ARTICLE IN PRESS
CRAS2B:3628

C. R. Mecanique ••• (••••) •••–•••

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Comptes Rendus Mecanique

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Computational methods in welding and additive manufacturing / Simulation numérique des procédés de soudage et de fabrication additive

Numerical modelling of fluid and solid thermomechanics in additive manufacturing by powder-bed fusion: Continuum and level set formulation applied to track- and part-scale simulations

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A R T I C L E I N F O

Article history:
Received 21 March 2018
Accepted 18 April 2018
Available online xxxx

Keywords:
Additive manufacturing
Powder-bed fusion
Finite element modelling
Level set formulation
Continuum assumption
Thermomechanics
Track and part scales

A B S T R A C T

The thermomechanical analysis of powder-bed fusion using a laser beam is simulated in both meso- and macroscales within a framework combining continuum assumption and level-set formulation. The mesoscale simulation focuses on laser interaction with the powder bed, and on subsequent melting and solidification. Modelling is conducted at the scale of material deposition, in which powder-bed fusion, hydrodynamics in the melt pool, and thermal stress are simulated. The macroscale model focuses on part construction and post-deposition. During construction, by contrast with the mesoscale approach, the fluid flow in the fusion zone is ignored and material addition is simplified by modelling it at the scale of entire layers, or fractions of layers. The modelling of the energy input is adapted accordingly. This thermomechanical model addresses heat exchange, residual stress, and distortion at the part's scale. In both approaches, adaptive remeshing is applied, providing a good compromise between the needs to provide accurate prediction and maintaining sustainable computation times.

0. Introduction

Additive manufacturing (AM) consists in building a part layer by layer directly from the data of a 3D computer-aided design (CAD) model. As such, and contrary to traditional manufacturing approaches, it may offer a customized design for complex geometries in a rapid design-to-manufacture cycle [1]. Selective laser melting (SLM, also called laser beam melting, LBM) and electron beam melting (EBM) are two powder-bed AM techniques. As both processes can fabricate quasi-fully dense near-net-shape components and are suitable for various metallic powders, great interests are received from both industrial and academic fields [2]. The present paper deals with SLM, but most of the modelling concepts presented here could be adapted to EBM.

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https://doi.org/10.1016/j.crme.2018.08.008

Powder-bed fusion AM still suffers from defects having a thermomechanical origin, such as porosities and cracking. Cracks may consist of solidification cracks that form at the rear of the fusion zone, which undergoes tensile stress during cooling. Cracks may also form in the solid state, at lower temperature, as a result of the stress build-up in the part under construction. An additional effect of such build-up of thermal stresses is the distortion of the part, which is of course an issue as it affects the capacity of obtaining a good geometrical accuracy on the final product. In total, process control is difficult to optimize in order to manufacture sound and high-precision near-net-shape parts. To minimize costly trial-and-error approach of AM processes by repeated experiments, numerical simulation has been introduced and continuously developed to model the thermal and mechanical responses during and after processing. Up to now, this has been done at different scales, as detailed hereunder.

