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Simulating the Geometric Distortion of Remanufactured Parts Using the Inherent Strain Method

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Abstract

Directed energy deposition (DED) is an additive manufacturing technique that is very well adapted for remanufacturing metallic components. The process works by depositing material onto either a substrate or, in the case of remanufacturing, existing component using a metal wire or powder that is fed into an energy source, usually either a laser or electron beam. DED naturally introduces a large amount of heat into the component in a manner that generally produces both large and sharp temperature gradients. These gradients generate residual stresses in the material which cause the component to warp in ways that are often difficult to accurately predict. To use this method for remanufacturing components with specific geometrical demands, such as turbine blades, any potential warping must be accounted for and minimized. A simulation methodology based on inherent strain (IS) is proposed as a high-throughput high accuracy method of evaluating the warping based on the geometry and parameters of an individual component. The study compares the results of this high throughput IS-based simulation tool with more traditional thermomechanical simulations with respect to both accuracy and time efficiency when applied to an industrial case.

Keywords: Remanufacturing; Additive Manufacturing; Inherent Strain; Compressor Blade; Directed Energy Deposition.

1. Introduction

Remanufacturing is a growing trend in recent years due to the increased efficiency of being able to reuse worn and/or damaged parts by only consuming a fraction of the cost, energy, and materials of manufacturing a new part. When it comes to turbine blades specifically, it has been found that remanufacturing is an improvement of at least 45% on the carbon footprint over conventional manufacturing [1]. While this is extremely promising, the manufacturing process also introduces new challenges that need to be accounted for. One of these is that the manufacturing techniques used for producing the product are unlikely to be able to properly remanufacture the same part. Since the damage and wear that is accrued during use is unique to each part, the remanufacturing process is often labor intensive. Due to the uniqueness of each part, high amounts of customization and inspection are generally required so remanufacturing processes are generally highly manual [2–4]. Additive manufacturing has recently become an increasingly viable method to automate processes that require high degrees of customization. Directed Energy Deposition (DED), an additive manufacturing technique, has been found to be effective for remanufacturing metallic parts [1,5,6].

DED is a category of techniques that combines principles of both laser cladding and welding to fuse material by melting it as the material is being deposited upon a substrate [7]. Material can then be added repeatedly, creating a 3-dimensional structure layer by layer. The reason why DED is especially well

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suited to remanufacturing of metallic components is that there are very few requirements on the geometry of the substrate, in contrast to techniques such as laser powder bed fusion, where a planar surface is required [8]. However, the substrate must be suspended such that the deposited material stays in the melt pool, i.e. horizontally [8]. The power source used for DED varies between implementations but include high powered lasers, electron beams, and various arc welding style sources [7]. Regardless of the source, the amount of energy transferred to both the deposited material and the substrate is enough to cause significant residual stresses as well as distortions in the geometry [9].

While these stresses and distortions are unavoidable to some extent, they can be minimized by controlling parameters such as the build rate, cooling time between layers, scan strategy, and fixturing. In order to evaluate whether or not it is possible to remanufacture a given part and retain a geometry that is within tolerance, a simulation of the process is likely to be necessary. Furthermore, if the simulation is sufficiently fast, it would be possible to use it to optimize the process parameters to minimize the distortion of the part. Depending on exactly how fast it is possible to run the simulations of a given geometry, the strategy of this kind of optimization could be more or less comprehensive. One could either perform a relatively generic optimization where some kind of procedure could be run for each model of blade. Given a faster simulation, individual blades could be scanned and the geometric variation of each blade could be taken into account for tuning certain key parameters. The ideal would of course be to perform a full run of optimization of each parameter for every individual blade, which would necessitate an extremely fast simulation.

