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*part distortion,  
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## **SIMULATION OF PART DISTORTION IN MILLING OPERATION OF FORGED AEROSPACE COMPONENTS USING BOOLEAN SUBTRACTION**

Aerospace industry requires the production of complex, multi-functional components with very low geometrical tolerances using difficult to machine materials such as Ti-6Al-4V. One of the main challenges when machining such materials is the resulting part distortion after milling due to the release of residual stresses generated in previous manufacturing steps such as forging or heat treatment. To prevent costly scrap parts and manual rework, finite element method (FEM) can be utilized to predict resulting part distortion during the machining process development phase. This paper presents a novel approach for part distortion simulation by directly integrating relevant machining data from computer aided manufacturing (CAM) system for the FEM using Boolean subtraction operations. A developed software interface enables a step-by-step mechanical material removal simulation providing manufacturers with an efficient and flexible tool for automated process evaluation. The approach is implemented in a laboratory setup using commercial CAM and FEM systems and evaluated by using aerospace relevant demonstration parts.

### **1. INTRODUCTION**

Part distortion is one of the main concerns during milling of components like forged, aerospace parts. In a 2001 report, Boeing estimated that stress-related distortion led to additional annual costs of 280 MEUR, factoring in rework and scrap [1]. A main reason for part distortion is initial residual stress generated due to pre-machining process steps such as forging and heat treatment. Forging induces residual stress through plastic deformation [2] while heat treatment relaxes these stresses and can introduce new ones due to non-uniform thermal gradients [3]. During final machining such as milling processes, these initial residual

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stresses are released leading to part relaxation and potentially cause severe quality problems [4]. In the aerospace supplier market, modification of manufacturing processes after customer approval is often not possible, thus, virtually optimizing the final machining step using physics-based multi-step simulation during the process development phase is desired [5].

Recent research focuses on the application of numerical models such as finite element method (FEM) to simulate the material removal process. Wei et al. [6] used FEM to predict machining deflection due to initial residual stress in symmetrical aluminium parts. Material removal is modelled using element deactivation method, which deactivates workpiece mesh elements according to a predefined machining sequence and cutting toolpath [7], requiring extensive manual modelling and programming effort when applied for complex workpiece geometries and machining strategies [8]. Cerutti et al. [9] analysed part distortion behaviour of aluminium aerospace structural components using FEM and the Massive Removal Method, highlighting the importance of the part position within the raw material blank and the machining sequence. A comparison of Boolean deactivation and Massive Removal Method is given in [10]. In Landwehr et al. [11] a Finite Cell Method (FCM) is applied to numerically evaluate the impact of final machining on part distortion for aerospace titanium components. Compared to the Material Removal Method, FCM avoids computationally expensive re-meshing steps utilizing a voxel-based workpiece mesh, Boolean subtraction and cutting volume geometries. Fixture layout is another important factor when analysing final part distortion [12]. Research highlights a correlation of distortion with the positioning and the number of clamping elements [13]. However, several studies such as Landwehr et al. [14] on part distortion refrain from integrating the influence of the fixtures in their simulation models and assume stable clamping conditions. The presented modelling approaches require various data inputs such as cutting tool geometry, cutting toolpath, machining sequence and fixture setup to simulate the material removal process accordingly. For easy part geometries and machining processes, these inputs can be implemented manually in the FEM directly. However, more complex setups typically require specialized computer-aided-manufacturing (CAM) systems to create and maintain the relevant data. Cerutti et al. [15] mentioned potential use of such CAM systems for efficient provision of machining data towards FEM systems for part distortion analysis using Boolean subtraction. In the context of additive manufacturing, a FEM-CAM software interface is demonstrated by Maier et al. [16], linking CAM generated toolpaths and FEM mesh to automatically model the deposition process. However, while the importance of interoperability and defined system interfaces increases [17], technical use-cases demonstrating end-to-end integration of commercial CAM and FEM systems in the context of part distortion analysis remain limited.

In summary, post-machining part distortion is investigated by various researchers applying different numerical methods. However, the majority of previously work is limited to simulate simple part geometries and material removal processes. To sufficiently analyse aerospace typical free-form part geometries and the influence of various machining strategies on part distortion, an enhanced simulation workflow integrating CAM and FEM systems is required, however, is not yet demonstrated in literature.

The goal of this paper is to develop an integrated method for part distortion simulation after final machining processes utilizing relevant data from CAD/CAM programming systems. This advances the state-of-the-art by enabling distortion simulation even for free-

form geometries such as forged components and complex machining processes using numerous cutting operations, cutting tools and clamping conditions. By developing a FEM-CAM interface using commercially available software systems, an automated simulation workflow is created, providing a useful engineering tool to understand and mitigate the influence of residual stress and machining strategies on final part distortion. The approach is evaluated using a forged and heat-treated Ti-6Al-4V aerospace relevant demonstration part. Various cutting experiments and part distortion measurements are performed.

