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# Simulating the effects of machining induced residual stress on geometric variation

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**Abstract**

Most metallic components undergo machining to some extent during manufacturing. It is a very complex process where extreme temperatures and forces are generated on the surface, primarily due to friction. These conditions often give rise to significant residual stress on the surface of the finished product, which may be sufficient to alter both the behavior of the material and the geometry of the product. The geometric effects of these stresses are further complicated by the presence of residual stresses from previous processes, such as casting or additive manufacturing (AM). A methodology for applying machining-induced residual stress onto a geometry to estimate the geometric distortion that can be expected from a machining process in an AM context is proposed. This study compares a range of feasible residual stress magnitudes to demonstrate the importance of tailoring the process parameters to minimize the effects of machining induced residual stress on the geometric variation.



*Keywords:* Geometry assurance; RD&T; Machining; Residual stress; Additive manufacturing

## 1. Introduction

Achieving high dimensional accuracy in machining of metallic components is a persistent challenge that is influenced not only by limitations in the geometric control of the machining process, but also the stress state of the component before, during, and after machining [1]. In general, this stress state is caused by a combination of external forces currently acting on the component (via e.g. fixturing and cutting forces) and residual stresses caused by previous processing. External forces can often be measured during the process, but the residual stress state, defined as the stress that remains in a body that is stationary and in equilibrium with its surroundings, is extremely challenging to characterize fully [2]. This is further complicated in the context of machining, as the process generates machining induced residual stresses (MIRS) into the surface and also releases bulk residual stresses (BRS) from upstream processes [3].

Mechanistically, MIRS result from a combination of plastic deformation under the tool, frictional heating, and strain gradients in the near-surface zone. These stresses can be tensile, compressive, or mixed, and their magnitude and depth profile depend on process parameters such as cutting speed, feed rate, tool geometry, cooling conditions, part geometry, and material. While these parameters can typically be controlled, the interplay is complex and the stress profiles are sensitive to even minor changes. MIRS typically vary in the range of approximately −400-1600 MPa with the peak stress appearing approximately 10 μm under the surface and fading with a sharp gradient, reaching zero at 100-500 μm [4, 5]. Typically, compressive surface stresses are desirable as it reduces the risk of crack initiation from cyclic loading [6].

When it comes to the effect that the MIRS have on the geometric distortion of a component there are several things that become critical to consider. Firstly, the magnitude and distribution profile of the MIRS will clearly have an impact. Distortion along a particular direction is proportional to the total force pro-

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duced by the residual stress, i.e. the stress profile integrated over the cross section:

$$\vec{F} = \iint_S (\vec{\sigma} \cdot \vec{n}) dA \tag{1}$$

Where $\vec{F}$ is the total force vector, $S$ the cross section, $\vec{\sigma}$ the stress vector of a point on the cross section, and $\vec{n}$ is the normal vector to the cross section. This means that not only is the peak stress of interest, but also the stress profile. However, it is critical to see that the stress profile will only have an impact on the force via the integral, the actual shape of the profile is inconsequential. This results in a feasible simplification, assuming a uniform stress applied to the elements on the surface. This will result in a similar distortion of the part, assuming that the force, as calculated in Eq. 1, is kept constant and the stresses in both scenarios are below the yield stress of the material.

The geometry also contributes in several ways, but only as it pertains to the effect of MIRS, rather than the magnitude of the MIRS themselves. A stiffer geometry will naturally be less sensitive to stresses in general, but the thickness of the geometry will affect the distortion independently of the stiffness by changing the relative effect of MIRS vs. BRS, as MIRS are limited to the surface layer [7]. Since the final stress state is a superposition of the BRS and MIRS, the magnitude and direction of the BRS will also be critical, as the final stress state may involve plasticity even if both BRS and MIRS are well below the yield limit, which in turn may be affected by potential strain hardening from upstream processes. In order to simulate a realistic case where MIRS may become a relevant contributor to the geometric distortion, some conditions must therefore be fulfilled:

- Sufficiently large MIRS
- A compliant geometry
- Strict geometric requirements
- A well characterized processing history