Simulating metal additive manufacturing (MAM) is a topic that has rapidly gained traction in both academia and industry in the last couple of decades. There is an abundance of numerical modeling strategies that attempt to describe the fairly complex phenomena that occur throughout all the different techniques [10–12]. These strategies vary widely in scope, accuracy, and computational time. The aspects that are the most critical for the application discussed here are the computational time as well as the accuracy in predicting geometric distortion due to the thermal loads introduced by the process. This means that topics such as rheology, metallurgy, and thermal history can either be excluded or simplified to a large extent to decrease the computational time. Additionally, the macroscopic scale of the application further narrows the list of possible simulation models. With this in mind, a technique known as the inherent strain method is an apt choice due to its focus on the prediction of part scale distortion and short computation time [10]. The concept of inherent strains was first proposed as a way of estimating residual stresses in welded structures [13]. However, in recent years this has been implemented for predicting residual stress and distortion during metal additive manufacturing. This has primarily been focused on laser-based powder bed fusion (LPBF) [14–17], but DED has also been successfully simulated using inherent strain [18,19].

2. Theory

The inherent strain method is based on a simplified view of the thermomechanical phenomena that occur before, during, and after the material is both melted and subsequently solidified. It is assumed that the stress and strain distribution of the process can be generated by applying a specific strain tensor, known as the inherent strain, to each Gauss point within the mesh element that is expected to have been melted throughout the process [20,21].

Generally, the total strain accrued during (rapid) melting and solidification can be decomposed into four parts:

$$\varepsilon^{tot} = \varepsilon^{e} + \varepsilon^{p} + \varepsilon^{th} + \varepsilon^{phc} \tag{1}$$

Where ε^{e} is the elastic strain, ε^{p} is the plastic strain, ε^{th} is the thermal strain, and ε^{phc} is the strain due to solid phase transitions. While the strain due to phase change can be significant in some materials, it is neglected here as it was estimated to be small enough to be insignificant, which is a common assumption when employing the inherent strain method [22]. Since the final distortion of the component is due to the inelastic portion of the strain, the inherent strain is defined as:

$$\varepsilon^{inherent} = \varepsilon^{tot} - \varepsilon^{e} = \varepsilon^{p} + \varepsilon^{th} \tag{2}$$

While these equations are rather simple, the value of the inherent strain may be difficult to estimate. The thermal strain can be assumed to be $\varepsilon^{th} = \alpha\Delta T$ where α is the heat expansion coefficient of the material, and ΔT is the temperature difference the element experiences after solidification, normally the difference between the solidus temperature of the material and room temperature. The plastic strain that forms in each Gauss point during cooling, which is commonly the largest part of the inherent strain, is mainly due to the surrounding material restricting the element's ability to shrink. This causes stresses to form, which sometimes exceed the yield stress of the material.

In this paper, a two-level framework is used to first estimate the inherent strain values using a mesoscale model. This mesoscale model uses a full thermomechanical simulation of the DED process on a smaller, simpler geometry. The inherent strain is calculated for a set of representative elements, which are then used as input into a part scaled model.

3. Method

A simplified geometry of a compressor blade was chosen for this study to realistically emulate a remanufacturing case, see Fig. 1. Alloy 718 was chosen as the material as it is a common material for high pressure compressor blades. The influence of solid phase transformation was not considered in the simulation, as it is unlikely to introduce large strains during the process, provided that the time that the material spends at elevated temperature is relatively short, as the blade is assumed to be given sufficient time to cool down between beads [23].

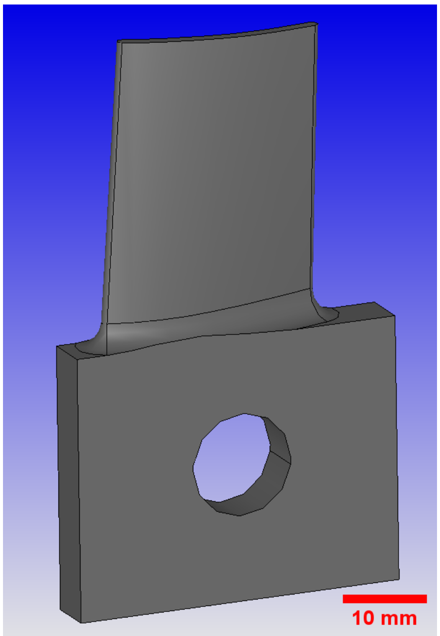

Fig. 1. Nominal geometry of the compressor blade.