## 2. DEVELOPMENT OF PART DISTORTION SIMULATION

Based on state-of-the-art modelling approaches, an automated simulation workflow for part distortion simulation is targeted. The workflow considers model input from previous manufacturing stages such as forging or heat treatment, relevant machining data from CAM systems, as well as the clamping configuration, and performs part distortion simulation utilizing Boolean subtraction method.

### 2.1. SYSTEM ARCHITECTURE

The goal of the proposed method is to provide an automated simulation workflow capable to perform part distortion simulation even for complex part geometries and machining processes. In the envisioned system, a FEM tool is responsible for computing the physical part distortion caused by the initial residual stress field, selected machining strategies as well as clamping configurations. Complementary, a CAM system provides relevant data about the planned machining strategy such as selected machine setup including clamping elements, cutting tools and respective toolpaths, the machining sequence as well as relevant technological cutting data. The numerical part distortion simulation is built on Boolean subtraction method and requires four main inputs in order to compute a material removal simulation: (a) CAD geometries of the workpiece blank, (b) initial residual stress condition of the part after the pre-machining steps, (c) detailed information about the final material removal process including the cutting volumes for Boolean subtraction, and (d) data about utilized clamping geometries, position and respective clamping forces. Required data inputs for the FEM simulation are created within the CAD/CAM system as well as previous FEM simulations and can be exchanged using available software interfaces to automatically generate and execute the simulation workflow addressing the material removal process. Figure 1 illustrates the main elements considered in the presented model.

To enable automated simulation workflows, an interface for data exchange between the selected FEM system and a CAM software is proposed. At full integration, a CAM process plan is imported into the FEM environment and used to automatically generate the model setup including mesh and boundary conditions, define the cutting sequence, and execute the numerical simulation. For this study, commercially available software systems DEFORM 3D v14.0.1 (FEM) and NX CAD/CAM v2412 have been selected exemplary. DEFORM enables

a distortion simulation workflow module built on Boolean subtraction method for material removal and an open file-based structure for data exchange. NX CAD/CAM enables the creation of complex machining setups and multi-axis toolpaths, which are accessible via their proprietary interface NXOpen. Both systems are frequently used in the aerospace industry, thus, support industrial know-how transfer of the proposed concept. In DEFORM, machining workflows can be configured by linking initialization, boundary conditions, and stress equilibrium steps with process actions such as clamping, unclamping, and material removal sequences.

