GEOMETRIC DISTORTION ANALYSIS USING CAD/CAM BASED MANUFACTURING SIMULATION

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Machining of components may cause geometric distortions and thereby quality issues and increased costs. This paper presents an engineering approach of CAD/CAM based manufacturing simulation in order to be in control of geometric distortions after machining. The method utilises STEP AP209 for communication of CAD/CAM simulation data. The method improves the ability to optimise process parameters, geometry, and material, in order to fulfil the design requirements. The method supports concurrent design and process planning using 3D models in CAD/CAM and FEM.

Keywords: Process planning, manufacturing simulation, fixture design, CAD/CAM, FEM.

1. INTRODUCTION

The problem of geometric distortions after machining is well known and cause high costs and rejection rates. The necessary adjustment of process parameters in order to get correct dimensions and shape are today mainly based on "trial and error". This current approach is time consuming and there is a need for a more efficient method. Besides from a single manufacturing process itself also other factors like geometry, material and previous processes do influence the geometric distortions. Thus there is a need to consider all those factors when analyzing the geometric distortions after machining. This paper proposes a systematic methodology to be used in order to be in control of shape deviations. The methodology scope is process planning including fixture design, process simulation, and process design, starting during product design and completed during manufacturing preparation, see Figure 1. The method is based on a combination of Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) and process simulation using the Finite Element Method (FEM).

Section 2 describes possibilities and limitations with process sequence simulation and discusses various methods for machining simulation. Section 3 describes the proposed CAD/CAM based method whereas the usability is concluded in section 4. The study is delimited to manufacturing of forged components.

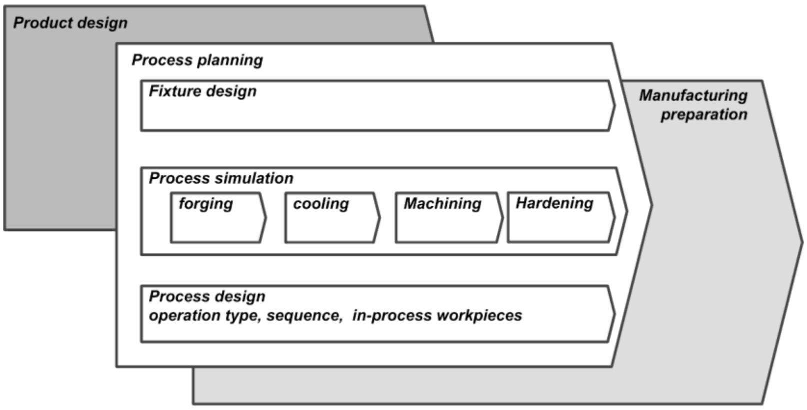

Fig. 1. Methodology scope for CAD/CAM based manufacturing simulation.

2. SIMULATION OF MANUFACTURING SEQUENCES

The physical state of a workpiece is the summation of the material transformations through several process steps and it is therefore important to use the output data from one process step as input data to next step in the process chain. Thus, when simulating geometric machining distortions on e.g. forged components it is necessary to simulate the previous processes, like forging and cooling, in order to develop the necessary input state variables to the machining simulation. A sequential simulation setup for hot forging, cooling and machining is schematically described in Figure 2.

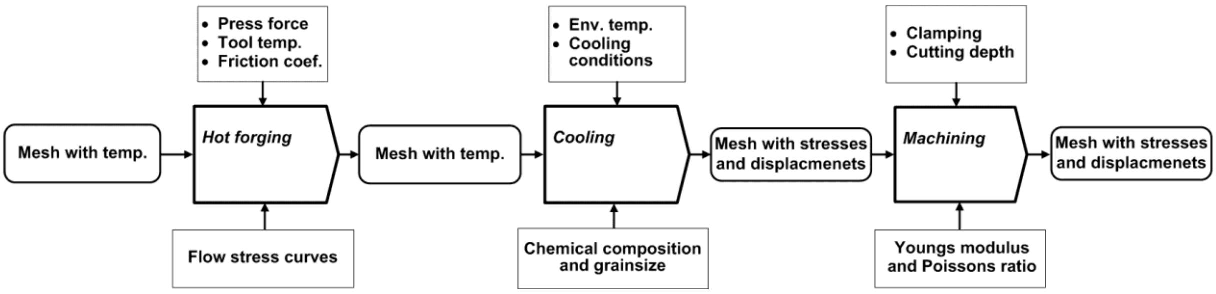

Fig. 2. Sequential simulation with typical process- and material data.

