Efficient Distortion Prediction of Laser Melting Deposited Industrial-scale Parts Using Modified Inherent Strain Method

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Abstract. As a result of the large temperature gradients, residual distortion becomes a major technical challenge for laser powder-based Laser Melting Deposition (LMD) process, since excessive distortion may cause building failure, cracks and loss in structural integrity. In this paper, the theory of a modified inherent strain method is firstly developed. On the basis of this method, the prediction results of a small-scale model are compared with those obtained from the traditional thermo-mechanical coupled analysis. The deviation of the maximum distortion predicted by the modified inherent strain method is 7.72%, and the average deviation of the distortion of the substrate’s free end is 8.73%, demonstrating a good accuracy (< 10% error) of the modified method for predicting the residual distortion of the LMD components. Compared to a small loss of accuracy, the calculation time is significantly shortened by the modified inherent strain method. After verification, the distortion prediction of industrial-scale camshaft model during LMD process is realized by using the proposed method. It is found that the maximum distortion is 3.18mm, located at both sides of the camshaft. After the support is removed, the two ends of the camshaft are warped upward, while the position of the maximum distortion doesn’t change, but the value increased to 4.62mm. Moreover, the whole analysis takes only 3300 seconds, which is extremely significant for the distortion prediction for industrial-scale parts fabricated by LMD.

1. Introduction
Laser powder-based Laser Melting Deposition (LMD) technology is a special additive manufacturing process which offers an effective way to fabricate parts with complex internal structures by simultaneous delivery of powders and laser beam. In the process of LMD, powders are blown from nozzles and carried by gas to desired deposition area, as can be seen in Figure 1. During the flight, they interact with the laser beam and are heated due to laser irradiation. Laser beam is attenuated by the powder stream and then irradiates onto the surface of melt-pool and substrate [1]. However, large thermal gradients during the LMD process will result in undesirable distortion and residual stress. In order to reduce the distortion and residual stress without expensive trial-and-error experiments, an accurate prediction model is needed.
Finite Element (FE) modeling could represent an effective tool to tackle issues such as distortion and residual stress, since it can be used to optimize process parameters, deposition paths and to test alternative mitigation strategies [2]. FE modeling for the prediction of distortion has a significant computational cost due to the increased amount of deposited material, passes, and process time [3], which make it nearly impossible to predict distortions for the industrial-scale parts.

In the past few years, many researchers had presented some verified methods which could be followed to improve the simulation time efficiency. Monteverchi et al. [2] used the FE mesh coarsening method for effective distortion prediction in Additive Manufacturing (AM) process. This method allowed to reduce the number of FE elements used to discretize the workpiece, without introducing significant errors in estimating the temperature filed. Denlinger et al. [4] performed a 3D thermo-elastoplastic analysis using a hybrid quiet inactive element activation strategy combined with adaptive coarsening. The effectiveness of the modeling strategy was demonstrated and experimentally validated on a large-sized part. In Jayanath’s [5] work, a new framework called Additive Finite Element Analysis (AFEA) framework which embraced the layer-by-layer build philosophy of AM process as the basis for its formulation was developed. Two new methods named Selective Mesh Coarsening (AFEA-SMC) method and Hybrid Modeling Method based AM Process (HMM-AMP) simulation were proposed based on the AFEA framework. For relatively large parts, the HMM-AMP method appropriately combines traditional thermal-mechanical simulation with Inherent Strain Tensor-based AM Process (IST-AMP) simulation to conduct the simulation. The Inherent Strain method was firstly proposed by Ueda et al. [6] to predict residual stress and distortions of large parts in welding process. Similarly, in order to improve the efficiency of numerical prediction of part distortion caused by Laser Selective Melting (SLM) process, a methodology known as inherent shrinkage, previously developed for multi-pass welding processes, was applied to predict SLM process induced distortion in testing geometry (cantilever) by Alvarez et al [7].

Albert et al. [8-10] applied a modified inherent strain method to predict distortions for AM parts. A large number of experiments were carried out to compare the prediction results with those obtained from the inherent strain method. The numerical results predicted by the method were almost the same as those obtained from the experiments, and the calculation time was reduced significantly. As the calculation time was greatly shortened, this method was applied to topological optimization to design the form of support structure to handle the deformation and cracking issues.