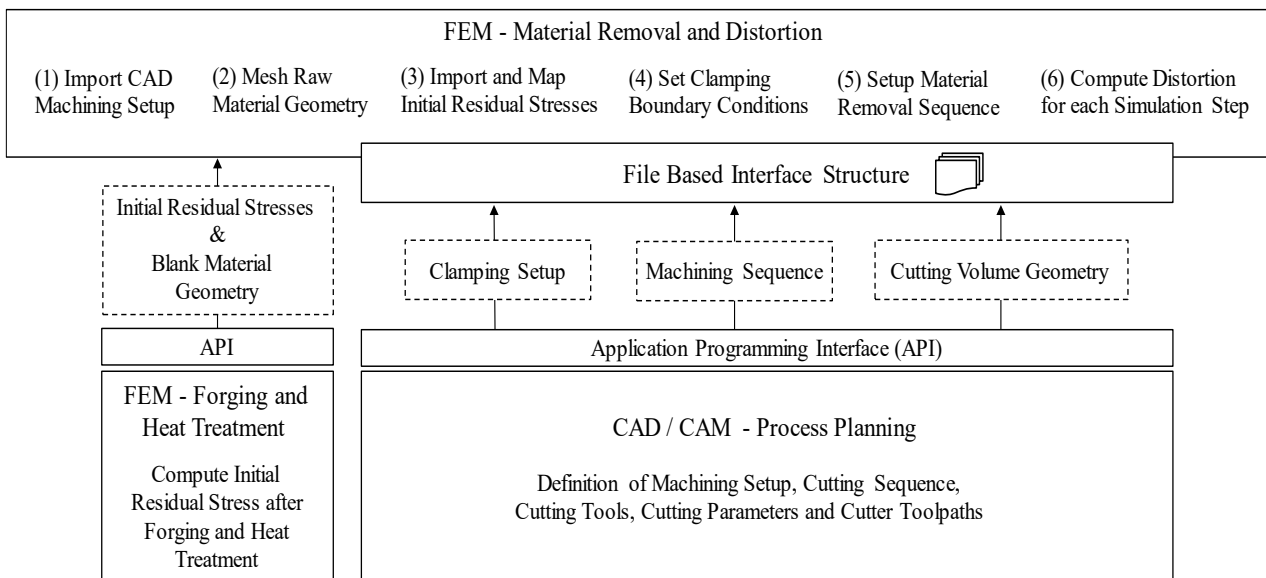


Fig. 1. Overview about envisioned system architecture

## 2.2. FEM-CAM SOFTWARE INTERFACE DEVELOPMENT

In the beginning, the user defines the starting point by setting up the blank workpiece including the mesh and initial residual stress conditions from pre-machining steps such as forging or heat treatment. The initial conditions are imported through a DEFORM specific .key file that contains the initial finite element state, including node coordinates, element definitions, connectivity, and stress tensors. Pre-machining steps may be computed in external FEM tools such as ANSYS or ABAQUS and transferred to DEFORM via its import functions. Next, model boundary conditions need to be added. In the context of part distortion simulation, reflecting clamping and unclamping of the part is of particular importance. Fixture geometries such as vises, chucks or custom-designed jigs can be imported using .key or .stl file format and required fixture-workpiece-contact boundary conditions can be set. Changing a setup from “clamped” to “unclamped” in the workflow is modelled by prescribed motion of the fixture bodies to define the constrained contact interface and vice versa. When executing the workflow, the model adaptations are done automatically by DEFORM. Building on this, one can set up various “cutting steps” in the workflow. A cutting step requires a cutting

volume as .stl mesh, to subtract this geometry from the original workpiece, thus performing virtual material removal. Depending on the required resolution, one cutting volume may represent the full operation or be split into multiple volumes representing milling steps. If a cutting volume passes through existing elements, DEFORM splits the intersected elements and generates new elements along the cut boundary, producing a clean edge largely independent of the initial mesh topology. Related stresses are projected onto the new element centroids to preserve a consistent stress field. Cutting volumes are imported as separate bodies, so their position and geometry remain fixed in space even if the workpiece deforms before a cut, so Boolean subtraction with CAM imported cutting volumes requires the workpiece and cutting volumes to share the same coordinate reference system. If the part deflects into the toolpath, the next operation removes the material located in that spatial cutting volume. This avoids the implicit transfer of prior distortion between cutting steps and provides a more realistic model of the physical cutting process. Lastly, a computation step is added to the workflow, performing numerical calculations to simulate the residual stress equilibrium and related part distortion accordingly. The system can execute any number and combination of the described workflow steps. Additionally, the entire workflow and model setup is driven by a file based, open project structure which can be modified manually, or automatically using suitable programming tools such as PYTHON. This provides a flexible interface to interact with a variety of CAM systems.

In the present study, the focus was on generating and extracting cutting volumes from a Siemens NX CAD/CAM setup for machining distortion simulations in DEFORM. In NX CAD/CAM, the CNC machine, the fixtures, the blank, the final part geometry, the machining operations and their logical sequence, tool geometry and technological cutting parameters are put together into a virtual model of the actual machining process for the respective part. After setting up the virtual process, the system derives cutting toolpaths for each operation and provides geometrical material removal simulation. Utilizing the application programmable interface (API) NXOpen, one can generate and export relevant geometrical and technological data fragments that can be deployed within an automatic simulation workflow in DEFORM. At least the following data from CAM are relevant for an automated workflow in this study: (a) the number and sequence of the cutting operations, (b) geometries and position of fixture elements as .stl mesh and most importantly (c) the cutting volumes for the Boolean subtraction for each operation as .stl mesh. Geometric and positional consistency across CAM and FEM remains critical. The CAM setup should use the FEM blank and global coordinate system as the common reference for toolpaths, fixtures, and cutting volumes. A practical approach to import the meshed FEM geometry into CAM and use it as the blank for toolpath generation. This keeps all CAM derived inputs in a shared coordinate system. Using different blank geometry sources might lead to remeshing, boundary deviations, and discretization differences, which can compromise Boolean subtraction. Furthermore, the number and sequence of cutting operations can be derived by simply using standard functions of the provided interface. Additionally, one can add clamping/unclamping information on each operation (e.g. as User Defined Event, UDE) that can be extracted via NXOpen as well. Next, the position of the fixtures and their bodies can be saved as .stl files using standard functionality in NXOpen. In general, the fitting surfaces of the workpiece and its fixtures are used for part alignment in the virtual setup of the machining process in the CAM. This