Given the first three conditions, there are many applicable components, especially in the aerospace industry [1, 8, 9]. However, since these parts generally go through multiple stages of processing and heat treatment, the state of the BRS is complex and difficult to characterize, especially non-destructively. In order to avoid the complexity of chaining multiple manufacturing processes, this simulation study will focus on additive manufacturing (AM), which has rapidly been adopted in both the aerospace and automotive industries [10]. The two most widely used in metallic materials, directed energy deposition (DED) and powder bed fusion (PBF) result in a part with minimal post-processing requirements, often only requiring a machining step to refine the surface and a heat treatment [11, 12]. However, metal AM processes still result in substantial plastic strain and BRS of a similar magnitude to the MIRS, that need to be accounted for [13, 14]. For this scenario, PBF is an ideal candidate, as the process is based on successively adding layers of metal powder, building the geometry by selective melting [15]. This creates a natural fixture as the material is stuck to the build plate, allowing stresses to build up with minimal distortion during the process.

Generally, machining simulations are focused on local effects, such as chip formation, surface integrity and the local stress profile [16, 17]. While there are previous examples of machining simulations evaluating the effect of MIRS on part scale geometries, they are often based on simplified linear elastic behavior and/or computationally expensive [7, 18]. The computational efficiency is critical when considering the utility of a simulation model for the purpose of evaluating variation, as variation simulations are based on performing the same simulation hundreds to thousands of times [19, 20].

This simulation study aims to highlight the necessity of including MIRS when considering geometric distortion and variation, even in contexts where there are large BRS already present. This is done by applying a lightweight machining simulation on a model that is sensitive to residual stress in general, with realistic initial levels of BRS from additive manufacturing.

## 2. Method

A simple cantilever geometry, similar to ones used by previous authors in similar studies on PBF [21, 22, 23] was chosen for this study in order to easily quantify the distortion upon release from the baseplate, see Fig. 1. The material model is an elasto-plastic model with strain hardening, based on Ti-64, as it is both commonly used in aerospace components and AM [24]. The FE mesh of the cantilever beam is made up of approximately equiaxed hexahedral and wedge shaped volume elements arranged in layers with a thickness of 0.5 mm, with the exception of the top of the cantilever, where the height of the elements is halved to increase the density close to the machined surface. An additional AM-simulation was also performed with a finer mesh with minimal changes in the results to ensure that the mesh is sufficiently fine. The cantilever is assumed to be completely stuck to the baseplate for both the AM and machining simulations, and then released and placed in a measurement fixture (held in the bulky part on the left in Fig. 1) as the nodal displacement is evaluated. In order to account for the cumulative nature of the AM and machining processes, the simulation procedure is set up as a sequence where the results of each simulation (including node displacement, stress states, and plastic strain with associated hardening) are fed as input into the next:

1. PBF simulation, which will primarily generate residual stress because of the fixturing of the cantilever
2. Machining simulation, where some elements are removed from the cantilever, and residual stress is added to the machined surface
3. Release, the removal of the cantilever from the build plate, causing springback proportional to the residual stress introduced by the previous processes

### 2.1. Additive manufacturing simulation

The simulation of the PBF process is based on the inherent strain method, which is implemented in the software RD&T as described in [23, 25]. This method is a simplified thermomechanical simulation where it is assumed that the results of the process can be represented by a strain tensor defined as:

