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The Development of an Effective and Comprehensive Modeling Technique for Thermomechanical Analysis of Selective Laser Melting Process

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Selective laser melting (SLM) is an additive manufacturing process that can be used to digitally fabricate three dimensional products by selectively sintering material powders in a powder bed layer by layer. The heat transfer with melting and solidification, the flow in the melting pool, and the transient thermomechanical behavior of the material during the process are critical for the properties of workpieces fabricated via SLM process. The typically high heat input along with rapid heating and cooling of the material in SLM lead to high thermal stresses in fabricated specimen, which in turn leads to distortion, cracks, and fatigue failure of the workpiece. In this study, a new modeling technique coupled heat transfer, melting pool flow, and thermomechanical analysis was developed to investigate temperature and thermal stress during the SLM process. Inconel 718 powders were used as the material in the experiment. The proposed two-stage quasi-transient model composes a transient thermal analysis followed by a transient thermomechanical analysis by using a hopping heat source to approximate the continuously moving laser heating. The thermomechanical analysis employed element birth and death technique. Material phase change, such as the melting and solidification of the powder, and the formed metal layer as well as the re-melting of the solidified layer were all considered. In a representative case, it was demonstrated that this novel quasi-transient model significantly reduces the computation cost by 99% as compared to the conventional simulation of SLM with a reasonable accuracy on the molding shape. Including the re-melting process in the analysis enabled accurate prediction of stress release in the overlapped laser scanned region of the specimen. The residual stress distributions obtained from the developed two-stage quasi-transient thermomechanical model were compared with measurement results from electron back scatter diffraction (EBSD) analysis. It is shown that the quasi-transient thermomechanical model provides important characteristics of residual stress consistent with that from a conventional full transient model in 68% less computation time. The dynamic stress release due to re-heating and re-melting in overlapped laser scanned regions was in close confirmation with experimental results. This efficient quasi-transient model is useful for rapid analysis and optimization of SLM processing parameters

NOMENCLATURE

$\mathbf{D}$ = elastic stiffness matrix
E = elastic modulus, Pa
H = enthalpy, J
k = thermal conductivity, W/(m·K)
l = length, m
$\dot{q}$ = volumetric heat source, W/m^3
T = temperature, K
t = time, s; powder layer thickness, m
v = scanning speed, m/s; fluid velocity, m/s
w = width, m
α = coefficient of thermal expansion, K^{-1}
δ = height, m
ε = strain
η = hatch, m
ρ = density, kg/m^3
σ = equivalent stress, kg/(m·s^2)
υ = Poisson's ratio
ω = laser spot radius, m

1. Introduction

Selective laser melting (SLM) is an additive manufacturing process. SLM process is used to manufacture complex geometries from a computer aided design (CAD) model by attaching the materials layer by layer [1]. The volumetric heat input along with rapid heating and cooling of the material lead to the development of high thermal stresses in fabricated specimen. These high thermal stresses also leads to distortion, cracks and fatigue failure of the specimen [1, 2]. Many researchers have studied the temperature [3], [4] and thermal stress generation [5, 6], during a SLM process. In this study a modified meso-scale finite element model (FEM) model for insights of the transient thermal and residual stresses evolution and distribution, especially in the overlapped regions, during a SLM process. The proposed thermomechanical simulation used a two-stage consequential coupling method. In the thermal analysis, material phase change such as the melting and solidification of powder and formed metal layer as well as the re-melting of solidified layer were all considered. The re-melting consideration enables an effective prediction to the stress release in the overlapped laser scanning region of the fabricated specimen.

2. Thermo-mechanical model

A coupled thermo-mechanical numerical model was developed using ANSYS to investigate both temperature and thermal stress during the selective laser melting process. Initially, transient thermal analysis was carried out for three lines of scanning. Subsequently, a transient mechanical analysis was performed by using the temperature data obtained from the previous thermal analysis. The mechanical analysis employed the element birth and death technique. The elements of the powder bed are de-activated initially, the elements whose temperature is more than melting point of the materials gets activated using APDL code. The elements activated provides the thermal stress value during melting phase and also after solidification.