2.1. Forging and quenching simulation

During hot forging the workpiece is plastically deformed between the forging dies and it is well established to simulate the process using Finite Element based commercial simulation software´s like “Forge” and “Deform”, see (Hartley and Pillinger, 2006). The flow stress is described as a function of strain, strain rate and temperature and is retrieved from physical testing of the material see (Doege and Meyer-Nolkemper, 1986).

Quenching processes are possible to simulate using FEM with support from routines for thermo metallurgical phase transformations, see (Gur and Pan 2009). With support from information concerning chemical composition and average grain size it is possible to calculate the necessary input data using software´s like JMat Pro, see (Guo and Sanders, 2009).

2.2. Machining simulation

Typical machining processes such as turning, milling and drilling create the geometric shape using a cutting tool that removes material from the workpiece. One approach is to simulate the *local* surface deformations with support from stress strain related material formulations according to e.g. Johnson and Cook, see (Umbrello 2008). The chip removal is simulated as a continuous material separation procedure where the elements close to the cutting tool are separated using a damage criterion. Another approach is to simulate the *global* workpiece deformations using techniques for instantaneous material removal. The material removal may be accomplished using the level set method, see (Belytchsko *et al*., 2001), where the elements are deleted on the cutting side of a geometric machining path or by deleting elements using Boolean operations. The Boolean operation approach in conjunction with the software Deform, is described below for a crown wheel, see Figure 3.

Fig. 3. Crown wheel (left) and pinion (right).

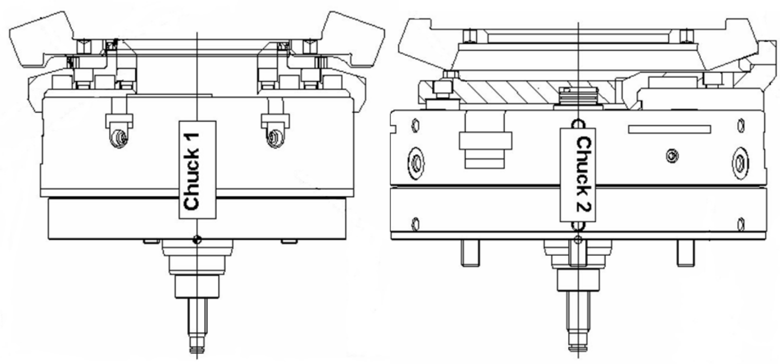

Fig. 4. Clamping in chuck 1 and 2.

Two turning operations are performed in sequence, using chuck 1 respectively chuck 2, see Figure 4. The clamping force from the 3-jaw chuck is applied at the inside of the ring in chuck 1 and in the second operation the workpiece is rotated upside down and the clamping is applied at the outside.

The workpiece mesh with a residual stress field is imported from the previous forging and cooling simulation. Solid models for the clamping devices are created and applied against the workpiece using contact elements. The clamping force is applied and the deformations with accumulated stresses are simulated using a linear Finite element (FE) analysis. In the next step the machining features are modeled as 3D solid models and the material from the workpiece is removed instantaneously where the solid model of the machining feature "cut away" elements from the workpiece using a Boolean operation. A new solid model of the remaining geometry of the workpiece is created and re-meshed and the stress field from the initial workpiece is then mapped onto the "machined" workpiece mesh. In the last step the clamping force and support tool is removed and a linear "spring back" analysis is conducted. The machined workpiece mesh from chuck 1 with residual deformations and stresses is used as input to the next machining operation in chuck 2 where the procedure is repeated. Since this type of machining simulation is conducted using a linear elastic material model it is sufficient to define Young´s modulus and poisons ratio for the material. The methodology is illustrated in Figure 5 using the global machining simulation integrated as a CAD/CAM based simulation tool.

