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Review

A literature review of powder-based electron beam melting focusing on numerical simulations

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ABSTRACT

The Electron Beam Melting (EBM) process is an additive manufacturing process in which an electron beam melts metallic powders to obtain the geometry of a specific part. The use of an electron beam in the AM field is relatively recent. Numerous applications have already been made in the aerospace and medical fields, in which the EBM process is used to produce complex parts, made of an excellent quality material, for which other technologies would be expensive or difficult to apply. Because of the growing interest of industry in this technology, the research community has been dedicating a great deal of effort to making the EBM process more reliable. The modelling of the EBM process is considered of utmost importance as it could help to reduce the process optimisation time, compared with the trial and error approach, which is currently the most widely used method. From this point of view, the aim of this paper has been to provide a literature review of numerical simulation models of the EBM process. The various studies on numerical modelling are presented in detail. These studies are mainly classified according to the level of approximation introduced into the modelling methodology. The simulations have first been categorised according to the powder modelling approach that has been adopted (i.e. mesoscopic or FE approach). The studies have then been categorised, as far as FE-based simulations are concerned, as either uncoupled or coupled modelling approaches. All the current approaches have been compared, and how the researchers have modelled the EBM process has been highlighted, considering the assumptions that have been made, the modelling of the material properties, the material state change, and the heat source. Moreover, the adopted validation approaches and the results have been described in order to point out any important achievements. Deviations between numerical and experimental results have been discussed as well as the current level of development of the simulation of the EBM process.

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1. Introduction

The term additive manufacturing (AM) today refers to a large number of technologies that allow components to be fabricated using a layer-by-layer strategy. This approach has revolutionised the manufacturing process [1], because it offers the possibility of manufacturing parts of any geometric complexity without using additional tools or machines [2–4]. The advantage of AM over conventional subtractive or formative methods is clearly illustrated by the great design freedom that can be achieved [5], such as the possibility of producing customised geometries or topologically optimised geometries for lightweight components. Industry is showing a growing interest in AM process applications, because these processes allow increased flexibility, compared to the production costs and lead-times of traditional manufacturing [6]. The currently available AM technologies allow complex end-usable parts to be manufactured and metal components in particular [6–8]. As far as AM processes for metal components are concerned, numerous review papers have been presented in the literature to highlight the strengths and limitations of each process. Frazier [9] and Sames, List, Pannala, Dehoff and Babu [10] provided classifications for metals in which the AM technologies were divided into three main categories: (i) powder bed systems, (ii) powder feed systems, and (iii) wire feed systems. Frazier [9] provided a summary of the material sciences for each process according to this classification. Moreover, Frazier [9] discussed the factors that favour the AM process, compared to conventional manufacturing. Some of these include the fixed costs and the nonrecurring manufacturing costs, the cost of process qualification and component certification, logistical costs and the cost of time. This summary showed the AM process as being a potential manufacturing process that enables distributed manufacturing and the production of parts-on-demand, while offering the possibility of reducing costs, energy consumption and the carbon footprint. The overview of the science of AM metals provided by Sames, List, Pannala, Dehoff and Babu [10] instead focused on processing defects, heat transfer, solidification, solid-state precipitation, mechanical properties and post-processing metallurgy. However, both papers agreed that the most common AM processes for metal, in industrial applications, are currently based on the powder bed process, in which a laser beam, or an electron beam, is used to sinter or melt powder material. These metal AM processes are named Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS) and Electron Beam Melting (EBM) also in some cases referred to as Electron Beam Additive Manufacturing (EBAM) [11], despite EBAM is the registered trademark symbol for the additive technology based on the wire-feed electron beam system.

Laser-based systems operate in an inert atmosphere, unlike electron beam systems, which work in a vacuum environment. Good thermal isolation is ensured during the EBM process, because of the vacuum environment, and high temperatures can be used during the process, without the risk of oxygen uptake. Although the vacuum system is more expensive, it offers the advantage of a lower residual stress than laser-based systems [12], and electron beam–processed parts can be used without any stress-relieving operations [12]. In fact, parts manufactured by means of the laser-based system require a post heat treatment to release the internal stresses caused by the gas flow during the SLM process, which leads to rapid component cooling and solidification [13]. Furthermore, the EBM process, unlike the laser-based AM process, involves the preheating of the powders before the melting phase, which reduces the temperature gradient [13] and thus helps avoid the formation of heat cracks. On the other hand, SLM and DMLS systems offer better surface finishing, because they use smaller beam sizes and thinner layer thicknesses than EBM technologies [12], while the melt scan rate is usually two orders of magnitude greater than the EBM melt scan rate [13]. The comparative study presented by [14] pointed out the differences, in terms of final microstructure and hardness of the material, by considering examples of SLM and EBM fabricated components made up of a range of metals and alloys. Although the material science and process simulation of the laser-based AM process have already been dealt with in numerous extensive literature reviews [15–21], the existing review articles on the EBM process have only dealt with material science aspects (microstructure, mechanical properties) [11,22]. However, Gong, Anderson and Chou [11] briefly addressed EBM simulation and provided a short overview of the modelling approach. Schoinochoritis, Chantzis and Salonitis [23] instead considered both EBM and SLM processes and provided a literature review focused on finite element (FE) numerical modelling and simulation models at the state of the art in 2014. This study concluded that most simulation studies have focused on the SLM process and that EBM has received less attention. However, in the last few years, due to the growing interest in EBM process applications, the research community has been making a great deal of effort in the EBM simulation field in order to make the process more reliable, and to reduce the process optimization time, compared to the trial and error approach, which is the method that is currently used. Thus, the aim of this paper has been to provide a literature review of all the numerical approaches currently used for the modelling of the EBM process. In particular, the various studies on numerical modelling have been detailed and classified according to the level of approximation introduced into the modelling process. The modelling approaches have first been divided, according to the adopted powder modelling approach, into mesoscopic and FE approaches. The reviewed studies have then been categorised as uncoupled or coupled modelling approaches, and they have been compared by highlighting how the researchers modelled the physical phenomena that occur during the EBM process. The comparison included: 1) modelling of the heat transfer, 2) modelling of the material properties and the material state change, 3) modelling of the electron beam as the energy source, and 4) validation of the numerical models and differences between the simulation and experimental results. Finally, the various works have been summarised and a number of concluding remarks have been made.

2. Electron beam melting process

Electron Beam Melting (EBM) process is a full melting additive process that is based on metal powder and a high energy beam [8,24]. EBM is one of the few AM processes that are capable of making full density functional parts, especially complex parts made of excellent quality material [25,26]. The EBM process can be used to work with many different material classes, such as stainless steel (17-4), tool steel (H13), Ni-based super alloys (625 and 718), Co-based superalloys (Stellite 21), low-expansion alloys (Invar), hard metals (NiWC), intermetallic compounds, aluminium,