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A methodology for precision additive manufacturing through compensation

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ABSTRACT

Maturation of powder-bed additive manufacturing (AM) is essential for the business benefit the rapid adoption of AM offers to industry. One of the principal challenges in powder-bed AM is the mitigation of distortion due to material shrinkage and residual stresses induced during the build process. In order to address this, a new methodology for distortion compensation is developed and presented in this paper. The novelty of the methodology lies in the use of a mathematical model for pre-distorting the design geometry based on 3D optical scanning measurement data. The methodology has been applied to two industrial Inconel 718 components (a turbine blade and an impeller). It was experimentally demonstrated that distortion compensation is achievable using the proposed methodology. The results showed the compensation methodology reduced distortion from approximately ±300 μm to approximately ±65 μm for both components. In summary, the novel methodology can be used to deliver near-zero distorted parts for industry using powder-bed AM processes.

1. Introduction

In manufacturing, distortion can be described as a change of a component's geometry during the material processing. There are different types of distortion depending on the manufacturing processes used, including shrinkage (thermal processes), deformation due to induced residual stresses (joining, additive, subtractive, mass containing processes), springback due to release of elastic energy (forming processes) and deformation due to stress relief (heat treatment). The two most common types of distortion in electron beam powder bed fusion (EB-PBF) and laser powder bed fusion (L-PBF) are shrinkage and deformation due to residual stresses induced during the build. In EB-PBF, distortion can also be accumulated due to creep of the material as the process operates at elevated temperatures. Also, local overheating of the material, known as "swelling", can create local deformations in EB-PBF.

Different approaches have been researched to mitigate distortion in AM. One of the most common approaches is the development of optimum process parameters aimed at introducing less heat into the material, and subsequently reducing the generation of residual stresses [1]. Some researchers have investigated different toolpath planning strategies to reduce the level of distortion [2]. This approach can be successful in reducing the level of distortion by rebalancing the induced residual stresses in the material, but it cannot entirely eliminate them. Other approaches, applied mainly in large additive manufacturing processes, have introduced surface hardening processes to replace the tensile residual stresses with compressive stresses, for example using a rolling process [3]. The aim is to rebalance the stress state in the component after unclamping, which may lead to distortion reduction. The use of heating during the build in L-PBF is another approach [4]. The goal is to decrease the thermal gradients during the build and generate lower levels of residual stresses. Another approach is the use of an optimum build orientation [5], as the build direction can affect the generation of residual stresses due to a change of the stiffness orientation of the component, relative to the build direction.

All approaches mentioned above are focused on reducing the level of distortion, rather than its compensation. One approach to compensate distortion is to pre-distort the initial shape of the geometry. In order to do this, the final deformed shape needs to be known. Some researchers have worked towards distortion compensation using the finite element method [6–9]. The distortion compensation in that approach consists of inverting the predicted deformations by changing the coordinates of the finite element mesh. The main challenge in using numerical approaches is that a very high accuracy is required for the prediction of distortion, which may present a challenge for some complex geometries and materials. The most common approach adopted in powder-bed AM

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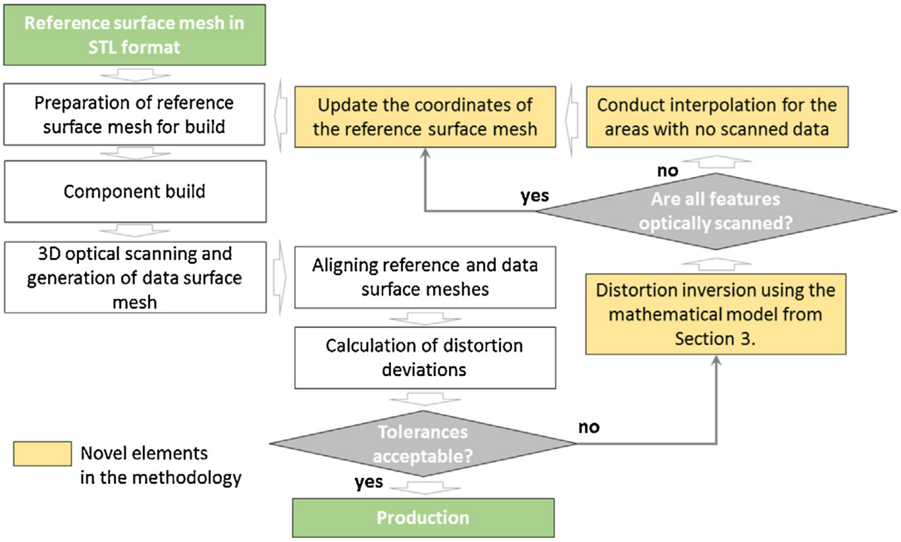

Fig. 1. Methodology flow diagram.

machines is the use of global uniform scaling or Cartesian directional scaling to account for shrinkage. The disadvantage of this approach is that it cannot compensate for local deformations and can only account for overall geometry.