3.1. Mesoscale simulation

The mesoscale model that was used for this study is based on a block with base dimensions 40 × 12 mm with a height of 6.3 mm. This block was used as a substrate and a fully thermomechanical simulation was used to simulate the deposition of five layers of material using the DED process. Each deposited layer was 0.25 mm thick and was deposited in a straight line, lengthwise from one end of the substrate to the other. A set of representative elements from the center of the deposited material was then chosen and the plastic strain from these were averaged. The sum of this averaged plastic strain and the thermal strain calculated from the difference between the solidus and room temperatures was then used for the part scale simulation.

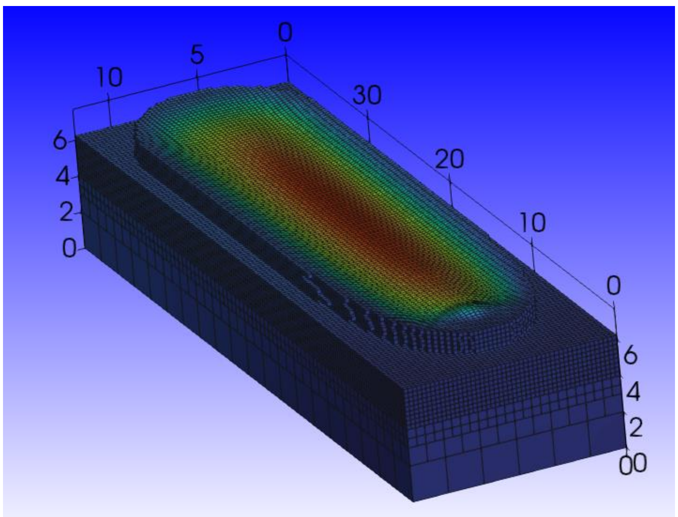

Fig. 2. Final state of the meso-scale simulation, with measurements of the base plate included in millimeters.

3.2. Part scale simulation

A portion of the nominal model seen in Fig. 1 was removed for the part scale simulation in a manner similar to how the damaged areas of used blades are machined away prior to repair. This modified blade was then meshed and an additional mesh representing the deposited material was added, see the grey part in Fig. 3. The inherent strain from the mesoscale simulation was applied to the deposited material in the part scale model in a layer-by-layer fashion, as the layers in the deposited mesh were activated and given stiffness. These layers were also 0.25 mm thick, matching the mesoscale simulation.

3.3. Validation

In order to get an idea of the accuracy of the inherent strain based simulation, the results were compared to those from a more established method. The method chosen for this purpose is a transient thermo-elasto-plastic welding simulation which has been described more in detail elsewhere [24,25]. This method used welding parameters similar to those introduced in the mesoscale simulation and the geometries were the same as the part scale inherent strain simulation.

4. Results

The inherent strain tensor that resulted from the mesoscale simulation was calculated to be the following:

$$\varepsilon^{inherent} = \begin{bmatrix} 0.072 & 0.014 & 0.042 \\ 0.014 & 0.078 & -0.035 \\ 0.042 & -0.035 & -0.110 \end{bmatrix} \quad (3)$$

The distortions resulting from the part scale simulation where the normal components of the inherent strain have been applied can be seen in Fig. 3, where the displacement magnitude of each node has been used to color the part. These can then be directly compared to distortions in the same state after the transient simulation, see Fig. 4. Specific measures along the top of the blade show that both the magnitude and general trend of the two simulations agree quite well.