information can be used to define the fixture elements as rigid bodies with contact pair conditions to restrict the movement of the workpiece. For each operation, the respective cutting volume needs to be exported and saved as .stl mesh in the workflow of DEFORM. An automatic cutting volume generation is essential for an overall automated workflow and scalability of the system towards complex, free-form aerospace components. Considering state-of-the-art literature, cutting volumes can be generated in conventional CAM systems by generating swept solids derived directly from the cutting tool geometry and toolpath. For complex, multi-axis machining, this requires generating separate swept volumes per operation, which increases setup effort and can be computationally expensive for long toolpaths with multiple depth increments. An alternative approach utilizing the in-process-workpiece (IPW) and a bounding box is presented in this study. The IPW represents the targeted geometry after a certain material removal operation. Using NXOpen, this IPW can be automatically subtracted from a bounding box enclosing the workpiece area, thus creating a negative of the target geometry. This resulting geometry can be exported and saved as .stl mesh for later use in the actual Boolean subtraction of the FEM system. The proposed method generates tool independent cutting volumes, optionally groups similar operations, and rapidly translates CAM setups into FEM input. Lastly, all data generated and extracted via NXOpen interface can now be used to automatically set up the simulation workflow and the file structure in DEFORM. Data extracted via the NXOpen interface is transformed and written into the DEFORM project structure, including the required directory layout, operation definitions, and mesh bodies, so that the simulation can be executed directly in the DEFORM Integrated Manufacturing Editor. Figure 2 illustrates the steps to derive cutting volumes in NX CAD/CAM for the Boolean subtraction and part distortion simulation in DEFORM.

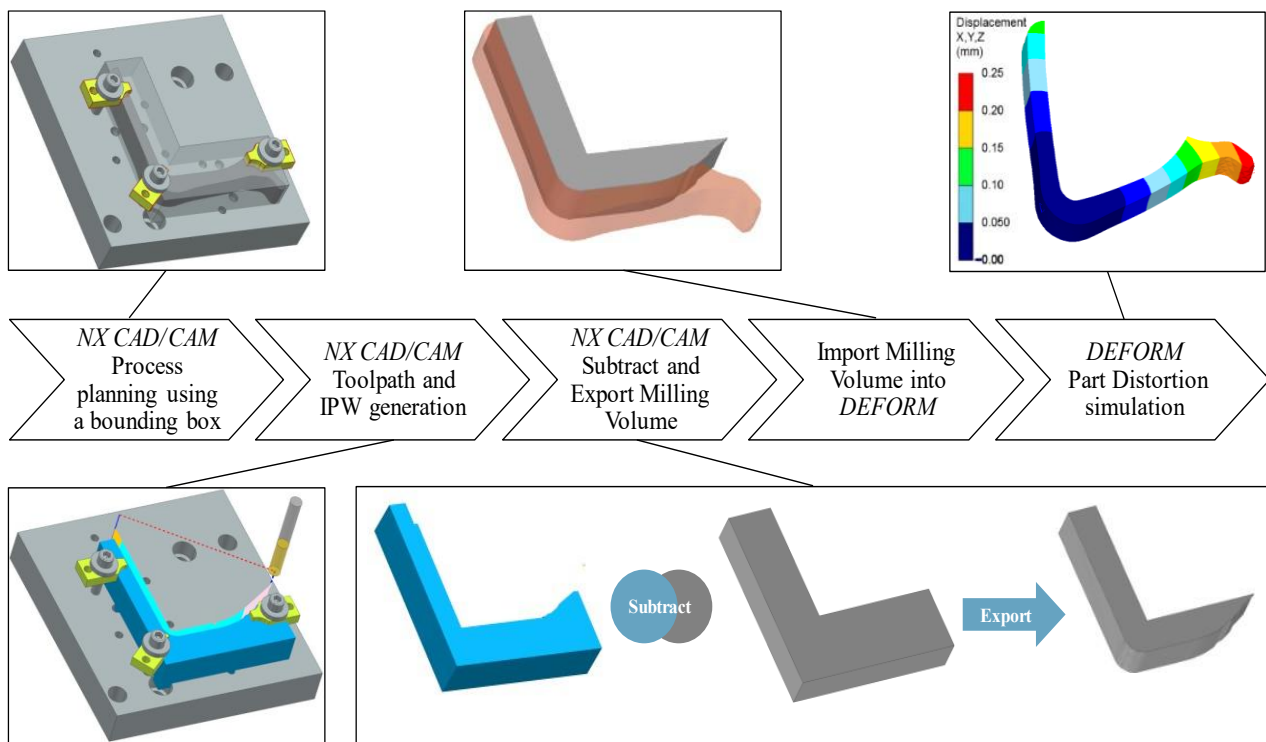


Fig. 2. Process to derive cutting volumes in *NX CAD/CAM* for Boolean subtraction and distortion simulation

