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A REVIEW OF THERMAL MODELLING FOR METAL ADDITIVE MANUFACTURING PROCESSES: BASIC ANALYTICAL MODELS TO STATE-OF-THE-ART SOFTWARE PACKAGES.

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Abstract: This contribution will review computer modelling of metal Additive Manufacturing processes that involve a moving point heat source, with attention given to powder bed fusion . Modelling AM processes is important; because it allows AM practitioners to enhance understanding and will help improve the process at the planning stage of the manufacturing process. Full thermal modelling of PBF processes is a significant challenge but it will facilitate improved prediction of levels of porosity and the formation of microstructures. Thermal history of a part is the starting point for a residual stress analysis and therefore imperative. Advancements have been made in modelling approaches, evolving from Rosenthal's basic analytical model progressing into Goldak's continuum model. Initially considered in a welding context, these two basic models are adaptable and are commonly used for laser heating processes. DIABLO, a continuum thermomechanical model associated with the Lawrence Livermore National Laboratory, is reviewed. The significance of powder bed models and fluid flow in the melt pool, particularly Marangoni convection, will be investigated within the literature. Presently the market offers several commercial software packages for AM, including packages offered by ANSYS, COMSOL and MSC. State-of-the art software packages will be reviewed by comparing their specific claims and investigating those claims where possible.

***Keywords*:** Additive Manufacturing, Powder Bed Fusion, Thermal Modelling, Simulation.

INTRODUCTION

Additive Manufacturing (AM) is a versatile technology that can be used throughout the product development process. AM is used in numerous sectors including; medical, automotive, aerospace, defense, architecture, consumer packaged goods and cartography. ISO 17296 defines the seven commercially available technologies however, only some are suitable for the manufacturing of metals yet they all necessitate a heat source. Metal AM processes require a concentrated moving point heat source such as a laser, electron beam or arc. Arc is typically used in a process called Wire Arc Additive Manufacturing (WAAM) whilst the laser and electron beam are used in the process of Powder Bed Fusion (PBF) in which this review will focus.

THERMAL HISTORY

Thermal history influences residual stress, material properties and distortion of a final product. (Shipley et al., 2018) identified three primary challenges when using Ti-6Al-4V in the PBF process, including martensitic microstructures, undesired porosity and residual stresses. Thermal history determines the extent and contagion effect that these may have on the end part.

(Lee et al., 2017) found by increasing the laser hatch spacing, the average temperature in the powder bed is not affected; however a large laser hatch spacing may result in a non-uniform temperature distribution and microstructure inhomogeneity. (Shipley et al., 2018) indicates that control of the microstructure can be achieved by controlling the cooling rate during solidification.

PBF is prone to melt pool instability and when used with insufficient process parameters it can lead to microstructural defects and porosity. Balling can occur when using Ti64 and causes the deposition of the consecutive layer to be obstructed; leading to poor layer deposition, cracking or process failure. When localised melting takes place due to an increase in absorbed laser energy; respectively, sharp temperature gradients are formed between the laser processed powder and the unsintered powder. The temperature gradient gives rise to a surface tension gradient and resultant Marangoni convection (Shen et al., 2006).

Porosity can have an unfavorable influence on fracture properties and has a preeminent effect on fatigue performance as cracks initiate from internal pores and propagate outwardly. Qiu et al., 2015) concluded that an unstable melt flow and increased powder layer thickness increases porosity levels and surface roughness. (Shipley et al., 2018) observed that the extent of porosity can be determined by the melt pools stability, dimensions and behaviour.

Further work is required examining the cracks observed at the interface of a porous support and solid printed material. The porous structure has a different coefficient of thermal expansion and weaker mechanical strength than the solid printed part, leading to crack initiation and propagation at the interface during the process prior to warping. (Zhang and Zhang, 2017) produced a thermal-mechanical finite element (FE) model of PBF and identified that maximum thermal stress occurs at the support-solid interface during the printing process when the first solid layer is printed above the support material.

Large thermal gradients in PBF equates to huge amounts of residual stress; leading to deformation, reduced resistance to crack formation, reduced fatigue performance and anisotropic mechanical behavior when unmanaged. To minimize residual stresses, post processing is required to relieve stress and considered vital for High Cycle Fatigue (HCF) components (Shipley et al., 2018).

