Materials and Design 52 (2013) 638–647

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Technical Report

Finite element simulation of the temperature and stress fields in single layers built without-support in selective laser melting

Ahmed Hussein, Liang Hao *, Chunze Yan, Richard Everson

College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, EX4 4QF Devon, United Kingdom

ARTICLE INFO

Article history:
Received 5 February 2013
Accepted 23 May 2013
Available online 7 June 2013

ABSTRACT

Overhanging and floating layers which are introduced during the build in selective laser melting (SLM) process are usually associated with high temperature gradients and thermal stresses. As there is no underlying solid material, less heat is dissipated to the powder bed and the melted layer is free to deform resulting undesired effects such as shrinkage and crack. This study uses three-dimensional finite element simulation to investigate the temperature and stress fields in single 316L stainless steel layers built on the powder bed without support in SLM. A non-linear transient model based on sequentially coupled thermo-mechanical field analysis code was developed in ANSYS parametric design language (APDL). It is found that the predicted length of the melt pool increases at higher scan speed while both width and depth of the melt pool decreases. The cyclic melting and cooling rates in the scanned tracks result high VonMises stresses in the consolidated tracks of the layer.

1. Introduction

One of the limitations of SLM is the thermal distortion of the part during forming, which may lead to undesired shrinkage and cracks. The elevated temperature gradients developed yield a non-homogeneous permanent strains and residual stresses distributed within consolidated layers [1]. As a result, the dimensional size, shape, and mechanical properties of the fabricated parts are affected considerably. The processing parameters such as laser power, scanning speed, laser spot size, and scanning strategy all play a crucial role on the development of temperature gradients and residual stresses in the part [2]. These parameters are usually optimised through experimental means for specific machines and materials. However, detailed investigation of all different parameters and materials for SLM through experiments can be time consuming and costly. Therefore, numerical methods are mainly used as a tool to study the role of these parameters on temperature distribution, residual stress and other thermal mechanisms.

The finite element method is the most commonly used numerical method for predicting temperature and stress fields in SLM. Childs et al. [3] investigated the influence of process parameters on the mass of melted single layers in SLM and found that melted mass increased with increasing scanning speed. The effect of layer thickness on part deformation in SLM parts was investigated by Zaeh and Branner [4]. A thinner layer thickness resulted in a higher deformation due to the effect of higher temperature variation concentrated within thin layers. Matsumoto et al. [5] developed a finite element analysis (FEA) method for single layer parts on the loose powder in SLM. A 2D non-linear heat transfer with volume internal heat source problem is numerically solved based on the coupling of Matlab and ANSYS FEM models [6]. The surface temperature distribution during SLM of 90W–7Ni–3F materials was predicted by Zhang et al. [7]. Dai and Shaw [8] use the finite element analysis to investigate the effect of laser scanning strategy on residual thermal stresses and distortion. Nickel et al. [9] developed FEA model to simulate the laser deposition process and found that the deposition pattern has a significant effect on the part stresses and deflections. Yin et al. [10], Ibraheem et al. [11], Shuai et al. [12] report their research results of temperature fields in single metallic layer SLM processes by using element birth and death technique. In [13], a more comprehensive understanding of the SLM thermal field has been achieved by creating a 3D model and considering the interval time for new powder recoating.

Ma and Bin [14] proposed a 3D FEA model with fixed temperature heat source for calculating the evolution of temperature and thermal stresses within a single metallic layer formed on the powder bed using two different scanning patterns in SLS. It was found that the distortion and transient stresses of a layer processed by a moving laser beam decreased with fractal scanning pattern. From this review, it is evident that using 2D analysis with generalised plane strain conditions seems to be convenient with less computer processing requirements, but 3D analysis remains absolutely necessary to fully understand the problem. An in-depth understanding of the materials and laser interaction in overhanging regions and its associated thermal and stress mechanisms is essential step for the design of efficient and reliable support structure and improving surface quality of overhanging geometries.

* Corresponding author. Tel.: +44 (0) 1392 723665.
E-mail addresses: Ayh203@exeter.ac.uk (A. Hussein), l.hao@exeter.ac.uk (L. Hao).

0261-3069/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.05.070

In this study, a 3D non-linear transient finite element model based on sequentially coupled thermo-mechanical field analysis was developed in ANSYS programme to predict the temperature distribution, thermal stresses and melt pool dimensions of laser scanned single layers built on the powder bed. Simulation of the moving heat source and changing boundary conditions are accomplished by a user written subroutine implemented in ANSYS parametric design language (APDL). Since the heat energy is transported well below the surface of the powder bed in SLM, the laser energy density was applied as a volumetric heat source rather than a surface heat flux. Temperature dependent physical properties of 316L stainless steel powder material are taken into account and latent heat of fusion is considered.