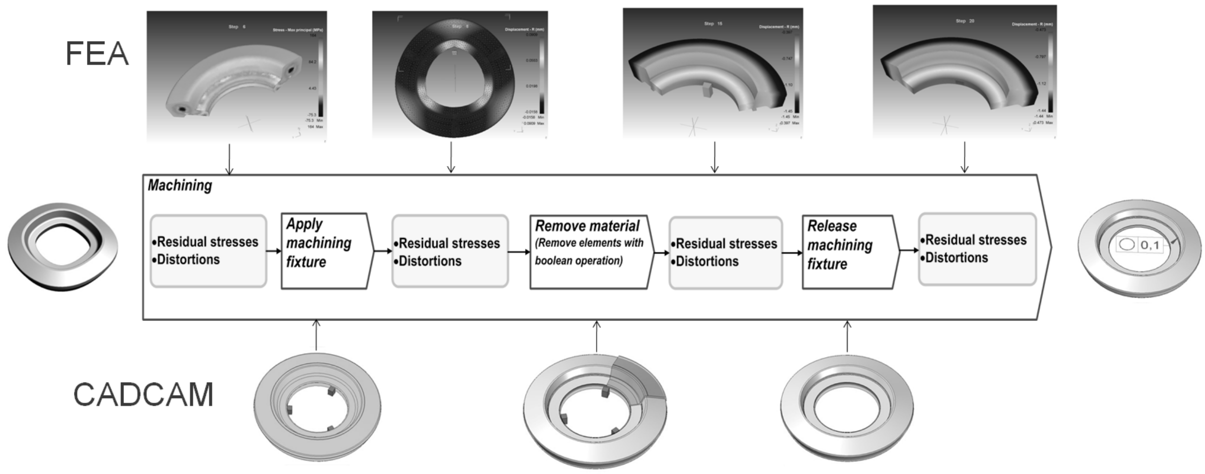

Fig. 5. Machining simulation in chuck 1, starting with input data from previous process step.

The above mentioned methods and models describe material transformations on a macroscale level. However, in order to study the effects on product properties from grain deformation, recrystallization and material segregation it may be necessary to define and connect models on several levels depending on the phenomena which are under consideration. For this, Madej *et al*. (2008) describe various approaches for connection of various scales of models for a process step. A future vision is to establish a sequence of interconnected models on various scales, from macroscopic descriptions down to atomistic levels, see Figure 6.

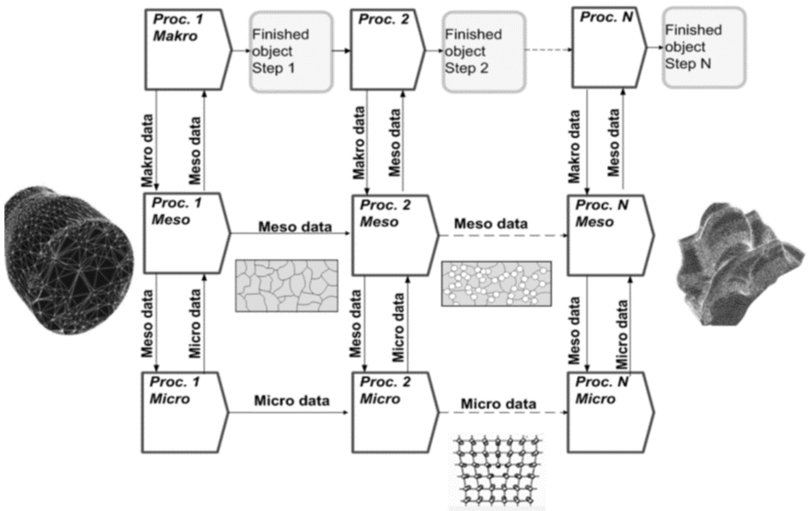

Fig. 6. Multiscale modelling of manufacturing processes in a sequence.

In order to describe e.g. the influence of anisotropic phenomena on distortions, like banded microstructure and grain flow, it may be necessary to include several scales of modelling. This is a subject for research and e.g. Simsir *et. al*. (2012) describe a simplified method for retrieving the banded microstructure after forging using the output flow net topology as a support for the development of an anisotropic mesh for heat treatment simulation. Thus the material transformations through a sequence of manufacturing processes is complex and depends on a variety of material and process parameters, see Figure 7.