MODELLING APPROACHES

Various challenges exist within the production of metal AM parts and modelling plays an important role in tackling this issue. Rosenthal’s analytical model, a moving heat source weld model developed in the 1930’s still holds its relevance today. As it is capable of providing a swift estimation offering visibility to the thermal characteristics of PBF.

Developmental work on the Rosenthal model lead to Goldak’s continuum model; a double ellipsoid model for a welding heat source. This has the ability to analyse thermal history of both shallow and deep penetration welds or asymmetrical welds (Goldak et al., 1984). This is still one of the most widely used models for laser heating. Despite being initiated in a welding context, the Goldak model contains various parameters that are extremely flexible however they do need to be adapted for specific problems.

(Hodge et al., 2014) recently developed a multi-physics FE code; DIABLO, this was developed off the basis of Goldak for the use of laser melting of powder. DIABLO allows for the evolving temperatures that are dependent on the material, state of the material, specified heating and the configuration to be determined. The code was written by the Lawrence Livermore National Laboratory (LLNL) with its primary focus being on nonlinear structural mechanics and heat transfer. DIABLO is capable of representing the radiation transport of laser energy into a powder, along with the phase change that occurs from powder to a consolidated material (Hodge et al., 2014).

COMPUTATIONAL MODELLING APPROACHES

ALE3D developed by LLNL allows for 2D and 3D engineering problems to be solved. It enables the modelling of fluid and elastic-plastic responses of materials and has the ability to model melt flow and solidification of AM processes. (King et al., 2015) completed work on a multiscale modelling strategy that simulates single track or single multilayer builds at the scale of the powder providing thermal data for the powder bed and melt pool. Further development led to a second model that computationally builds a part whilst predicting residual stress and dimensional accuracy. The effective medium model is based on DIABLO and evaluates the metal AM part as a multi-physics problem; the metal powder is modelled as a solid with reduced density and low strength. The powder model is based on ALE3D and is capable of resolving individual powder particles in 3D. An effective energy deposition model is used to demonstrate the laser-material interaction examining the flow of liquid and behavior of trapped gas.

(Lee et al., 2015) used a 3D transport simulation examining melt pools produced during a single track multiple layer PBF process of IN718 walls. It was noted that Marangoni convection led to deeper fluid penetration into the substrate resulting in a prominent convex shape at the bottom of the pool. (Lavery et al., 2014) conducted a review on computational modelling of AM processes. The study indicated that omission of Marangoni convection increases dimensions of the melt pool by up to 10% however; prediction of the microstructural boundaries are affected. Furthermore, it was noted that a melt pool dominated by Marangoni convection can lead to gas bubbles becoming trapped if absorbed and retained during solidification.

Modelling allows for increased understanding to address known problems. ANSYS is a global leader in engineering simulation that works across a diverse range of industries. ANSYS Additive Suite allows for Design for AM using topology optimization and lattice structures, complete design validation, enhancing the build setup with additional design features for part manufacturing such as part orientation and automatic generation of support structures. ANSYS can simulate the print process and accommodate exploration to gain a greater understanding of materials.

COMSOL is a software provider that offers solutions for multi-physics modelling. The software includes a suite of discipline-specific add on modules for Structural Mechanics, High and Low Frequency Electromagnetics, Fluid Flow, Heat Transfer, Chemical Reactions, MEMS and Acoustics. Recently a “LiveLink” has been added allowing for a seamless integration between COMSOL and CAD Software, MATLAB, and Excel. COMSOL provide solutions to leading technical enterprises, research labs and universities across a wide range of disciplines.

Simufact Additive is a simulation environment for optimizing powder bed AM processes for metals. This tool allows for the accurate prediction of distortion and residual stresses in the printed part whilst providing the necessary guidance for design and manufacturing process modifications, ensuring a quality part is manufactured right the first time, whilst reducing time and material waste. At present the software is used in the aerospace, automotive, consumer goods, medical and robotics industry. Simufact allows for a quick analysis to be completed on the entire AM process.

CONCLUSION

In this paper the application of computer simulation to metal AM was reviewed and demonstrates the importance of thermal history and how it closely relates to offering an understanding via modelling. It outlines the primary challenges faced by AM practitioners and suggests areas recommended by literature for future work. Finally, it highlights the specific claims made by commercial software packages.

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