Figure 1 illustrates the geometry and dimensions of the computational domain used in this study. The FEM simulation was constructed using ANSYS Fluent and Workbench. The dimensions are specified in the inset. The length (l) and width (w) were carefully decided such that the specimen can be simulated without influences from applied boundary conditions. The computation domain is divided into two layers: IN718 powder bed (top) and carbon steel substrate (bottom).

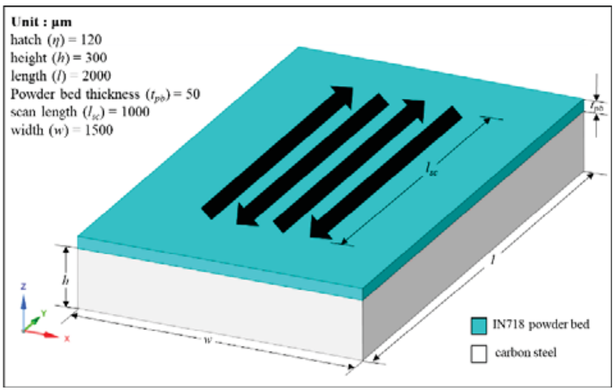

Fig. 1 Geometry and dimensions of the computational domain of thermomechanical model

Figure 2 shows the block diagram of the proposed coupled thermomechanical model, including the sequence of modelling in both (thermal and mechanical) model. Both the models use the same geometry and dimensions. A volumetric heat source is used in the thermal model to obtain the temperature. The temperature history is then exported to the mechanical model for stress calculation. Material properties and boundary conditions are properly plugged into both the models based on governing equations during the analyses. Data flow between the two models during computational process is also shown in the figure.

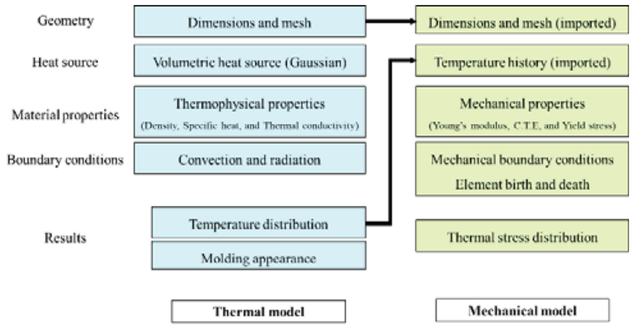

Fig. 2 Block diagram of coupled thermomechanical model for selective laser melting.

2.1 Thermal model

The thermal model has considered heat transfer along with phase change, i.e., melting and solidification of powder material. The thermal model is governed by energy Equation 1:

$$\frac{\partial(\rho H)}{\partial t}+\nabla\cdot(\rho\vec{v}T)=\nabla\cdot(k\nabla T)+\dot{q} \tag{1}$$

In this study, two types of the moving laser heat sources (effective-transient and quasi-transient) were applied, respectively, to predict temperature and residual stress. The first type is a standard effective–transient heat source corresponding to a continuously moving laser spot. The laser spot is considered to be of circular shape with radius ω. The laser intensity follows Gaussian distribution on the powder bed surface, while the intensity decays exponentially along the depth into the powder bed due to absorption. The second type of the simulated heat source is a quasi-transient hopping heat source ($\dot{q}_{hp}$) that was modified from the continuous moving heat source in order to reduce the computation cost [3]. The heat source is of an elliptical shape.

2.2 Mechanical model

The mechanical model calculates the stress generated in the specimen. The relationship between stress and strain is defined in Equation 2:

$$\{\sigma\}=[D]\{\varepsilon^{e}\} \tag{2}$$

Thermal strain and equivalent stress is calculated by Equation 3 and Equation 4, respectively.

$$\varepsilon^{th} \equiv \alpha_e \Delta T = \alpha_e (T - T_{ref}) \tag{3}$$

$$\sigma_{eqv} = \sqrt{\frac{1}{2}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]} \tag{4}$$

Figure 3 shows the schematic of element birth technique. This technique has been used to effectively simulate the temperature and stress distribution in a specimen [7]. This technique uses element activation and deactivation for depositing the material onto the substrate. Originally, all elements in the powder bed are deactivated. When the laser power is irradiated on to the powder bed, elements with temperature higher than melting temperature are activated as red elements. The newly activated elements undergoes thermal and thermomechanical loading together with its solid phase surroundings (i.e. the substrate and the adjacent activated elements), which results in the generation of thermal stress. The element birth technique prevents automatically the impact to the stresses in the specimen from the remaining powders [8].