The novelty of this paper is in the development of a new methodology for distortion compensation based upon 3D optical scanning measurements in powder-bed AM. The approach of pre-distorting the design geometry is utilised in this research where 3D optical scanning measurement data is used for the distortion inversion. The advantage of this approach is that it can build upon the state-of-the-art developments in distortion mitigation, as mentioned above, and further compensate distortion to a near-zero distortion level. Another advantage is that the methodology is material, equipment and process independent. This makes it applicable to a wide range of AM applications.

The motivation behind this research is to address some of the key challenges highlighted in the UK National Strategy for Additive Manufacturing [10], where the MTC, as part of the High Value Manufacturing Catapult and home to the National Centre for Net Shape and Additive Manufacturing, has a key role to deliver innovative solutions in additive manufacturing.

2. Overview of methodology

Fig. 1 shows the proposed methodology workflow for distortion compensation using 3D optical scanning measurement data. The novel elements in the methodology are the development and implementation of a mathematical model for distortion inversion and the interpolation of distortion where 3D optical scanning measurements are not possible due to access limitations, such as internal features in the geometry. The mathematical model for distortion inversion is presented in Section 3, while the interpolation of distortion for the areas with no data is conducted using the field of points method implemented in the open source software FEDES and described in details in [11,12]. The remaining elements of the methodology represent a standard workflow for design, manufacture and measurement of AM parts.

3. Mathematical model for distortion inversion

The raw 3D optical scanning measurement data is typically converted into a surface mesh with triangular elements. This mesh is referred to as a data surface mesh in this paper. Every triangular element is defined by three nodes. The first step is to obtain the nominal vector from a node from the reference surface mesh to the data surface mesh. Fig. 1 shows three nodes (A, B and C) defining an element from the data surface mesh, and Node P, which is an arbitrary node from the reference surface mesh.

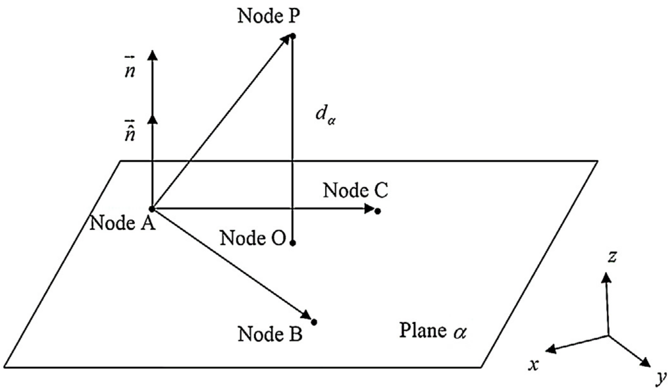

Fig. 2. A schematic description of the mathematical model.

The main task is to identify the element from the data surface mesh which the projection of Node P (denoted Node O in Fig. 2) belongs to, in order to invert the coordinates of Node P in the opposite direction of the Plane α. The position of Node P is checked relative to all elements of the data surface mesh using a search algorithm.

The mathematical model for defining the distance from a point to a plane is determined by Fig. 2. Knowing the coordinates of nodes A, B, C and P from the reference and data surface meshes, the direction vectors $\overrightarrow{AB}$, $\overrightarrow{AC}$ and $\overrightarrow{AP}$ can be given by:

$$\overrightarrow{AB} = (B(x) - A(x))i + (B(y) - A(y))j + (B(z) - A(z))k \quad (1)$$

$$\overrightarrow{AC} = (C(x) - A(x))i + (C(y) - A(y))j + (C(z) - A(z))k \quad (2)$$

$$\overrightarrow{AP} = (P(x) - A(x))i + (P(y) - A(y))j + (P(z) - A(z))k \quad (3)$$

or in abbreviated forms:

$$\overrightarrow{AB} = a_1 i + a_2 j + a_3 k \quad (4)$$

$$\overrightarrow{AC} = b_1 i + b_2 j + b_3 k \quad (5)$$

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