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Review Article

SYSTEMATICAL REVIEW ON THE NUMERICAL SIMULATIONS OF LASER POWDER BED ADDITIVE MANUFACTURING

Melih Cemal KUŞHAN[1], Özgür POYRAZ*[2], Yağız UZUNONAT[3], Sezan ORAK[4]

[1]*Eskişehir Osmangazi University, Department of Mechanical Engineering, Odunpazarı-ESKİŞEHİR;* **ORCID: 0000-000**
[2]*TEI, Tusaş Engine Industries Inc., Tepebaşı-ESKİŞEHİR;* **ORCID: 0000-000**
[3]*Vocational School of Transportation, Anadolu University, Tepebaşı-ESKİŞEHİR;* **ORCID: 0000-000**
[4]*Eskişehir Osmangazi University, Department of Mechanical Engineering, Odunpazarı-ESKİŞEHİR;* **ORCID: 0000-000**

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ABSTRACT

Additive manufacturing technologies, depending on melting of metal powder particles layer upon layer for building 3D functional objects, have widened their application area within biomedical, automotive, aerospace and die/mold industries. Along with the increased application of additive manufacturing, a better understanding of different aspects for the technique has become necessary to fulfill the high demands of quality and productivity. One of the significant process limits of additive manufacturing technologies are residual stresses induced by heating the fine metal powder to the melting point and sudden cooling to the initial temperature. Process simulations performed in a computer environment is of critical importance to predict and to prevent this risk. This paper represents a systematical literature review on the numerical simulations of laser powder bed fusion additive manufacturing. It covers the background and development of analytical models with the contributions of previous ones used for traditional manufacturing techniques such as welding. The details of the numerical modeling studies are provided for thermal and mechanical analysis with the arrangements and assumptions made to reduce the simulation times. Application features are also referred like part material, part size, validation case and the software used for simulations. As a result of these, gap analysis are conducted, needs are established and future research opportunities are expressed.
Keywords: Additive manufacturing; Finite element analysis; Laser powder bed fusion; Thermo mechanical simulations.

1. INTRODUCTION

ASTM F2792-12a standard defines AM (Additive Manufacturing) as a process of joining materials to make objects from 3D model data usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining [1]. The Additive Manufacturing group of technologies includes a wide range of processes, such as: photo polymerization, powder bed fusion, extrusion, printing, sheet lamination, beam deposition and many more aiming at plastics, metals and ceramics. With the development of additive manufacturing in recent years,

* Corresponding Author: e-mail: ozgur.poyraz@tei.com.tr, tel: (222) 211 23 51

good mechanical properties, high dimensional accuracy and surface quality of the final part production with geometrical complexity allow this process to be favored for different sectors such as aerospace and medical [2]. One of the most important recent developments in AM has been the proliferation of direct metal processes [3]. Today, various metallic materials can be produced utilizing different AM techniques such as Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and Electron Beam Melting (EBM) [4-5]. Most of these systems feed material in the form of metal powder and input energy as a point source. Except EBM, which uses electron beam as the energy source, this energy is normally a high power laser. Powder feed can be utilized through spreading it in a layer-wise manner or deposition by the help of a nozzle. Although there are differences between various systems, process mechanism is remarkably similar. During the process, melting takes places in the areas with high energy input applied, and afterwards liquid metal solidifies as the energy source move away. Large thermal gradients occur as a result of this highly localized heat input and short interaction times. This leads to residual stresses on most metals regardless of the alloy type [6]. These residual stresses pose the risk of distortions, delamination and cracking which are undesirable part failures before or during service life.

Process modeling is an expanding practice in order to predict residual stresses and thus part distortions for additive manufacturing of functional metallic parts. In general, a model is an imitation of reality and process modeling is a difficult task where various aspects are required in order to achieve simulation results with admissible convergence to real situation. These aspects are knowledge of manufacturing process, background in mathematical and numerical modeling techniques, specification of machine capabilities and development of empirical equations for realistic constraints [7].

Even though modeling works performed for the prediction of residual stresses and distortions in additive manufacturing increase, challenges still exist caused by the complicated nature of the process and expectations on process modeling. Therefore, many different approaches have been adopted for the analysis of moving heat source, heat transfer phenomena during phase transformations, changing part geometry and the influence of temperature distribution on mechanical structure. This paper presents different approaches for process modeling, assumptions made within related approaches, and simulation tools used for analysis, methods to improve computational performance, changes according to process and material variety, and methods for verification.

1.1. Review Methodology

This review is based on academic peer reviewed publications such as scientific journal articles, conference proceedings, books and PhD dissertations. The main focal points of this review are thermo-mechanical simulations and finite element analysis for modeling of laser powder bed fusion additive manufacturing.

In the scope of this review, a combination of specific keywords are utilized within scientific databases. The keyword combinations include the type of laser powder bed fusion additive manufacturing process (selective laser sintering, direct metal laser sintering, selective laser melting) in the beginning. It is connected by the Boolean operator “and” to the multiple keyword groups: “simulation” or “modeling” or “finite element analysis”. The review is continued by evaluation of the abstracts following to keyword search to confirm the relevance of publications with the topics of interest. In the final stage of the review, full text reading is completed in order to group the contents of the publications. Grouped information is used and relevant publications are cited within the chapters of this review.

