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Understanding the effect of laser scan strategy on residual stress in selective laser melting through thermo-mechanical simulation

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ABSTRACT

Selective laser melting (SLM) is an attractive technology, enabling the manufacture of customised, complex metallic designs, with minimal wastage. However, uptake by industry is currently impeded by several technical barriers, such as the control of residual stress, which have a detrimental effect on the manufacturability and integrity of a component. Indirectly, these impose severe design restrictions and reduce the reliability of components, driving up costs. This paper uses a thermo-mechanical model to better understand the effect of laser scan strategy on the generation of residual stress in SLM. A complex interaction between transient thermal history and the build-up of residual stress has been observed in the two laser scan strategies investigated. The temperature gradient mechanism was discovered for the creation of residual stress. The greatest stress component was found to develop parallel to the scan vectors, creating an anisotropic stress distribution in the part. The stress distribution varied between laser scan strategies and the cause has been determined by observing the thermal history during scanning. Using this, proposals are suggested for designing laser scan strategies used in SLM.

1. Introduction

Selective Laser Melting (SLM) as an Additive Manufacturing technology has proliferated in interest through enabling designers to realise geometrically complex metallic structures [1], with a rapid design to manufacture cycle compared with conventional manufacturing methods [2]. Owing to its ability to incorporate advanced design techniques, such as topology optimisation [3,4] and lattice structures into components [5], and individual customisation, SLM has gained significant attention from many industrial sectors, in particular aerospace and automotive. Despite its great potential, technical barriers prevent manufacture ‘right first time’ and impose several manufacturing constraints that reduce design freedoms and design optimization unnecessarily.

The SLM process belongs to the family of powder-bed fusion technologies [6] whereby a powder bed is exposed to a laser beam with a high density flux, causing the powder to fully melt and solidify upon cooling. Laser based manufacturing methods generate large temperature gradients in the vicinity of the applied exposure area owing to the high energy density input. The effect of non-uniform thermal expansions and contractions in the Heat Affected Zone (HAZ) result in the formation of residual stresses in the finished part. Unmanaged, these may have the immediate consequence of causing failure during manufacture, as shown in Fig. 1, or other undesirable artefacts of residual stress, including distortion, increased susceptibility to crack formation and reduced fatigue performance [7].

Parts produced by SLM generally require additional support structures to constrain the part to restrict ‘curling’ or distortion during manufacture. After manufacture, the relief of residual stress requires further post processing either by heat treatment or hot isostatic pressing (HIP) [8].

A method to mitigate the need for support structures was proposed in [9] by utilising the eutectic point of a zinc alloy (Bi3Zn) to minimise the melt temperature required thereby reducing the direct energy input. This enabled them to build parts without support structures although they did not report the effects of distortion caused by residual stress. This method is, however, considerably limited in the choice of alloys usable.

The correct choice of laser scan strategy is critical in generating the desired microstructure [10,11] and is also known to affect the build-up of residual stress in components [12]. Previous studies have observed that the largest planar residual stress component is generated parallel to the scan vector and increases with scan vector

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Nomenclature

c_p	Specific heat capacity[kJ/kg K]
E	Young's modulus [GPa]
f_{po}	Spot point overlap factor
H	Enthalpy [J]
h_C	Heat transfer coefficient [W/m^2 K]
H_P	Plastic tangent modulus [GPa]
k	Thermal conductivity [W/m K]
P	Power of laser input [W]
q_S	Surface heat flux [W/m^2]
q_V	Volumetric heat flux [W/m^3]
T	Temperature [°C]
T_A	Temperature (ambient) [°C]
T_L	Temperature (liquidus) [°C]
T_S	Temperature (solidus) [°C]
α	Thermal diffusivity [m^2/s]
α_{th}	Linear thermal expansion coefficient of thermal expansion [1/K]
ε	Strain
ε_{em}	Emissivity
ν	Poisson's ratio
ρ	Density [g/cm^3]
σ	Stress [MPa]
σ_B	Stefan-Boltzmann constant $(5.67 \times 10{-}8\,\mathrm{W/m^2K^4})$