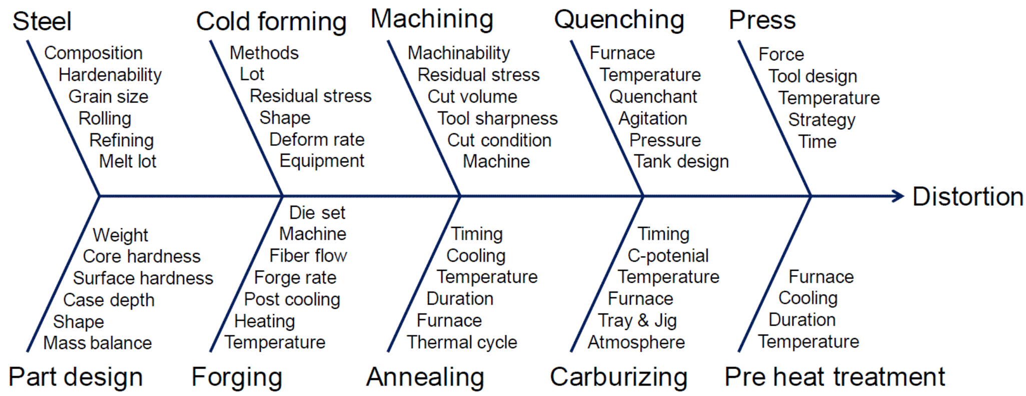

Fig. 7. Potential reasons for distortions, see (Bagge, 2014).

Regardless of the described limitations the simulation of manufacturing sequences may be used as an engineering support when selecting process steps and optimising process parameters.

2.3. CAD/CAM based process simulation

No effective integration of process simulation in CAD/CAM to be used in process planning has been found in literature. Cunningham (2010) describes a module within the Deform simulation software to be used for process planners in order to optimise select and optimise process steps. The module consists of workpiece and process attributes. The workpiece object attributes include geometry, which can be supplied from a 2D CAD-file, material data and mesh density. The process attributes include process parameters, tooling and fixtures etc. and by assembling these objects a sequence of operations can be built up and simulated, beginning with workpieces in their initial state which are then subjected to successive processes, each of which determine the new attributes of the workpiece. The above described approach is however not integrated with a CAD/CAM system.

Several options exist for communication of data between process step models and Werke (2009) has developed software for data communication between Abaqus, Deform, Forge, MSC Marc and LS Dyna, whereas Afazov *et. al.* (2012) has developed software for data transfer and mapping, between Abaqus, Ansys, MSC.Marc, Deform and Morfeo. Another possibility is to utilize ISO 10303 (STEP) for data representation and communication with Application Protocol 209 (AP 209) addressing integrated CAD- and FE-models. The FE representation is illustrated in Figure 8. With support from ISO 10303-209 it is possible to communicate CAD-models, FE-models and simulated data like stresses, strains, displacements and temperature.