A first class of numerical models directly addresses the particles' scale. Studies focus on laser/matter interaction, melting of particles, formation of the fusion zone, and thermohydraulics. Körner and co-workers have developed a particle scale numerical model based on the Lattice–Boltzmann method with a volume of fluid approach for free surfaces [3]. Recently, they applied their model to the study of the influence of the stochastic powder bed on the EBM process window for dense parts [4]. By use of an adequate method to model the formation of 100 layers with their 2D approach, simulations show a good agreement with the experimental statistical occurrence of porosities, and with the surface roughness for the samples produced. Still by particle-scale modelling, King et al. [5] simulated track formation in LBM at the particle scale with and without surface tension by coupling thermal diffusion with hydrodynamics using finite-volume/finite-element implementation. They found that considering surface tension tends to provide smoother melt pools and improved heat transfer with the substrate. Qiu et al. [6] developed a hydrodynamic numerical simulation based on the finite volume method, including surface tension, Marangoni force, and recoil pressure associated with vaporization. They applied their model to a powder bed of very small dimensions consisting of 50 to 60 regularly packed Ti-6Al-4V powder particles. They found that the driving forces are responsible for melt pool instability leading to melt splashing, which could explain the occurrence of porosities. A similar method is adopted by Megahed et al. [7] and Mindt et al. [8] in particle scale, different samples of powder beds being considered to investigate the influence of the powder bed structure on the processed surface. Ly et al. [9] used and developed a finite element (FE) model, but in an Arbitrary Lagrangian–Eulerian (ALE) formulation. They carried out particle-scale simulations of LBM, on a slightly more extended powder bed (about two hundred particles). The model is capable of simulating the ejection of molten droplets from the melt pool, as a result of the intense liquid flow prevailing there. Besides, the authors explain the denudation process by metal-vapour-driven particle entrainment. As it can be seen from the previous references, particle-scale models are well suited to model particle motion, fluid flow in the melt pool, and phenomena like liquid spattering and porosity formation. However, they have not been applied yet to the modelling of thermomechanics-driven defects such as distortions, and different types of cracking.

A second class of numerical models addresses the part scale. These macroscale approaches are more specifically dedicated to part distortions and stress build-up. In the macro scale, the details of the local laser/matter interaction, and of the local fluid flow in the fusion zone are ignored. Efforts are focused on modelling heat transfer and mechanical response at the scale of the part. Modelling techniques are generally based on the FE method in a Lagrangian framework, and matter deposition is simulated by element activation or element birth techniques. Many FE thermomechanical models have been developed using this approach, and only a few contributors will be mentioned here. Among them, Gu and He [10] used a commercial three-dimensional transient FE software, with the element activation technique. They simulated the formation of three parallel tracks scanned back and forth. The calculated stress distribution was in agreement with the location of the cracks in experiments. With a similar numerical method, Hodge et al. [11] studied the issue of the change in thermal distribution and melt pool extension during the addition of overhang regions, which are regions non-supported by pre-deposited tracks, but supported by non-consolidated powder. They showed that the method could be applied to the scale of a small part of the order of 1 mm^3 consisting of a dozen of layers, for the prediction of residual stress and distortion. However, when element activation is applied to simulate the exact laser scan path like in the two latter studies, modelling LBM processing of real components is out of reach due to prohibitive computational times. In order to keep calculation times sustainable, the build-up of parts is often simulated by adding all the powder elements in one layer simultaneously – or even in groups of several layers [12] – at the top of the construction. In the recent period, significant efforts have been done to reduce computational times. The inherent strain method has been developed by Alvarez et al. [13]. They demonstrated that the proposed model is possible to accurately predict the distortion induced by different scanning strategy in short times. In addition, Li et al. [14] have developed a practical multi-scale modelling methodology for fast prediction of part distortion by integrating a microscale laser scan model, a mesoscale layer hatch model, and a macroscale part model. A concept of equivalent heat source has been developed based on the microscale laser scan model. By using the equivalent heat source, local residual stress field was predicted in the mesoscale layer hatch model. The residual stress field was then imported to the macroscale model to predict part distortion and residual stress.

In this paper, an original method is presented, which is based on finite elements in a level-set formulation and can be applied to both track and part scale. The method has been first developed by Chen et al. [15] at the track scale. Contrary to particle-scale methods, the powder bed is considered as a continuum enduring continuous evolution when being transformed in a dense melt, and further solidified. The formation of the melt pool, the hydrodynamics and the resulting shapes of the deposited tracks can be simulated. In the present paper, the extension of the method to solid thermomechanics will be presented. The same FE–level-set method was adapted to macroscale simulations, first to model heat transfer [16], and more recently to model thermomechanics. The paper aims at giving a unified presentation of this method. It is organized

Please cite this article in press as: Y. Zhang et al., Numerical modelling of fluid and solid thermomechanics in additive manufacturing by powder-bed fusion: Continuum and level set formulation applied to track- and part-scale simulations, C. R. Mecanique (2018), https://doi.org/10.1016/j.crme.2018.08.008