 11. Out of plane stresses after material removal.

Fig. 12 Tests with different cutting positions, increased workpiece thickness and a change in component geometry.

4. Validation

4.1. XRD measurements

Residual stress measurements were performed using X-ray diffraction measurements (XRD measurements) and layer removal. The surface residual stresses were measured directly from the raw forged surface and down to a depth of 200 µm below the surface with aid of electro polishing. In order to measure deeper in the workpiece, milling of 25x25 mm pockets were performed. see Figure 13.

Then the surface was electro polished 300 µm in order to avoid any influence from thermo-mechanical stresses induced by the milling operation. This was carried out in subsequent steps of 5 mm down to a depth of 14.4 mm below the surface at the pockets (P). The calculated FE-results were compared with the XRD measurements according to Figure 14. The correlation was good except for the near surface stresses. The XRD measurements shows higher compressive stresses compared to FE-calculations at depth 5 mm. The reason may be due to the fact that the FE-mesh was too coarse in order to adapt stresses close to the surface and different positions of the pockets (P) and the cut section for the FE analysis. Deeper in the material the results correlated well.

Fig. 13. Prepartion of in depth pockets (P) for XRD measurements and the first cut section for FE-analysis (dotted line)
4.2. CMM measurements

The calculated results after 5 stress mapping iterations were compared with CMM measurements at the top surface of the component according to Figure 15.

The correlation was good except for the discrepancies discussed below. The calculated twist \(0.4 + 0.5 = 0.9\) mm was 25% lower compared to the measured twist (1.2 mm). The reason is deduced to the fact that the FE-model is restricted to bulk stresses whereas the CMM, besides from bulk stresses also include clamping stresses and thermomechanical stresses introduced from the machining. The differences on the left side (-0.69 compared to -0.4 mm) may be due to the fact that the boundary conditions \(y=0\) in the front of the FE-model does not coincide completely with the twisting pivot in the measurement.

5. Conclusions

An overall methodology for analysis and adjustment of machining distortions due to bulk stresses is proposed. The method utilize linear FE-analysis and reduces the need to simulate the complete manufacturing chain using advanced nonlinear simulation models of e.g. forging, heat treatment and machining. The proposed approach will thereby considerably reduce the modeling complexity and improve the calculation accuracy. The application shows good results compared to both the XRD- and CMM- measurements. The discrepancies are mainly deduced to the coarse FE-mesh as well as different measuring and analysis positions.

The method may be used in order to study how variations in machining setups, workpiece- and component geometry influence geometric machining distortions. In order to improve the accuracy a mesh convergence analysis should be included in the FE-calculations. Also a future development of the iterative stress mapping approach is recommended together with validation using nondestructive neutron diffraction technique.

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