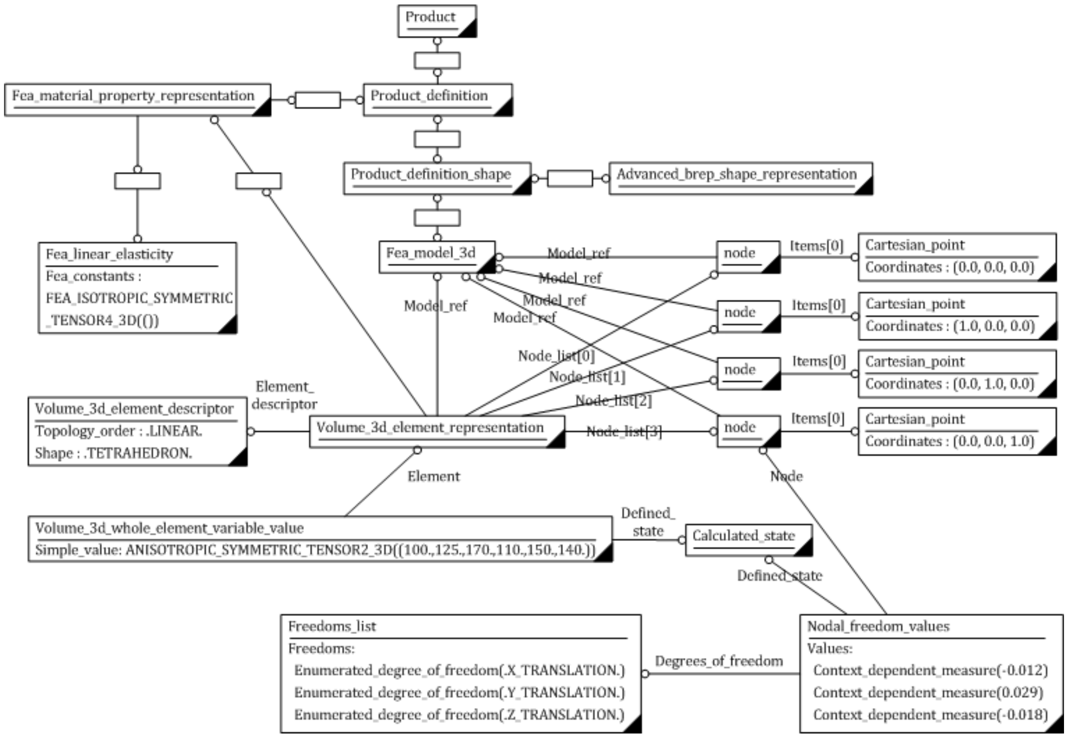

Fig. 8. Illustration of STEP AP209 data set for FE representation.

3. METHOD

Based on the discussions above a CAD/CAM based process simulation methodology for distortion analysis is proposed. The method consists of the following main activities, see Figure 9:

- Design component and fixtures in CAD
- Simulate forging, cooling and machining
- Analyze concept
- Prepare machining in CAM

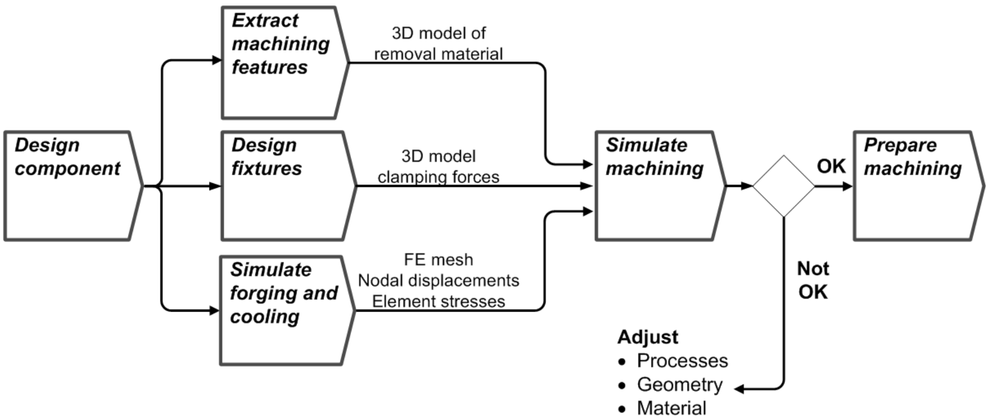

Fig. 9. Process planning using CAD/CAM based machining simulation.

3.1. Design of component and fixtures in CAD

The component is designed in a CAD system and intermediate machining workpiece models are developed. These models are achieved through calculating the material that is planned to be removed during each machining operation. The removed volumes are generated as separate solid models and identified as features in the product CAD model. The fixture is developed as solid models in the CAD system with localization surfaces, clamp positions and the clamping force to be used as input data for machining simulation.

3.2. Simulate forging, cooling and machining

The CAD model of the component is used in order to create CAD models of the forging dies and the billet. Typical process parameter variations that may be studied are billet temp, press force, tool temperature and lubrication. Also variations in material (variations in flow stress curves) may be studied.

The workpiece output from the forging simulation concerning geometry, mesh and temperature are used as input to the proceeding cooling simulation which is performed in a sequence with the forging simulation. Typical process parameters that may be varied are environmental temperature and cooling conditions. The output mesh with element stresses and nodal displacements are used as input to the proceeding machining simulation.