2. 3D finite element model

ANSYS provides the capability of performing indirect sequentially coupled thermo-mechanical analysis for both heat and stress analysis. In this study, a multiple physics environment was used in a single database as this allows a quick switching between physics environments for subsequent stress analysis. A non-linear transient thermal analysis was performed first to obtain the global temperature history generated during the laser melting. A transient stress analysis is then developed with an automatic exchange of the element type from thermal-to-structural, and applying the temperatures obtained from previous transient thermal analysis, as a thermal loading for the mechanical analysis. The 3D FEA model representing the single layers built on the powder bed can be seen in Fig. 1a. In order to reduce computational time, the elements which interact with the laser beam are finely meshed with hexahedral element sizes equal to 75 μm and coarser mesh is used for the surrounding loose powder.

For the thermal analysis, the laser beam with calculated energy density as in Fig. 1b strikes a number of elements equal to the laser spot size of 150 μm and moves with the specific scanning speed in the *X*-direction on the powder bed. When the laser moves to next load step, the previous load step is deleted to account for the cooling cycle. The analysis is divided into several steps in order to move the heat source from laser over few elements at the time in the laser path. The time period for which the laser beam is retained on each step, is given as,

$$T_{\text{step}} = \frac{dx}{V} \tag{1}$$

where d*x* is the length of elements under the laser spot in mm and *V is* the scanning speed of the laser beam in mm/s.

Table 1 summarises the parameters used in the finite element simulation.

2.1. Thermal modelling

The thermal equilibrium equation satisfies the following classical 3D heat conduction equation given by [15],

$$\rho c \frac{\delta T}{\delta t} = \frac{\delta}{\delta x}\left(k\frac{\delta T}{\delta x}\right) + \frac{\delta}{\delta y}\left(k\frac{\delta T}{\delta y}\right) + \frac{\delta}{\delta z}\left(k\frac{\delta T}{\delta z}\right) + Q \tag{2}$$

where ρ is the material density (kg/m^3); *c* is the specific heat capacity (J/kg K); *T* is the temperature; *t* is the interaction time; *k* is thermal conductivity (W/mK); and $Q = (x, y, z, t)$ is the volumetric heat generation (W/m^3).

The effective thermal conductivity is a function of porosity of the powder [16]. The porosity of the powder ϕ can be calculated as,

$$\phi = \frac{\rho_{\text{bulk}} - \rho_{\text{powder}}}{\rho_{\text{bulk}}} \tag{3}$$

where ϕ is the porosity of the powder; ρ_{bulk} and ρ_{powder} are the densities of the bulk and powder materials. The porosity is assumed to vary from $\phi = 0.4$ for powder state to $\phi = 0$ at solid state.

The thermal conductivity of the powder can be expressed as [17],

$$k_{\text{powder}} = k_{\text{bulk}}(1 - \phi) \tag{4}$$

where k_{powder} and k_{bulk} are thermal conductivities of powder and bulk materials.

The latent heat of fusion is simulated by an artificial increase in the liquid specific heat and the relationship between the enthalpy, *H*, density, *p*, and specific heat, *c* can be written as,

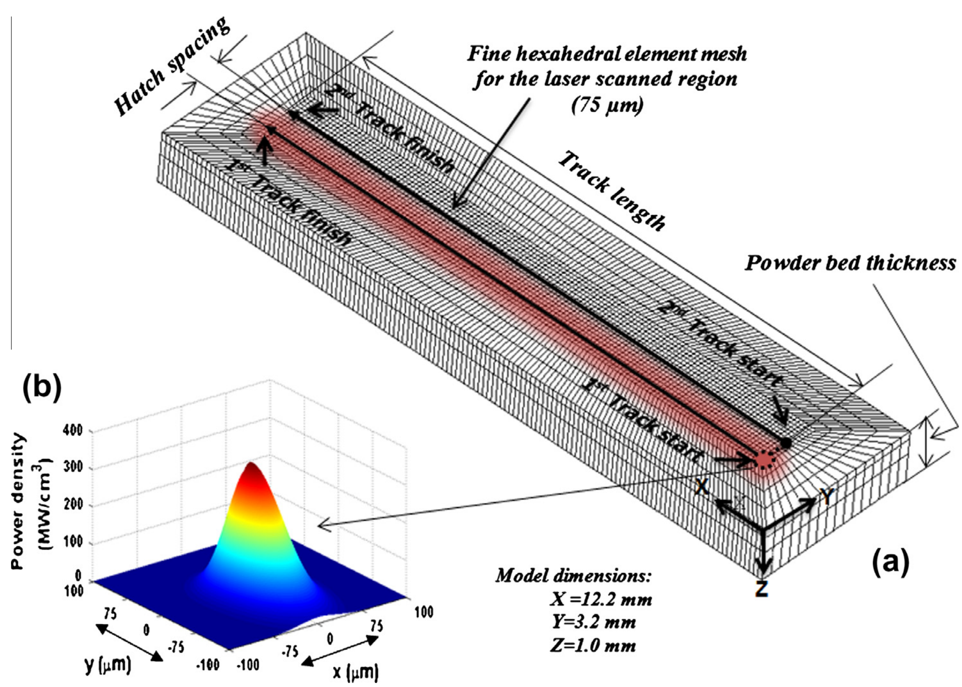

Fig. 1. (a) 3D finite element model and (b) Gaussian laser energy density.