In this paper, the predicted distortion results of a modified inherent strain method are compared with those of the traditional thermo-mechanical coupled simulation. This method greatly improves the efficiency of calculating distortions of industrial-scale parts fabricated by AM process, which could save computational resources and time. On this basis, the distortion prediction of a nuclear emergency diesel engine camshaft is carried out. The implementation steps and theory of modified inherent strain method will be briefly introduced in Section 2. A small-scale model and the results obtained from the two methods will be discussed in Section 3. In Section 4, an industrial-scale model of camshaft and its
distortion result predicted by the modified inherent strain method will be drawn. Finally, Conclusions are proposed in Section 5.

2. Modified inherent strain method

2.1. The implementation of modified inherent strain method

In the process of using the modified inherent strain method to simulate the distortions of industrial-scale parts fabricated by LMD process. Firstly, a small-scale model should be selected for traditional thermo-mechanical analysis to obtain the distortion results. In the second step, the inherent strain values are extracted from the distortion results, and the inherent strain values of the three directions (parallel to the path, vertical to the path and the building direction) are calculated and averaged. Then, they are converted into the coefficients of thermal expansion (CTEs), which are the inherent properties of the material. Finally, the thermal strain simulation is used to obtain the distortions of industrial-scale parts.

From the first step, it can be seen the implementation of the modified inherent strain method is based on the theory of traditional thermo-mechanical coupled simulation. The theory will be briefly introduced.

2.2. Theory of thermo-mechanical analysis

The distortion results of the small-scale model are determined by performing a 3D transient thermal analysis and a 3D quasi-static incremental analysis, respectively. The thermal analysis is independently performed, as the mechanical response has no effect on the thermal history of the workpiece [11].

The governing heat transfer energy balance is written as

\[ \rho c_p \frac{dT}{dt} = -\nabla \cdot q(r,t) + Q(r,t) \]  

(1)

where \( \rho \) is the material density, \( c_p \) is the specific heat capacity, \( T \) is the temperature, \( t \) is the time, \( Q \) is the heat source, \( \mathbf{r} \) is the relative reference coordinate, and \( \mathbf{q} \) is the heat flux vector, calculated as

\[ q = -k \Delta T \]  

(2)

The thermal model considered the heat loss through convection and radiation from the free surfaces. The governing stress equilibrium equation for the mechanical analysis can be written as follows:

\[ \nabla \cdot \sigma = 0 \]  

(3)

where \( \sigma \) is the stress. The mechanical constitutive law is

\[ \sigma = \mathbf{C} \cdot \varepsilon \]  

(4)

\[ \varepsilon = \varepsilon_e + \varepsilon_p + \varepsilon_T \]  

(5)

where \( \mathbf{C} \) is the elastic tensor and \( \varepsilon_e, \varepsilon_p, \) and \( \varepsilon_T \) are the elastic strain, plastic strain, and thermal strain, respectively.

2.3. The extraction and transformation of inherent strain values

In the process of LMD process, a large temperature gradient will appear in front of the heat source center. As the heat source moves away, the concerned material point cools down and solidifies rapidly, and experiences a significant amount of shrinkage (compressive strain). When the heat source is far away, cooling at this point of interest slows down while the material ahead has just solidified and is
undergoing large shrinkage, which induces non-linear tensile stress and strain into the material point of interest. One of the most critical issues is the elastic strain in each deposited layer is significant affected by the evolving mechanical boundaries [9]. Theoretically, the assumption in a welding problem that ignoring the elastic inherent strain is somewhat invalid and inaccurate for modeling residual stresses and distortions in LMD parts.

In order to accurately calculate the inherent strain produced in the LMD process, two states, an intermediate state and a steady state, are chosen to consider the elastic strain that is not fully released due to the evolution of the mechanical boundary in the deposition process. Because a two-layer deposition model are selected for the thermo-mechanical coupling analysis, the intermediate state is defined as the moment when the deposition of the next upper layer is just completed, and the steady state is defined as the moment when the temperature of the whole system cools to the ambient temperature.

Therefore, the modified inherent strain method is as follows:

$$\varepsilon_{In} = \varepsilon_{Plastic} + \varepsilon_{Elastic}$$  \hspace{1cm} (6)

where $t_1$ represents the intermediate state, $t_2$ represents the steady state.