$$\varepsilon^{inherent} = \varepsilon^{tot} - \varepsilon^{e} \quad (2)$$

Where $\varepsilon^{tot}$ and $\varepsilon^{e}$ are the total and elastic strains, respectively. A mesoscale simulation was performed by using LaStFEM, an inhouse structural mechanics solver developed at Fraunhofer Chalmers Centre [19, 23, 25], and estimating process parameters and tuning them to achieve a melt behavior that is expected in an AM process as the material is printed in a straight line, similar to previously published results [25]. The process parameters selected for the meso-scale AM simulations are a laser velocity of 1000 mm/s and a laser power of 234 W, set up the same way as has been done in previous studies [23]. The averaged normal inherent strain components were retrieved from the meso scale simulations as: $\varepsilon_{xx} = -0.014$, $\varepsilon_{yy} = -0.013$, $\varepsilon_{zz} = -0.030$, with the much smaller shear components excluded by assuming a symmetrical process, a common assumption [26]. The retrieved inherent strain values are of similar magnitude to what others have applied with high accuracy in PBF of Ti-64, and was thus deemed to be a reasonable approximation of a typical process [26, 27, 28]. In an industrial case, this mesoscale simulation would be based on real process parameters and calibrated with the specific equipment for accurate results. The part scale simulation was performed by adding one layer of elements at a time, and applying the inherent strain to each layer as it was being deposited. The bottom nodes of the first layer were completely fixed in space, which corresponds to the assumption of the build plate being completely rigid. This simulation has been validated experimentally in previous studies [23].

### 2.2. Machining simulation

The machining simulation step was initiated by selecting which elements to remove, which in this case is described by the position along the vertical axis. 2 mm of the top of the cantilever was machined away, reducing the bending stiffness and releasing the residual stresses associated with these elements. After the removal of the elements, MIRS were added to the newly machined surface. These MIRS are approximated based on reports from [5, 29] to be equiaxed in the surface and ranging between 400-900 MPa in compression, with stress profiles decreasing to zero at approximately 150-300 µm underneath the surface. Assuming linearity, this computes to be equivalent to stresses of approximately 200-400 MPa if applied evenly across the 250 µm thick elements on the surface of the cantilever. While these assumptions are quite coarse, the precision of the stress measurements is also quite limited, but indicates a reasonable range of expected stress values. Three separate machining simulations were then performed, one at each end of this range and one assuming no MIRS, to provide a range of the effects of the MIRS. The equiaxed stresses were applied assuming a plane stress condition, i.e. that there is no stress normal to the surface. As the final step of each simulation chain, part of the cantilever was released from the build plate, with the exception of the bulky part at the far left in Fig. 1. In order to separate the effect of MIRS from the removal of the top elements, the release was also simulated without any machining.

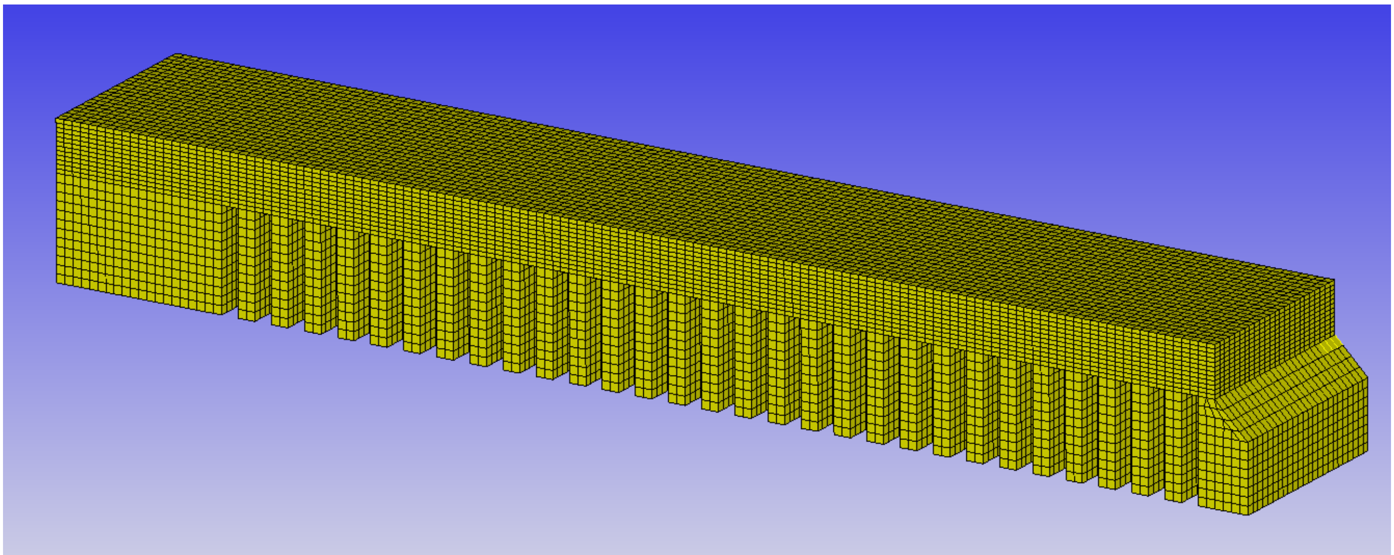

Fig. 1. Nominal mesh of cantilever beam. The length of the cantilever is 72 mm, height 9 mm, width 12 mm.