### 3. FEM MODELLING OF DEMONSTRATOR PART

Utilizing the proposed simulation chain, an aerospace relevant demonstrator component was developed, modelled in FEM and machined for validation purposes. The workpiece is made of Ti-6Al-4V and was manufactured following an industrially representative route consisting of forging and subsequent heat treatment. The blanks were sectioned by wire electrical discharge (EDM) into nine 20 mm thick angle specimens, and the central specimens were selected for later validation of the simulation results. As a starting point for the material removal and part distortion simulation, the initial residual stress condition of the overall part and the specimens need to be determined. The initial residual stress state was computed using a heat treatment simulation in ABAQUS FEM software and validated experimentally by X-ray diffraction measurements and Cut Compliance measurements taken at various locations. The forged blank workpiece was virtually divided into smaller specimens simulating the EDM process, and respective final computation of initial residual stresses has been executed. After specimen separation, stress magnitudes decrease, but the spatial distribution is assumed to remain comparable across specimens. Geometric variability, surface roughness effects on measurement, and position dependent material property variations are neglected. The initial stress distribution of the demonstrator and middle specimen is showcased in Fig. 3, indicating tensile stresses in the centre of the part, and compressive stresses in the outside region, which is a typical residual stress pattern after heat treatment.

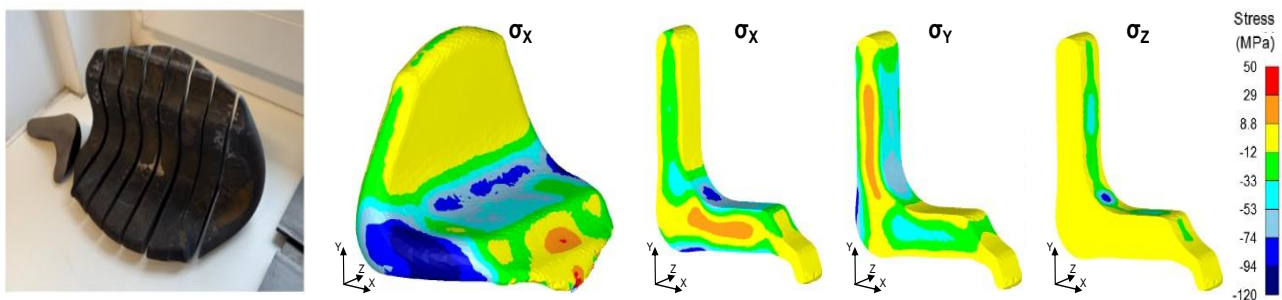


Fig. 3. Demonstrator workpiece cut into 20 mm thick blanks by EDM; Initial residual stress simulation after heat treatment for full demonstrator; initial residual stress result for specimens after EDM

The initial condition of the specimen after heat treatment and EDM is imported into DEFORM as a starting point for the final material removal and part distortion simulation workflow. The material response is modelled as isotropic linear elastic, consistent with common assumptions in the literature. The elastic parameters used in this study were adopted from the DEFORM database with 117 GPa (Young's modulus) and 0.31 (Poisson's ratio). In parallel, planning of the machining process starts in NX CAD/CAM accordingly. In this study, three different machining strategies (series) are deployed for the specimens. Series 1 and 2 machine the front inner side of the workpiece using an axial depth of cut of 11 mm and a target internal angle of 90 degrees. In Series 1, the fixture clamps are released in a clockwise sequence, starting with the bottom right clamp on the X axis. Series 2 isolates the fixture related influence by reversing the release sequence to counterclockwise starting with the top

left clamp on the Y axis, allowing the effect of the unclamping order on distortion to be quantified. Series 3 machines the outer side of the workpiece using the same 11 mm depth of cut and a 90-degree target geometry, and unclamping starts with the bottom right clamp on the X axis. This series serves two purposes. First, it provides an additional machining case for validating the simulation framework under modified boundary conditions. Second, it supports process interpretation by quantifying how changes in the location of removed material within the blank are reflected in the resulting distortion direction. After milling, each series uses an additional internal clamp before measurement to limit rigid body motion during unclamping and to keep the component referenced to the baseplate while minimally constraining distortion. An illustration of the investigated machining strategies is given in Fig. 4.