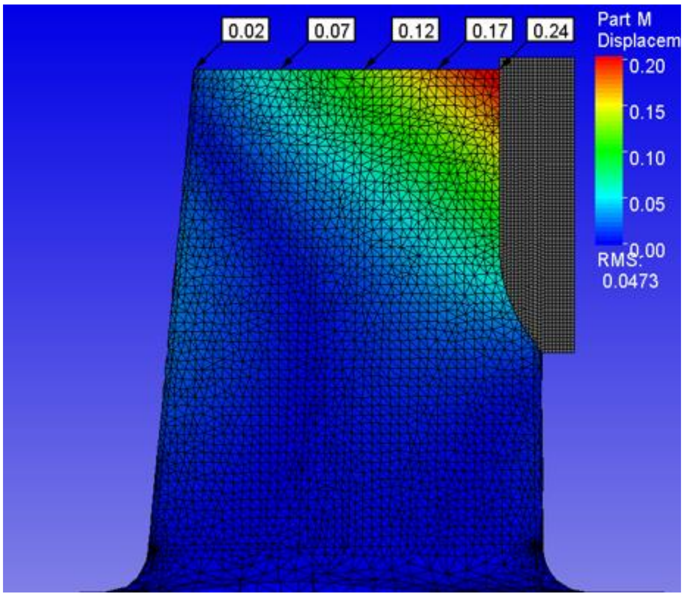

Fig. 3. Displacements of the nodes in the compressor blade resulting from remanufacturing using DED, simulated using the inherent strain method.

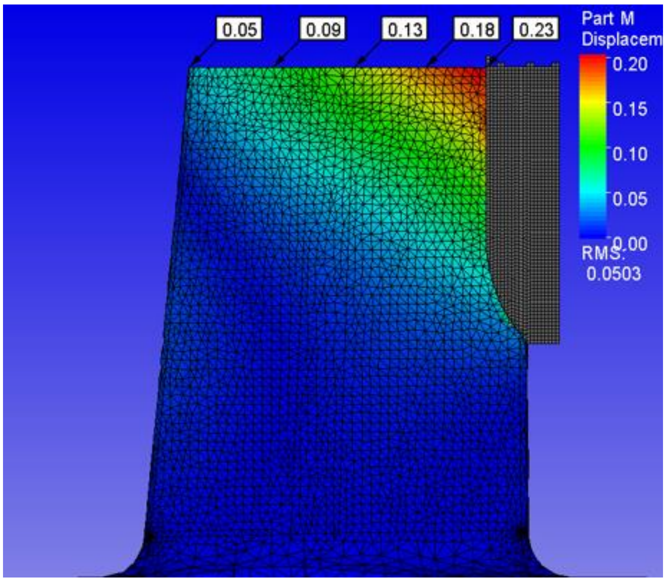

Fig. 4. Displacements of the nodes in the compressor blade resulting from remanufacturing using DED, simulated using a transient thermo-elasto-plastic welding simulation.

It is worth noting that the deposited material is not included in the quantification, because the excess material is going to be machined afterwards. The true shape of the deposit is also going to be largely dependent on the rheology of the molten metal, which is excluded from both simulations.

The part scale inherent strain simulation finished in approximately 280 seconds, while the transient simulation took approximately 4 hours and 23 minutes. This corresponds to about a 50-fold reduction in computation time.

5. Discussion

The two simulations seem to agree very well when it comes to the distortion of the compressor blade, despite the vastly different approaches to the problem. Both simulations show signs of the blade both bending as well as twisting. While the geometric requirements for compressor blades are fairly complex, a simple metric that is generally applied is that the blade profile should not be too twisted. Assuming a maximum allowed twist error of 0.5°, and given that the blade is 23 mm wide and excluding the cutout used, this would result in a difference of approximately 0.17 mm in the normal displacements of the two top corners of the blade. It is worth noting that the normal displacement is slightly different to the displacement magnitude that is used as the coloring in Figs. 3 and 4, as there is some in-plane displacement. This measurement is calculated to be approximately 0.20 using the inherent strain method and 0.18 using the fully thermomechanical simulation. This means that the blade is likely to be out of tolerance after remanufacturing according to both types of simulation methods used, suggesting that a different set of parameters or some post processing ought to be used in order to keep the blade within tolerance. The arguably biggest difference between the two results is that the inherent strain based simulation seems to show a slightly higher displacement further down on the blade while the transient simulation resulted in a higher displacement in the upper corner away from the deposited material. Acceptable levels of precision depend on the application and would have to be judged individually.

The slight difference may, in part, be caused by the inherent strain based simulation applying the strain in a whole layer at a time, while the transient simulation heats up the blade increasingly throughout each layer, only stopping to let the blade cool off between layers. While the difference between the two measurements is relatively small for the investigated blade, a different geometry could theoretically amplify the results of such effects and additional differences from e.g. inhomogeneous cooling could also start having a more significant effect with larger deposits and less symmetrical blades. Further research into how the inherent strain based simulation behaves with more complex geometries may show that some effects that are unaccounted for here need to be addressed, even if the results here show a small difference.