In the two-layer model, the nodes on the top surface of the first layer are selected to extract the inherent strain, because these points fully experience the melting, re-melting, and the inter-layer effect between two adjacent layers in the process of LMD. Since each deposition layer is printed by three single-direction paths, the nodes located on the center lines (a, b and c) are selected to extract the inherent strain, as shown in Figure 2.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2.png}
\caption{The method for extracting inherent strains}
\end{figure}

In the thermal strain simulation, the extracted inherent strain values are converted to orthogonal CTEs and uniformly assigned to the multi-layer models as thermal material properties. In the solution, the elements of the multi-layer models are activated layer-by-layer and unit temperature is applied as the external load. The calculation equation of CTEs is given by:

$$\alpha = \varepsilon_{In} / \Delta T$$  \hspace{1cm} (7)

where $\alpha$ is the CTEs, and $\Delta T$ is the temperature change, which is -1K in this paper.

3. Small-scale model

In order to verify the accuracy of the modified inherent strain method in a rapid distortion prediction of part fabricated by LMD, for a small-scale model, the verification procedure is introduced in this part.

3.1. Thermo-mechanical coupled simulation

The two-layer deposited model used in this paper to extract the inherent strain values is established in ANSYS 18.0, as shown in Figure 3. The two deposited layers have a dimension of 30mm(length) $\times$ 6
mm (width) × 2 mm (thickness). The deposited layers are placed on a 50 mm (length) × 50 mm (width) × 2 mm (thickness) substrate with constrained bottom. The powder layers have a fine mesh with an element size of 0.5 mm (length) × 0.5 mm (width) × 0.5 mm (thickness), while the maximum element size of the substrate is 1 mm (length) × 1 mm (width) × 1 mm (thickness). The element type used is the solid brick element containing 8 nodes named solid 70. The initial temperature of powder and substrate is set to room temperature (20 °C). The deposition layers are assigned the material properties of 12CrNi2, and the substrate is 45C.

Figure 3. Two-layer deposited model

In the LMD process, the power of laser beam is set to 2000W. The scan speed is 5mm/s. The width of path is 3mm, which is equivalent to laser spot diameter. Overlap ratio is set to 50%.

In the thermo-mechanical analysis, it is generally considered that the energy distribution of laser heat source accords with Gaussian distribution. The application of Gaussian heat source is achieved by selecting the element within a certain heat source radius to define its heat generation rate. The birth and death element technology is used to define the state of the elements. Firstly, all the elements of the deposition layers are killed, and then the elements at the position of the moving laser heat source are activated gradually. After the analysis of each step is completed, the heat source applied to the activated elements of the step is deleted. A cooling time of 2000 seconds is set after the forming process is completed.

3.2. Modified inherent strain simulation
The method described in Section 2.3 is used to extract inherent strain values from the results of thermal-mechanical coupled analysis. Extract the total mechanical strain of the nodes located on the three lines of the upper surface on the first layer at the intermediate state, and the elastic strain at the steady state respectively. The inherent strain values are calculated according to Equation (6), the results are shown in Figure 4.

Figure 4. Inherent strain components of line a, b and c
It can be seen from Figure 4 that the three inherent strain components of lines a, b and c have similar tendency, among which the values of nodes near the edge change greatly, that is because the laser beam starts or stops at the edge, making the energy input unstable. The inherent strain in Z direction is negative. Z direction is parallel to the scanning path, the melted material will induce compressive strain in the cooling process. The physical size of the model in X direction and Y direction is relatively small compared with that in Z direction. Therefore, due to the Poisson’s effect, their inherent strain value is positive.

As illustrated in Figure 4, mean strain vectors of (0.00188, 0.00280, -0.00608) are obtained from the two-layer model. According to Equation (7), the average inherent strain components obtained are transformed into the CTEs of the material, and the distortion of each layer after LMD process is obtained by reducing the temperature of each layer. The principle of the layer-by-layer activated method of assigning the inherent strain to predict distortion is shown in Figure 5.

![Two-layer deposition modeling](image)

**Figure 5.** Illustration of the layer-by-layer method of assigning the inherent strain

The example employed in the modified inherent strain method to predict the distortion of the substrate is same as the model shown in Figure 3. The only difference is the right end of the substrate is clamped in all directions. And what should be noted is that the thermo-mechanical coupled simulation is also used to predict the distortion of the substrate of the model with the same constrained conditions.