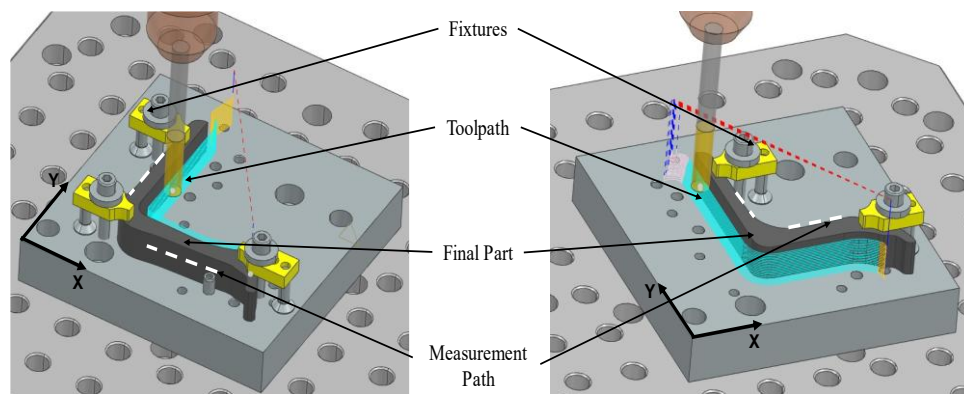


Fig. 4. NX CAD/CAM fixture and milling strategy for testing/validation purposes; left: series 1 and 2, right: series 3

Using the developed FEM-CAM interface, required cutting volumes for the simulation workflow are generated and exported. The blank workpiece geometry is imported with the initial conditions from ABAQUS and does not need to be provided again by the CAM system. To assess mesh sensitivity, simulations were carried out with 100 000 and 350 000 elements. The predicted distortion showed no significant deviation between the two discretisations, indicating limited benefit from further refinement. The 100 000-element mesh with a minimum edge length of 0.3 mm was therefore adopted in this study, as it provides sufficient accuracy at a reasonable computational cost. In DEFORM, contact interactions are defined through the geometric separation between the bodies. The fixture bodies and the machine table are defined as rigid bodies, following established modelling practice. Rigid clamping is assumed on the basis that deformation at the clamp contact locations remains negligible during milling. The applied clamping torque was selected to prevent slip during machining, such that the contact region beneath the clamps remains fixed. This was verified by comparing CMM measurement path coordinates before and after machining, prior to fixture release, which showed close agreement and negligible distortion during machining. Distortion is therefore expected to develop predominantly during unclamping, as the stored residual stress field is released, although for more complex parts with a pronounced Z component that cannot be tightly clamped, part distortion may already occur during machining. Consequently, all machining steps within a single clamping condition are evaluated together and are represented by one equivalent cutting volume, which reduces model complexity while retaining the global

distortion response. This simplification of the material removal modelling should be reconsidered for more complex parts with multiple features, where machining sequence effects and local stiffness changes due to progressive material removal may substantially influence the overall distortion. The FEM-CAM coupling used in this study supports such refinements, for instance by exporting separate cutting volumes for individual pockets or milling operations. The simulation results are shown in Fig. 5.

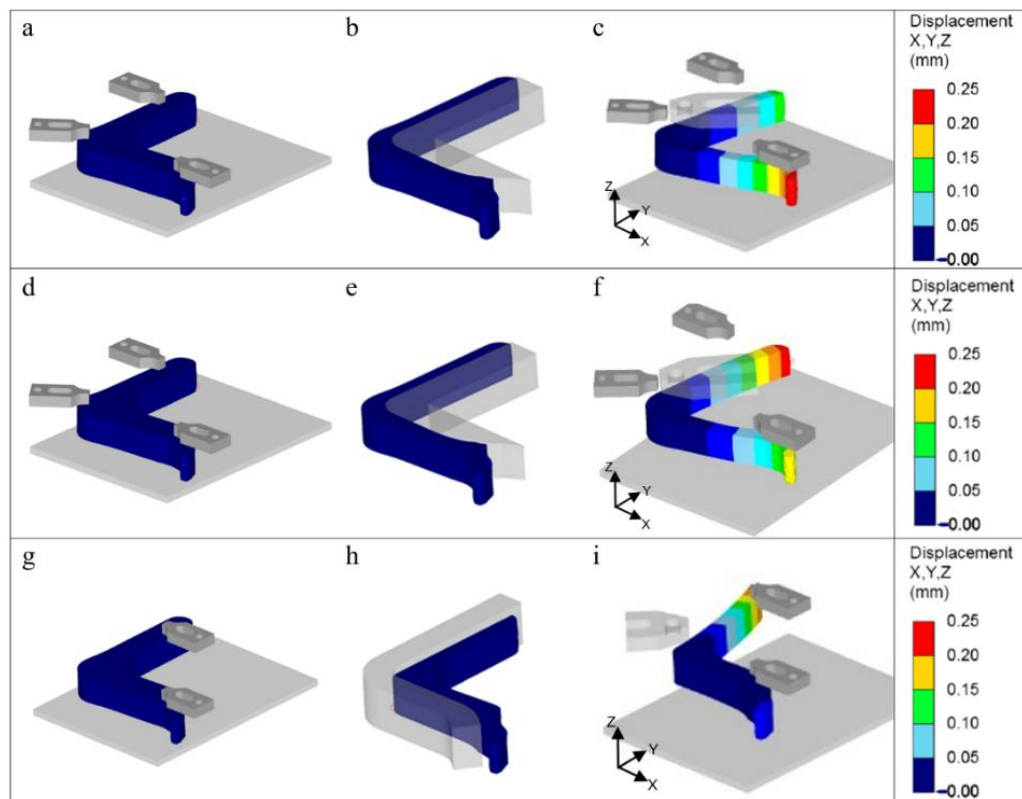


Fig. 5. Milling strategies for validation; Series 1 (a-c), Series 2 (d-f), Series 3 (g-i). For each series, the subfigures depict the initial state, the material removal step, and the final distortion after unclamping