However, in cases such as these the difference could be considered small enough to justify the vastly decreased computation time. This would allow for a simulation to be run for each step of the remanufacturing process, to judge in advance whether the final blade will be outside of the tolerances or not. A first estimate could be done based on the original shape of the blade and an estimate of the material that is to be cut away to be replaced with new material. If the simulation shows an acceptable level of distortion, the process may proceed, and the damaged portion of the blade can be removed. Once this is done, another simulation can be performed with the actual geometry post-machining, taking the real shape of the removed material and potential distortions due to the machining, e.g. release of residual stresses formed from manufacturing or use, into account. If this simulation once again shows that the remanufactured blade expected to be within tolerance, the DED process may be performed. Even at this stage the simulation tool could be of use, as the blade needs to be post-processed, primarily via machining away the excess material from the newly remanufactured area. This could once again release residual stresses, which results in distortions that can be predicted by inherent strain simulation. Further postprocessing is likely to include heat treatment, which may remove the residual stress resulting from the DED process. These kinds of simulation tools could also prove to be useful tools to investigate the order of these procedures, i.e. whether removing the residual stress from the deposited material before machining away the excess would bring the blade closer to nominal than the other way around. While all of these applications may be achieved with other simulation tools that are currently available, such as the transient simulation shown in this work, they often come at such computational cost that it becomes impractical to run a simulation for each step.

Additional benefits from the short computation time include the possibility of doing many repeated simulations with slightly altered parameters. One such application would be to be able to simulate geometrical variation if a large batch of nominally identical parts are to be remanufactured. Instead of measuring and simulating each of them individually, one could identify particular key measures that vary between the parts and find out how much these measures can vary before the part would be out of tolerance, after remanufacturing. Another example would be fixture optimization for the DED process. It is likely that an ideal fixturing of the blade during the process would reduce the distortion of the blade. However, the specific positions of the fixturing elements may be difficult to intuit and may even vary wildly from case to case. An optimization algorithm for optimizing the fixture layout could feasibly implement a simulation strategy similar to what has been presented in this work to iteratively find the best possible solution for a given blade. This hypothetical fixture optimization algorithm may take hundreds, or even thousands, of simulation runs depending on the specific case and algorithm. Assuming approximately 1000 runs, the optimization of a particular fixture layout could be reduced from ~200 days via the transient simulation shown here, to ~4 days using the inherent strain method.

There is also some freedom in the way the material is added for the part scale simulation. In this study, the material was added one layer at a time but this is not necessarily the ideal way. A cursory investigation into both dividing the layers into smaller segments and adding those one at a time showed minimal difference in the result but increased the computation time by a significant amount. Adding several layers at once was also attempted, which further reduced the computation time and showed relatively similar results. Further investigation into the different ways the part scale simulation can be performed is warranted.

Experimental validation of the inherent strain implementation shown here is required before implementation into an industrial application, but these initial results are promising. Further considerations that were neglected in both the present simulations, such as accounting for the accumulation of heat during the deposition as implemented by Dong et al. [19]. Extending the technique by including additional parameters such as rheological data to achieve a more accurate geometry for the deposited material may also help the method to conform with experimental data.

6. Conclusion

Remanufacturing using additive manufacturing is a potentially very promising concept for maintaining the function of compressor or turbine blades for aerospace applications. However, there are a great number of challenges in both making the process economically viable and optimizing it for the best possible results. A fast simulation tool such as the one presented in this work would be a useful addition for both the decision making process that goes into estimating whether a blade is viable for remanufacturing and optimizing certain parameters to improve the final result.

In this paper, a simulation method known as the inherent strain method has been implemented for a typical remanufacturing case. The inherent strain method has historically been used primarily for welding simulations but has also recently been successfully implemented for various additive manufacturing techniques.

This method was shown to conform well with more established, but much slower, simulation tools. Further development of the software involved is likely to further improve the agreement between both the inherent strain method and other simulations, as well as experimental data.

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