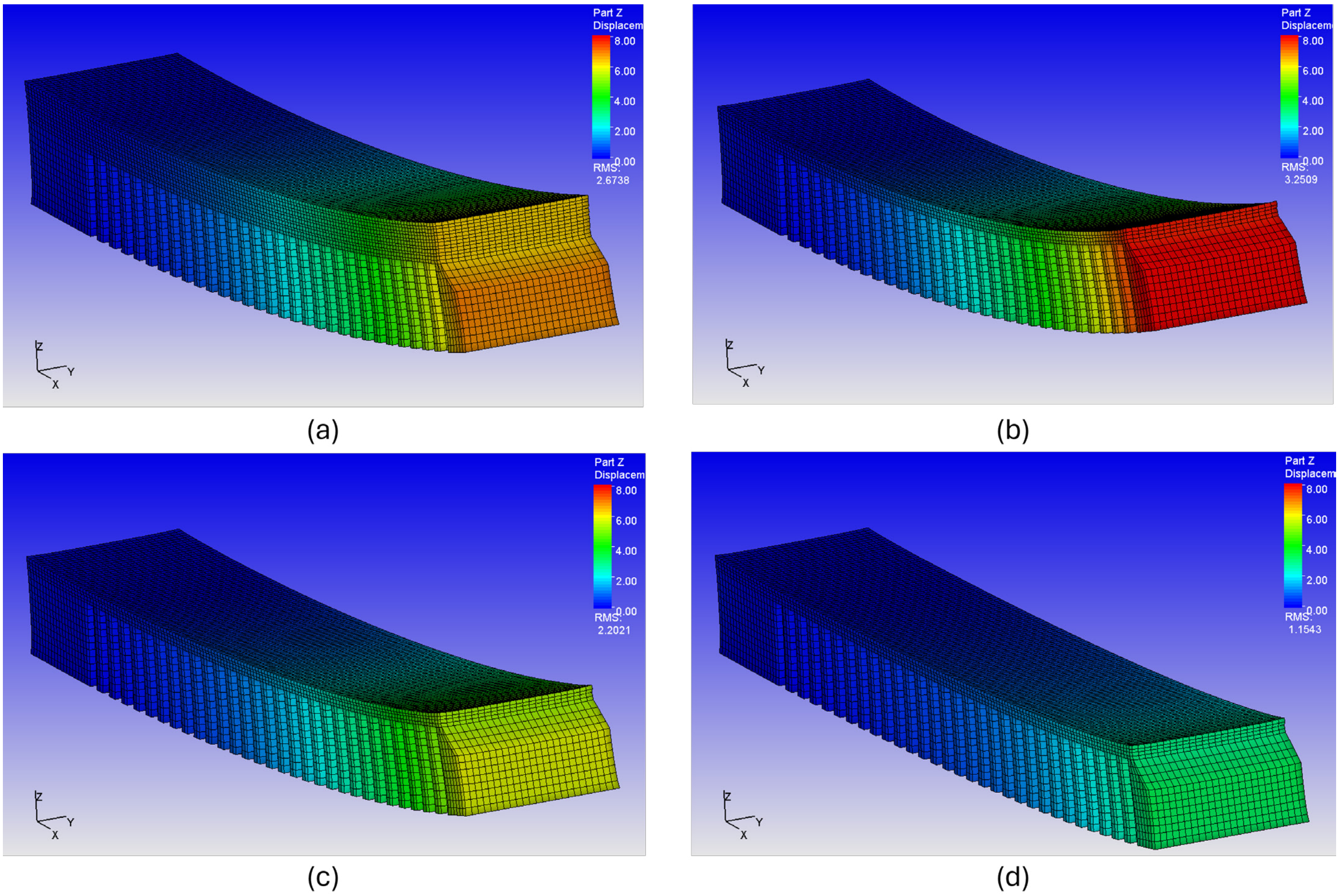


Fig. 2. Post-release nodal displacement of the cantilever beam after (a) Additive manufacturing (b) Machining assuming no MIRS (c) Machining assuming MIRS of 200 MPa (d) Machining assuming MIRS of 400 MPa.

## 3. Results and Discussion

The post release displacements of the cantilever beam can be seen in Fig. 2. The maximum displacements were in each case are 7.0 mm for the post-AM case, 8.5 mm for the machined case without MIRS, 5.9 mm for the 200 MPA, and 3.4 mm for the 400 MPa cases. The compressive MIRS are clearly sufficient to substantially reduce the bending resulting from the residual stress caused by AM. It is also clear that the added stiffness in the post-AM case in Fig. 2a has a greater effect on the displacement than the additional tensile stresses from the elements that were machined away in Fig. 2b. These displacements are consistent with the experimental observation that components manufactured via PBF have less residual stress than conventionally manufactured post-machining [14].

A limitation of the methodology presented in this work is the absence of the, often quite complex, stress profiles in the machined surface. While the particulars of this profile is unlikely to result in a significant change in the macroscopic distortion of the part, it is still quite relevant in many applications. More detailed simulation tools or measurements would be necessary as a compliment to provide a complete picture of the as-processed surface.

The range of the magnitude of the MIRS used for this simulation study was based on two reports, one of which used several different machining parameters [5, 29]. While these parameters may be more or less realistic in a well developed machining process, there is a clear indication that the choice of parameters will have a drastic effect on both the residual stress and the final geometry of large, slender parts. Both of these factors are problems on their own, but may also be further exacerbated by downstream processes such as assembly. While this may be common knowledge for well-established manufacturing workflows within e.g. the aerospace industry, the solutions are sometimes quite reliant on processes like shot peening to correct the surface residual stress and part distortion [8]. This drastically increases production costs and any way to reduce the need for such process could have large economic wins. A lightweight simulation tool that can be used to optimize process parameters by estimating their effect on the distortion from machining could be an important part of such a solution. However, according to some studies there are also significant sources of variations even when process parameters are controlled, which may be attributable to e.g. improper fixtures and wear on tools [30, 31].

