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

Approaches in computational welding mechanics applied to additive manufacturing: Review and outlook

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ABSTRACT

The development of computational welding mechanics (CWM) began more than four decades ago. The approach focuses on the region outside the molten pool and is used to simulate the thermo-metallurgical-mechanical behaviour of welded components. It was applied to additive manufacturing (AM) processes when they were known as weld repair and metal deposition. The interest in the CWM approach applied to AM has increased considerably, and there are new challenges in this context regarding welding. The current state and need for developments from the perspective of the authors are summarised in this study.

1. Introduction

Additive manufacturing (AM) describes various techniques for building a three-dimensional (3D) geometry in a layer-by-layer fashion. Powder bed fusion (PBF) and directed energy deposition (DED) are common examples of AM used for metals and alloys. The latter is more similar to welding in terms of equipment, but with many more ‘welds’. The filler material can be added by wire or powder, and the process can take place in a protected atmosphere or vacuum. Contrary to this, the PBF process is based on a special powder-bed machine. The heat source is either an electron beam or a laser beam, and the build of a component takes place in a special chamber with a vacuum or a protective gas. The PBF comprises a significant number of layers of molten material, as the average powder particle size is approximately 50 μm.

The study begins with two sections introducing AM modelling. Simulating PBF and DED processes is computationally demanding because of the large number of ‘welds’, and the techniques used to reduce the computing time at the beginning of computational welding mechanics (CWM) developments are once again of interest. Therefore, a short section on CWM is included. Thereafter follows an update of an earlier review concerning finite element (FE) modelling of AM [1] based on the CWM approach [2,3]. References to more recent works are added, together with discussions about computational efficiency and defect estimation. The possibility to model defects, which is a significant challenge but also of great interest, is discussed at end of the study.

2. Summary of the computational welding mechanics approach

The overall aim of CWM is to establish methods and models that are usable for the control and design of welding processes to obtain appropriate mechanical performance of the welded component or structure [3]. The thermo-mechanical

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Table 1
Modelling assumptions for various scopes of models.

Scale	Scope	Assumption/approach
Component	1. Minimum weight versus given load	Assume perfect process. Ideal geometry is obtained without any residual stresses, etc./Optimisation
	2. Tool path for DED process	Assume perfect process. Only considers motion of heat source/Optimisation
	3. Design support structure for PBF or evaluate residual stresses and deformations	Assume a residual state for each 'weld' which is accumulated to residual mechanical state of component
	4. Evaluate transient and residual state of component	CWM
	5. Evaluate microstructure	CWM with microstructure model
	6. Evaluate defects	CWM with additional models, see chapter 6
Process zone	7. Evaluate molten region	WPM including fluid flow of molten metal
	8. Evaluate beam–powder interaction	WPM including fluid flow of molten metal as well as powder particles
	9. Evaluate micro-structure, solidification details, grain structure, etc.	Models for representative volume elements/Phase field methods, etc.

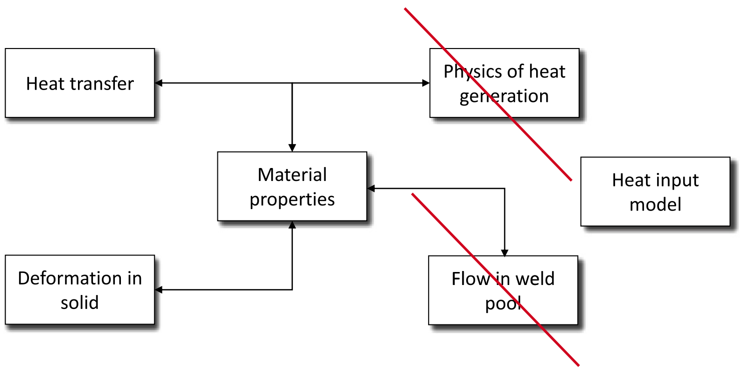

Fig. 1. Common modelling assumptions in CWM. Molten weld details are replaced by calibrated heat input model, and fluid flow is replaced by 'soft' elastic solid.

models can be combined with models for microstructure evolution, and thermo-metallurgical-mechanical interaction, as well as other features that enable the prediction of crack initiation. The description of heat generation requires only thermo-mechanics in the case of explosive welding, friction welding, or friction stir welding. However, resistance welding also requires the inclusion of the electrical field. However, the process becomes significantly more complex for fusion welding processes. Weld process modelling (WPM), levels 7 and 8 in Table 1, focuses on modelling the physics of the heat generation to predict heat distribution. The CWM models begin with a given heat input that replaces the details of the heat generation process, and utilises a heat input model where the heat distribution is prescribed, as shown in Fig. 1. This model must be calibrated or obtained from WPM models. The review in [1] contains more details about modelling and heat source models.

3. General modelling approaches for additive manufacturing

The required scope of the model decides the appropriate modelling approach, as described in Table 1. The focus in this study is on CWM models, as shown in levels 4–6 in Table 1. The CWM models have evolved significantly over the last 10 years, combining advanced dislocation density-based plasticity models with phase changes/precipitate models [1,4]. However, the great number of 'welds' in AM results in computational challenges, as will be discussed in the next section. The greatest modelling challenge for the future is the estimation of defect generation, about which little is known, and is discussed in chapter 6.

It can be seen from Table 1 that a macroscopic modelling approach cannot assist in choosing process parameters to obtain a stable process zone, as it does not, for instance, include the beam–powder interactions [5–7]. The CWM approach is more appropriate for determining the effect of the process on aspects including temperature, deformations, and microstructure. This is a consequence of excluding the physics of heat generation as well as fluid flow in the weld pool. The choice of process parameters requires an appropriate WPM. Although the focus of this study is on models, it is essential that the importance of experiments for better understanding, as well as model calibrations and validations, such as the NIST initiative AM-Bench (https://www.nist.gov/ambench), is not neglected.

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