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Parametric Finite Elements Model of SLM Additive Manufacturing process

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Abstract

An obstacle to the diffusion of additive technology is the difficulty of predicting the residual stresses introduced during the fabrication process. This problem has a considerable practical interest as evidenced by the abundant literature on residual stresses and distortion induced by the SLM (Selective Laser Melting) and EBAM (Electron Beam Additive Manufacturing).
The purpose of this paper is to evaluate the effect of different process parameters on the heat distribution and residual stresses in components made with SLM technique. Three aspects are developed and illustrated: a) thermomechanical modeling of the growth process, based on Finite Elements (FE), which considers changes in the behavior of the material (powder→liquid→solid) through the finite element "birth" and "death" technique that enables the progressive activation of the elements as the component grows; b) sensitivity analysis of the model to the physical characteristics of the material (conductivity, specific heat capacity, Young's modulus). This is an important aspect allowing to focus on the most significant parameters to be determined experimentally with high reliability; c) evaluation of the effects of different process parameters (laser power, scan speed, overlap between adjacent paths) on the process.
The article illustrates the theoretical thermal model and the detail of the strategy used in the FE analysis. The most influential characteristics of the material are highlighted and, finally, general criteria for choosing the optimal combination of process parameters to limit the residual stresses are provided.

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Keywords: FE model, Additive Manufacturing, Residual stresses, Selective Laser Melting

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Nomenclature

α	absorbance of the layer	
ε	surface emissivity	
Φ	void content (porosity)	
σ	Stefan-Boltzman constant	(W/m^2 °K^4)
ρ	density	(Kg/m^3)
τ	time	(sec)
Cp	specific heat capacity	(J/Kg °K)
E	Young modulus	(Pa)
h	convection coefficient	(W/m^2 °K)
k	thermal conductivity	(W/m °K)
R_0	laser spot radius	(μm)
Q	power of the laser beam	(W)
q	heat flux	(W/m^2)
Sv	overlap ratio between two laser scans	(%)
T	temperature	(°K)
V	beam scan speed	(mm/sec)

1. Introduction

Selective laser melting (SLM) is an additive manufacturing (AM) technique through witch a complex metal part can be fabricated by piling up layers of melted material, I. Gibson et al. (2010), A.E. Patterson et al. (2017). During the process, a thin metal powder layer is selectively melted by a controlled laser beam; the material undergoes many physical transformations (from powder to liquid and then to solid) and severe temperature fluctuations resulting in relevant residual stresses, significant distortions and, in some cases, cracks and delaminations, P. Mercelis et al. (2006). The evaluation and elimination of the residual stresses in parts fabricated with A.M. is a paramount aspect and many efforts are addressed to this goal, R. Paul et al. (2014); a review of the literature on FE analysis in SLM can be found in K. Zeng et al. (2012) , A.E. Patterson et al. (2017) and Markl et al. (2016).

In SLM, the laser spot scans the powder layer according to a particular pattern and builds up the component layer by layer; some areas will overlay previous solidified layers, other areas could overhang unprocessed powder areas, therefore some support structure must be foreseen to link the part to the base plate and limit the distortions that could be induced. The process parameters like laser power, scanning parameters, scanning speed must be optimized to ensure that the powder is fully melted and bonded to the underlying layer. The scanning strategy heavily influences the final result in terms of defects, porosity, resistance but also in terms of microstructure of the material and thermal behavior, L.N. Carter et al.(2014). The SLM process develops large cyclic thermal gradients generating high stresses and deformations depending on the scanning strategy, P. Mercelis and J.P. Kruth (2006), J.P. Kruth et al. (2012), J.P. Kruth et al. (2004).

A numerical model of the process can be a useful and cheap tool to compare different parameter settings and suggest the most suitable choice. A numerical model must rely on an accurate formulation of the thermal history the material undergoes during its transformation from a powder to a solid. Many studies are available on this subject; modeling of the laser spot was developed by many authors, J. Goldak et al. (1984), S. Kolossov et al. (2004); complete heating models are proposed, A.V.G. Gusarov et al. (2009), K. Dai and L. Shaw (2005); some models were experimentally tested with sophisticated techniques, A.S. Wo et al. (2014) and some specific experimental procedures are proposed, D. Cerniglia et al. (2015). All the numerical models, based on Finite Elements (FE), try to forecast residual stresses and deformations and many results are available, N. Contuzzi et al.(2011), A. Hussein et al. (2013), J.C. Heigel et al. (2015), A. Ahmadi et al.(2016), F. Mukerjee et al. (2017). An overview of the thermal analyses proposed can be found in K. Zeng (2012).

The present paper is intended to evaluate the sensibility of the model with respect to uncertainties on the real value of the main physical proprieties of the material in order to understand where to concentrate the experimental