3.3. Comparison and verification

The modified inherent strain method and traditional thermo-mechanical coupled analysis are used to predict the bottom distortion results of the substrate after LMD process respectively, and the results are shown in Figure 6(a)(b). The whole thermo-mechanical coupled analysis process took about 3180 seconds in ANASY 18.0 with Intel Core i7-4720HQ 2.60 GHz CPU and 8.00 GB RAM, while it took only 10 seconds to conduct the simulation with the modified inherent strain method in ABAQUS 2019.
(a) the modified inherent strain method  
(b) the thermal-mechanical coupled method

(c) the predicted distortion results of line A  
(d) the predicted distortion results of line B

Figure 6. Distortion results of the substrate predicted by the two methods

It can be seen the two methods have predicted almost the same maximum distortions of the bottom surface, and the maximum values both appear at the lowest edge. The maximum distortion predicted by the thermo-mechanical analysis is 2.93mm, while the result gotten from the modified inherent strain method is 2.70mm, the deviation is 7.72%.

The distortion results of two lines (A and B) calculated by the two methods are compared in Figure 6(c)(d). It can be seen the predicted distortions at the lowest edge of the substrate by the two methods are in good agreement, the average distortion (0.275mm and 0.251mm) deviation predicted by the two methods is 8.73%, which demonstrating good accuracy (< 10% error) of the modified method for predicting the residual distortion of the LMD components. Although the distortion near the clamped end predicted by the inherent strain method is not as large as that predicted by the traditional method, it is feasible to achieve fast calculation under the condition of certain prediction accuracy loss, and small distortion is usually not concerned.

It can be concluded that the inherent strain method can used to predict the distortion of parts fabricated by LMD, which can greatly shorten the time and ensure a certain degree of accuracy.

4. Industrial-scale model of camshaft

4.1. Geometry and layered model
The distortion results of a representative structure of nuclear power emergency diesel generator camshaft are predicted by the modified inherent strain method. The geometry model is shown in Figure 7(a). The length, maximum and minimum external diameter of the camshaft are 3000, 127.5 and 80 mm, respectively. And due to the repeatability of the structure, a 1/6 model is analyzed.
The inherent strain values are applied to a model printed horizontally with 42 equivalent numerical layers to calculate the residual distortion, as shown in Figure 7(b). In the layered model, the height of an equivalent numerical layer is 3mm (3 times of an actual deposited layer).

Regarding the mechanical constraint in this case, the bottom surface of the first layer is fixed in all directions.

![Figure 7. 1/6 model of camshaft](image)

(a) Geometry model  (b) Layered model

4.2. Predicted results
It took about 3300 seconds to finish the distortion analysis of the 1/6 camshaft model in ABAQUS 2019. Clearly, this would be orders of magnitude more efficient than performing a detailed process simulation of the part given the detailed and complex laser scanning strategy, which will take days or even months. The simulation results via the layer-by-layer application of orthogonal CTEs show that the maximum distortion on the outermost surface of the cylindrical structure located on both sides is 3.18 mm, as shown in Figure 8. The convex position of the three cams is deformed greatly, the maximum distortion is about 2.3mm.

The case of removing the support structure at the bottom of the camshaft is simulated after LMD process. Figure 9. shows the distortion result of the camshaft after removing the support structure. Compared with the result before the removal of support structure, the two ends of the camshaft are warped upward. The position of the maximum distortion is unchanged, but the value increased from 3.18mm to 4.62mm, the increased percentage of maximum distortion is 45.3%. The distortion of the right cam increases when the support is removed, while the distortions of the other two cams decrease. The left end of the camshaft is warped larger than the right end, because the camshaft model is not completely symmetrical.

![Figure 8. Distortion results of the 1/6 camshaft model](image)
(a) before the removal of support structure

(b) after the removal of support structure

Figure 9. Distortion results of the 1/6 camshaft model with and without supports

5. Conclusion
A multi-scale model for fast residual distortion prediction of LMD part based on the inherent strain method is proposed.

The accuracy and validity of the developed inherent strain method have been explained via comparison with the results of thermo-mechanical analysis. For thermo-mechanical coupled analysis, the time cost is 3180s; for the modified inherent strain method, the cost is only 10s, and the time is reduced by 99.7%, which makes the fast distortion prediction of industrial components possible.

In view of the distortion prediction of LMD industrial-scale part camshaft, the modified inherent strain method found that the maximum distortion is 3.18mm, located on both sides of the camshaft. After the support is removed, the two ends of the camshaft are warped upward, while the position of the maximum distortion isn’t changed, the value increased to 4.62mm. It took only 3300s to complete the analysis, which greatly improves the efficiency.

For future work, in order to improve the accuracy of industrial-scale distortion prediction, the varying thermal effects of part geometry on inherent strain values should be taken into account. The influence of different substrate preheating temperatures, process parameters, scanning strategies and support structures on the deformation of parts should also be studied.

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