Given the magnitudes of variation in the MIRS reported by Weber et al. and Clavier et al., and the strong relationship between stress and distortion shown here, there is a high potential gain from variation simulation within the field of machining [30, 31]. Given this general methodology, a Monte Carlo simulation could feasibly be set up by varying the applied MIRS within a predetermined range. Direct FEM simulations have been considered too slow for the number of iterations for variation simulation in the past [19]. However, since the machining and release stages combined take approximately a minute to simulate on a personal computer, this methodology could run hundreds to thousands of iterations within a day, depending on the complexity of the particular model. This could then assist designers to create components that are robust to variation in MIRS.

## 4. Conclusions and Outlook

A lightweight tool for applying machining induced residual stresses has been developed and applied in conjunction with a simplified additive manufacturing simulation. The direct chaining of these separate simulations and the release of the fixture includes the accumulation of both residual stress and plastic strains throughout the production cycle. These preliminary results indicate a good correlation with past experimental observations. Simulation times are low enough to enable optimization loops without requiring excessive simulation time or computer clusters. Implementations of Monte Carlo simulations to simulate random variation in the machining process are also feasible. However, the tool relies on a predetermined stress profile (from another simulation or direct measurement) in order to achieve high fidelity.

Future research on correlations between e.g. particular process parameters or tool defects on the residual stress profiles may widen the scope of variation simulations of machining. A detailed machining simulation could be implemented as a mesoscale simulation and used as a source of surface stress profiles in a manner similar to what is commonly done for inherent strain simulations in additive manufacturing [26].

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