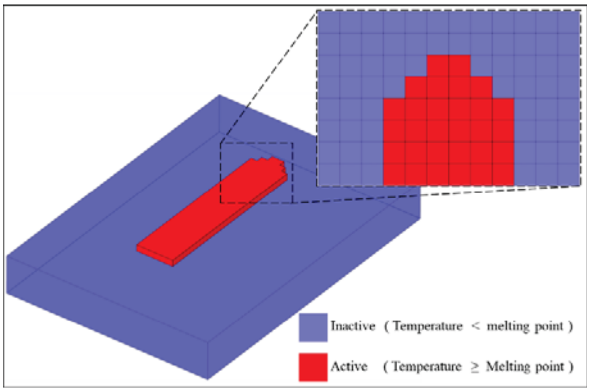

Figure 3 Schematic of element birth technique in the thermomechanical model.

3. Results and Discussion

Figure 4(a) and 4(b) shows the temperature and equivalent stress history of points G and G′, respectively. The two points are located in the same location in the overlapped region. Results (temperature and stress history) of G and G′ are calculated using the effective-transient and quasi-transient heat source, respectively. The distance between laser starting point and end point is 1000 μm in both cases. Table 1 lists the required computational resources using the quasi-transient and effective-transient heat sources for simulation of two lines by a SLM process. The simulations were carried out with the same processing parameters (P = 80 W, v = 100 mm/s, and H =120 μm). Both simulations were conducted in the same machine as specified in the table footnote. The mesh size of powder bed is 10 μm, and number of elements is 189,618 for both simulations. In these cases, the overlapped regions experience two temperature peaks. The stress is generated after the first heating-cooling cycle, then released during the second cycle due to re-melting. The final equivalent stress achieved from using the quasi-transient heat source is 24.5% higher than that from the effective-transient heat source. Total stress reduction in the overlapped region for quasi-transient heat source and effective-transient heat source were 37.18% and 52.38%, respectively. Regardless these differences due to the approximation of heat source, the overall trend of temperature and stress history using the quasi-transient heat source agrees with that from the effective-transient heat source.

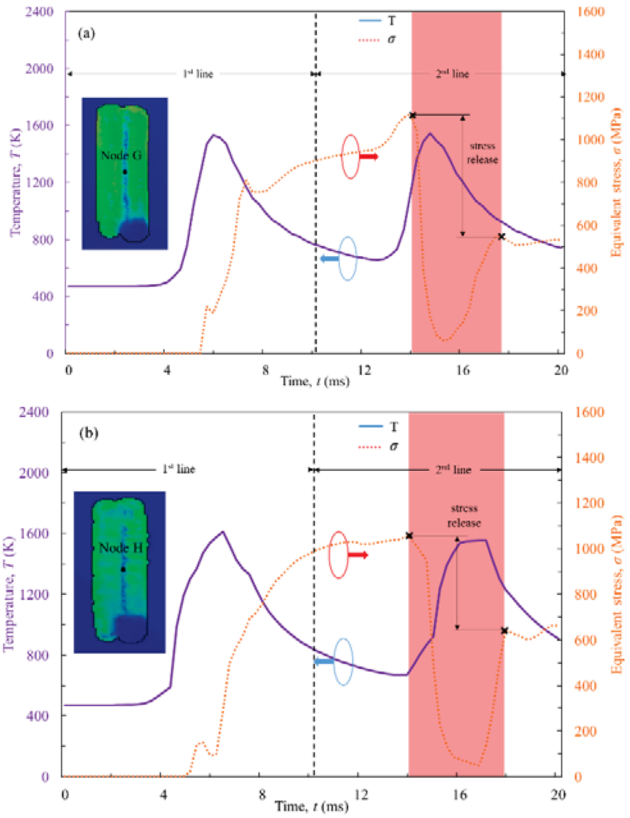

Figure 4 Temperature and equivalent stress history of points (G and G′) located in the same overlapped regions for models using different heat sources: (a) Effective-transient heat source (b) Quasi-transient heat source.