The models of the fixtures, machining features and machining raw piece are assembled in the CAD/CAM system and translated to machining simulation. Several steps of virtual machining are then performed where the output residual deformations and residual stresses from one machining setup are used as input to the proceeding machining operation, as described in Figure 5. The communication of data between the simulations of the process steps and between the simulations and the CAD/CAM system is performed conforming to STEP AP209.

3.3. Analyse concept

The effects from the variations in processes, material and geometry on the final displacements are analyzed using methods like full factorial design of experiments, see (Wärmefjord *et al*., 2014). Typical machining process parameters that may be varied are the number of machining setups, the cutting depth, the fixture design and clamping forces in each setup. Also the effect of variations in previous processes and component geometry may be studied, see Figure 10.

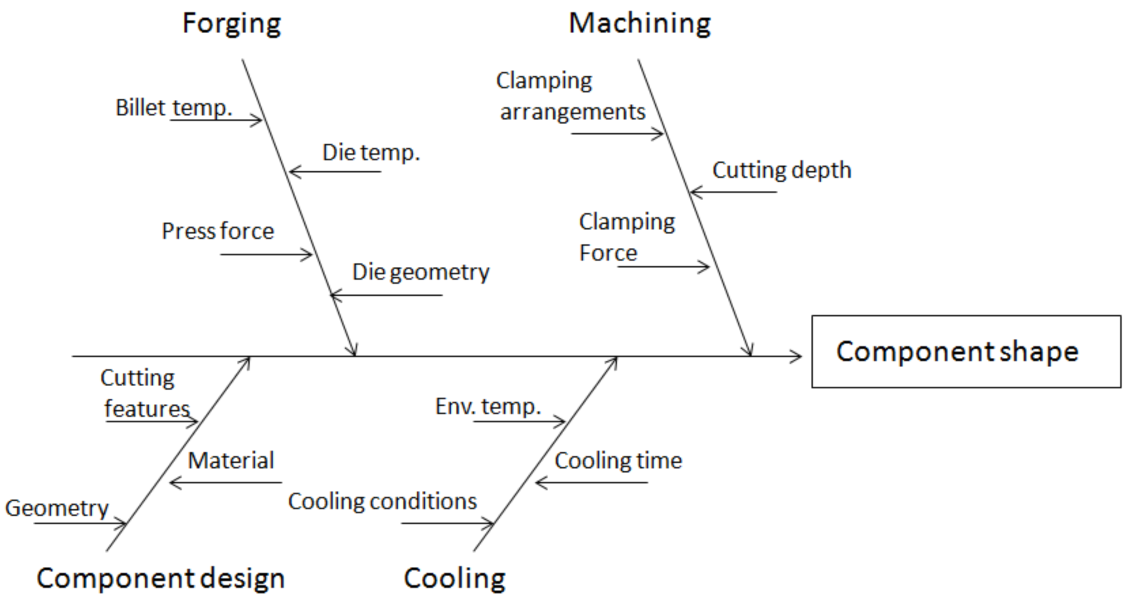

Fig. 10. Illustration of parameters to be analysed with support from the CAD/CAM based simulation methodology.

3.4. Prepare NC data in CAM

When all the necessary adjustments are performed and the product and process data are verified the final preparation of the machining operations are done in the CAM system. This includes e.g. detailed cutting tool data, fixture set-up and NC code.

5. CONCLUSIONS

This paper presents an engineering approach of CAD/CAM based manufacturing simulation in order to be in control of geometric distortions after machining. The communication of data between CAD/CAM and simulations can be performed conforming to STEP AP209. The method supports concurrent design and process planning using 3D models in CAD/CAM and FEM and has the potential to reduce machining distortions, product development time and costs. Several process parameters that influence distortions through a manufacturing sequence can be analysed such as fixture design with its clamping location and forces.

Future work should include further validation of the efficiency of the method in fixture design, integration of heat treatment simulation in the virtual simulation sequence and implementation of the method in a commercial CAD/CAM system using STEP AP209.

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