#### 4. VALIDATION AND RESULTS

The virtually computed machining strategies in the discussed DEFORM models (Series 1-3) are validated using laboratory CNC and measurement equipment. Process planning for the series starts in CAD/CAM by defining the milling toolpaths, which are transferred to the respective CNC machine as G-Code. The milling operations were executed on a 5-axis DMGMori DMU 75 monoBLOCK machining center. For validation of simulated part distortion, tactile measurements and dimensional inspection were carried out after every machining step using a Zeiss Prismo coordinate measurement machine (CMM). Before the first machining operation, a reference measurement is performed based on the planned machining strategy. To quantify part distortion, the CMM measurement uses the unmachined surface as the reference, which reduces measurable errors from fixture repositioning and

machine tool tolerances. Distortion is then characterized from the resulting X-Y-deflection profile, which provides a bending line that is directly comparable to the FEM predictions. The experiments were conducted three times for each validation series, and the resulting mean values were computed and compared with the simulation results. To compare the measurements with computed FEM results, simulated data points from FEM are exported, formatted, and spatially aligned to the measurement coordinate system, after which all datasets are superimposed and post processed in PYTHON. Exemplary illustrations of the machining and measurement setup as well as comparisons of final distortion profiles obtained in CMM measurements and DEFORM for validation series 1-3 are summarized in Fig. 6.

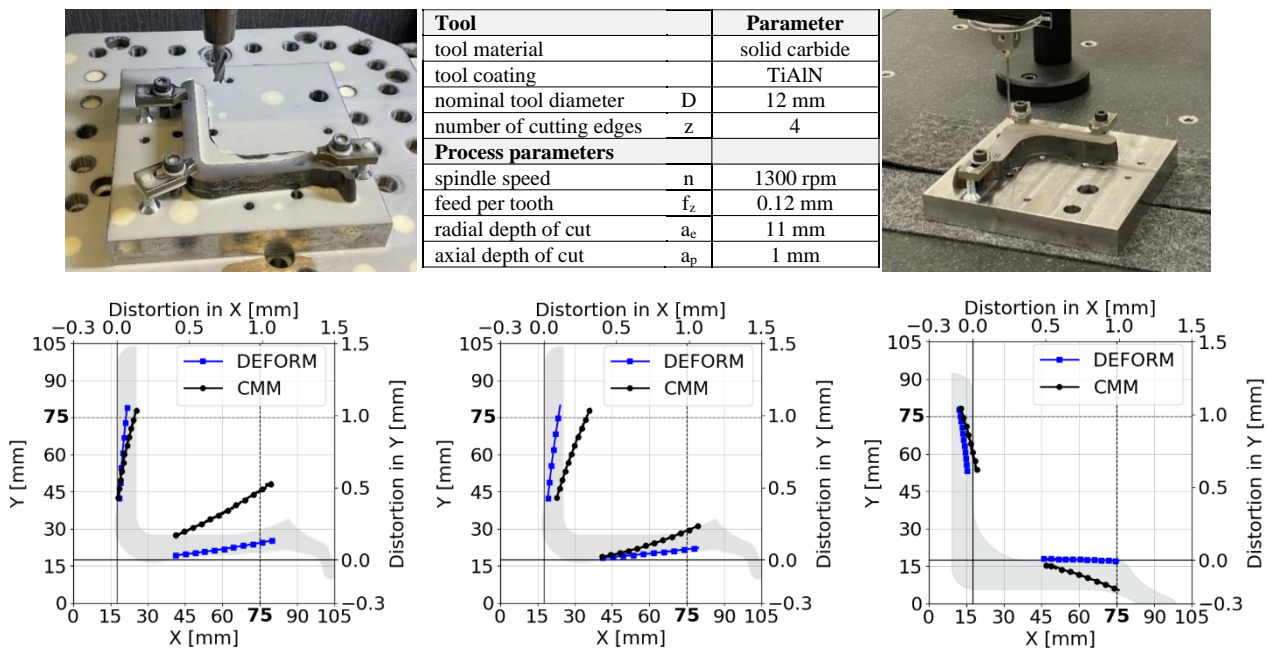


Fig. 6. Overview about experimental setup and final distortion results; top-left: milling on a machining center; top-middle: technological cutting parameters; top-right: distortion measurement on a coordinate measuring machine; bottom-left: validation series 1, bottom-middle: validation series 2, bottom-right: validation series 3