Table 1 lists the total computational time and required memory for both thermal and mechanical analysis required by quasi-transient heat source is considerably less than effective-transient heat source. The quasi-transient heat source showed a reduction of 68% in computational time and reduction of 65% in memory requirement from those using effective transient heat source. Noted that the size of the scanning area simulated in this section is about one-eighth of the real fabricated specimen. The computation cost for the real size specimen using the effective-transient heat source would be at least 900 hours and is apparently unaffordable for real applications. Therefore, only the quasi-transient heat source simulations were conducted for complete thermal and stress analyses in the following sections.

Table 1 Computation time and required computer memory for the effective transient and quasi-transient model.

		Effective-transient model	Quasi-transient model
Computation time (hr/case)	Thermal	0.26	0.17
	Mechanical	107.23	34.16
	Total	107.49	34.33
Storage memory (GB/case)	Thermal	1.76	1.27
	Mechanical	361.00	126.40
	Total	362.76	127.67

Processor: Intel® Xenon® CPU (2) E5-2680 v3 at 2.50 GHz, RAM: 256 GB, Cores: 48.

4. Conclusions

A meso-scale thermo-mechanical model with a quasi-transient heat source was developed to analyze transient temperature and stress variations during a SLM process of IN718. Initially, a transient thermal analysis was performed to estimate temperature distribution. The results obtained from thermal analysis was then used as an input thermal loading to calculate the residual stress generated inside the specimen due to the incompatible thermal expansion of the IN718 material and the carbon steel substrate. The effectiveness of the quasi-transient heat source simulation was firstly validated by comparing with the temperature and stress results for a reduced case simulated by using a conventional moving laser heat source. Both the numerical models result showed clearly a stress reduction in the overlapped region of the specimen due to re-heating and re-melting. Moreover, the quasi-transient heat source showed a reduction of 68% in computational time and reduction of 65% in memory requirement, while the trend of transient temperature variation and residual stresses obtained from the developed quasi-transient model reasonably agree with the original transient model.

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REFERENCES

1. J. P. Kruth et al., “Selective laser melting of iron-based powder,” J. Mater. Process. Technol., Vol. 149, No. 1–3, pp. 616–622, 2004.

2. H. Attar, S. Ehtemam-Haghighi, D. Kent, and M. S. Dargusch, “Recent developments and opportunities in additive manufacturing of titanium-based matrix composites: A review,” Int. J. Mach. Tools Manuf., Vol. 133, No. June, pp. 85–102, 2018.

3. N. Anand et al., “An effective and efficient model for temperature and molding appearance analyses for selective laser melting process,” J. Mater. Process. Technol., Vol. 294, p. 117109, Aug. 2021.

4. T. H. G. Childs, G. Hauser, and M. Badrossamay, “Selective laser sintering (melting) of stainless and tool steel powders: Experiments and modelling,” Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., Vol. 219, No. 4, pp. 339–357, 2005.

5. A. Hussein, L. Hao, C. Yan, and R. Everson, “Finite element simulation of the temperature and stress fields in single layers built without-support in selective laser melting,” Mater. Des., Vol. 52, pp. 638–647, 2013.

6. P. Mercelis and J. P. Kruth, “Residual stresses in selective laser sintering and selective laser melting,” Rapid Prototyp. J., Vol. 12, No. 5, pp. 254–265, 2006.

7. L.E. Lindgren, A. Lundbäck, M. Fisk, R. Pederson, and J. Andersson, Simulation of additive manufacturing using coupled constitutive and microstructure models, Addit. Manuf., Vol. 12, pp. 144–158, 2016.

8. I.A. Roberts, C.J. Wang, R. Esterlein, M. Stanford, and D.J. Mynors, A three-dimensional finite element analysis of the temperature field during laser melting of metal powders in additive layer manufacturing, Int. J. Mach. Tools Manuf., Vol. 49, pp. 916–923, 2009.