length [12–14]. Another study investigated the effect of material properties on the creation of residual stress, however, failed to reveal any systematic correlations [15]. Despite this previous work indicating the importance of residual stress generation in SLM, the underlying mechanisms for the generation of residual stress remains little understood. In order to better determine the factors influencing the build-up of residual stress, thermo-mechanical models for simulating SLM are potentially valuable, although this is challenging due to the complexity of the physics involved in the SLM process and the multiple analytical scale lengths.

Previous research in simulating SLM has focused on modelling the thermal transport behaviour in SLM and EBM, with relatively few studies that couple this with the mechanical response. General coupled thermo-mechanical analyses of SLM have been reported by several authors [16–19], but these did not examine in detail the effects of laser scan strategy and are mainly focused on developing modelling techniques. Observations from such simulations have included the reporting of an asymmetric melt-pool and that the largest stress component was generated parallel to the scanning direction, agreeing with previous experimental studies [14]. Another approach that has been proposed is applying an instantaneous, uniform heat flux to the entire cross-sectional surface, rather than simulating the motion of the laser path [20,21]. However, this method is limited by its inability to resolve the effect of laser scan strategy on residual stress. To overcome this limitation, a layer based model using a characteristic strain determined using a macro scale model has been proposed [22].

Fig. 1. Failure during manufacturing of a Ti-6Al–4 V component caused by the build-up of residual stress.

Computational Fluid Dynamics (CFD) coupled with a FE analysis has been used to account for thermo-fluid effects inside the melt pool but due to their inherent computational cost are limited to mesoscale simulations for small time scales [23–26]. Hodge et al. [18] advanced this area by incorporating a multi-phase stress term using volumetric fractions, and a phase expansion term to account for volumetric shrinkage during phase change between powder and consolidated form.

Current models have not identified the geometrical relationship between the choices of laser scan strategy with the generation of residual stress. Also, there is a lack of knowledge relating the temperature field created with the residual stress generated by the choice of laser scan strategy. Currently this information is not available in a way that would enable the prediction of distortion and failure, and consequently, the reliable manufacture of components in SLM.

In this paper, a coupled thermo-mechanical finite element model is established to determine the mechanisms that cause the generation residual stress during SLM. The model is then used to determine the implications of the temperature history, created by the choice of laser scan strategy and scan area size, on the development of residual stress during selective laser melting. This work sets the basis for the development of optimal scan strategies to mitigate residual stress effects in SLM built components.

2. Model definition

2.1. Simulation overview

This work uses a coupled thermo-mechanical finite element (FE) analysis for the simulation of the SLM of Ti-6Al–4 V with laser parameters chosen specifically for manufacture on a Realizer SLM-50 [27]. A commercial FE solution was deemed sufficient to provide a robust solution whilst reducing development time required. MSC Marc [28] was chosen because of its competency in modelling non-linear multi-physics manufacturing processes and the ability to extend models and functionality with user defined Fortran subroutines

The overall modelling strategy attempts to replicate the SLM process by directly simulating the machine build files to enable a direct comparison with experiments. The workflow is shown in Fig. 2 where it can be seen that two main inputs are required: an extensive list of material properties and the machine build file.

The simulation process interacts between Fortran user subroutines and an external c++ interface to control the simulation behaviour whilst running (Fig. 3). The c++ interface has several responsibilities. Firstly, it parses the machine build file and controls the laser position, laser power and state at a given simulation time. Secondly, it manages the adaptive time-stepping procedure ensuring that a consistent time step is used for varying laser scan speeds (Section 2.3). Finally, it provides an interface for managing the state variable of each element. This functionality is integrated separately with a general purpose, multi-physics FE solver to enable future additions of more complex modelling.