For consistent cross series comparison, distortion is quantified at a fixed evaluation position of 75 mm, providing an identical lever arm and thus comparable weighting across all fixture and machining configurations. Across the three series, DEFORM reproduces the distortion shape and sign but consistently underpredicts the magnitude. In series 1, measurements are 0.47 mm in Y and 0.12 mm in X versus predictions of 0.12 mm and 0.06 mm which underpredicts the magnitude by 74.5 % in Y and 50.0 % in X. In series 2, measurements are 0.20 mm in Y and 0.29 mm in X versus 0.07 mm and 0.9 mm, which corresponds to an underprediction of 65.0 % in Y and 68.9 % in X showing an approximately symmetric profile. In series 3, measured distortions are minus 0.20 mm in Y and minus 0.07 mm in X compared with predicted values of minus 0.006 mm and minus 0.083 mm. This corresponds to an underprediction of 97.0 % in Y and an overprediction of 38.3 % in X. Across validation series 1–3, the stepwise results show that the unclamping sequence measurably affects the orientation and sign of the final distortion. DEFORM captures this

sequence dependence in series 1 and series 2, where the predicted distortion direction switches consistently with which side is released first. A clear exception is series 3, in which DEFORM predicts an almost invariant response in the Y direction over the unclamping steps despite a pronounced distortion evolution observed experimentally. Overall, across validation series 1–3, agreement between simulation and measurement is typically better for the side released second, whereas the side released first exhibits larger bending in the experiments and is therefore underestimated more strongly by the model.

The deviations between simulation and measurement likely result from uncertainty in the initial residual stress input and modelling idealisations. Residual stresses are only validated near the surface, about 1.5 mm by XRD and 4 mm by Cut Compliance, as a result core stresses rely on the heat treatment simulation. To analyse the influence of the initial stress field on part distortion, series 1 was simulated with the initial stress field scaled by factors of 0.5, 2, and 3. The results confirmed the expected linear scaling for a linear-elastic material model, and the scaled profiles correlate well with the measured curvature, supporting the qualitative trends. However, a global scaling factor does not provide a robust correction because the required scaling varies with geometry, feature details, fixture setup and evaluation location. Consequently, the models remain best suited for qualitative strategy comparison rather than absolute tolerance verification. Additional scatter may arise from part-to-part variability within a heat treatment batch, forging induced differences, and unmodelled geometric deviations between raw bodies and specimens. The model assumes isotropic, linear elastic behaviour with uniform properties and idealised, rigid, frictionless clamping, and represents milling as instantaneous removal, while Boolean removal and remeshing in DEFORM may introduce interpolation errors.

## 5. CONCLUSION AND OUTLOOK

The workflow implemented in DEFORM with interfaces to NX CAD/CAM enables automated setup of machining strategies and cutting steps and supports distortion simulation during and after machining. DEFORM's Boolean subtraction is well suited for toolpath updates because it avoids repeated segmentation and re-modelling of the workpiece. The approach supports complex geometries, including forged aerospace components, and can transfer multi-operation, multi-tool, and multi-clamping strategies from CAM into multi-step FEM simulations, reducing model handling effort and runtime compared to state-of-the-art workflows. Regarding model accuracy, the developed FEM model reflects the distortion trend measured in the described experiments qualitatively. The dominant residual stress related distortion occurring during fixture release is visible in the simulation results. In particular, the direction of distortion during sequential release of clamping boundary conditions is captured consistently. However, the model underpredicts distortion magnitudes compared with the experiments, indicating limited quantitative accuracy under the current input and modelling assumptions.

Future work should improve the predictive quality of the FEM model by further analysing and refining the boundary conditions and underlying model assumptions. In particular, the modelling of contact conditions should be extended in more detail, including

friction and an improved contact definition, to quantify their influence on distortion and to achieve more accurate simulation results. In addition, the workflow should be used to investigate more advanced milling strategies by refining material removal from a single cutting volume to a sequence of cutting volumes derived from successive in process workpieces from CAM. This would represent the effects of machining sequences and progressive stiffness changes more realistically, while also addressing a possible source of deviation between FEM and experimental results. The proposed FEM-CAM workflow is readily extensible in this direction, making the investigation of the quantitative influence of this modelling choice a suitable topic for future work. Current qualitative simulation results are sufficient to compare various milling strategies to each other and to derive main impact factors on the observed results. A focused parameter study executing a series of new machining strategies using the same demonstration part geometry may show opportunities for overall part distortion optimization strategies in the process planning phase.

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