This paper begins by describing the basis of laser powder bed fusion additive manufacturing processes and explains physical phenomena from the perspective of material phase transformations, thermal and mechanical interactions. Following chapter describes the research work on analytical and num erical modeling. Later on, the modeling applications are presented with different features such as material types, part size, validation case, approach, software used for simulations and computational performance. Finally, gap analyses are conducted as a result of the current state-of-the-art, and future projections are given, needs and opportunities are emphasized.

2. LASER POWDER BED FUSION ADDITIVE MANUFACTURING AND THE NEED FOR NUMERICAL SIMULATIONS

Laser powder bed fusion additive manufacturing processes are known with various commercial names such as selective laser sintering (SLS), selective laser melting (SLM), direct metal laser sintering (DMLS) and direct metal laser melting (DMLM). Although the name of the processes differ for commercial reasons, the technique used is the same for SLM, DMLS, and DMLM.

Laser powder bed fusion AM uses a laser beam to selectively melt the metal powders by scanning cross sections on the surface of a powder bed layer by layer into an object that has a desired 3D shape based on a CAD model [8]. After each cross section is scanned through a mirror system, the powder bed is lowered by one layer thickness, a new layer of material is spread on top, and the process is repeated until the part building is complete (Figure 1(a)). The thermal process consists melting of metal powders as a result of the absorbed energy from the laser beam and the melted powder solidifies with the heat convection generated by the blowing inert gas. Hereby heat transfer mechanisms involves phase change, conduction, convection and radiation (Figure 1(b)). Finally occurring thermal gradients causes various adverse effects such as thermal expansions.

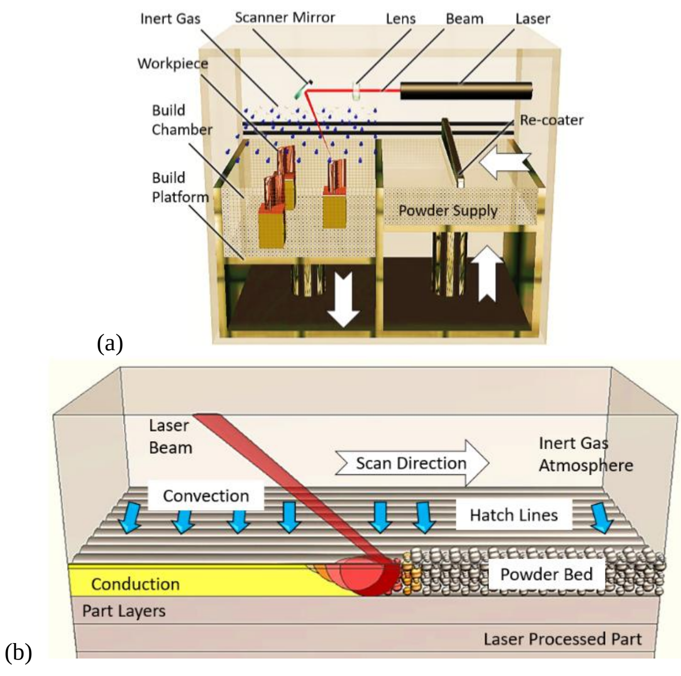


Figure 1. (a) Schematics of laser powder bed fusion AM; (b) heat transfer mechanisms occur as the result of process.

As cyclic thermal expansions and contractions far exceed the maximum elastic strain of the material, heterogeneous plastic strains are cumulated in the manufactured part generating internal stresses [9]. These internal stresses are called residual stresses [10] and they cause distortions and possibly failure by layer delamination or cracking [11]. Many techniques for measuring the residual stresses in a part are available. Usually a classification is made in two groups, whether the measurement is destructive or not. Destructive methods include the layer removal method, the crack compliance method, the contour method and the hole drilling method. Non-destructive methods include X-ray diffraction, neutron diffraction, ultrasonic and magnetic measuring methods [12].

Although there are many experimental techniques available for measuring residual stresses, it is not possible to employ those due to time, labor, machine and material costs. Moreover, understanding the residual stress effects of the process in one particular experimental case may not reflect other situations for different part geometries and/or materials. For these reasons computer based numerical simulation methods are developed and used in process predictions.
The literature studies on laser powder bed fusion AM simulations mainly focuses on numerical modeling to understand the process itself and the effect of process parameters on the quality of the produced parts. In this regard, investigated process parameters include laser power, layer thickness, laser scan speed, hatch distance and scanning strategy [13].

3. FUNDAMENTALS OF MODELING AND CLASSIFICATION OF SIMULATION STUDIES

Additive manufacturing modeling approaches are structured on the basis of the sub areas material, process, and structure similar to the classification made for thermal manufacturing processes [14]. Although these sub areas are interrelated to each other (Fig. 2), researchers focus on different sub areas or a combination of these for additive manufacturing simulations in the context of their studies.

One of the main reasons for focusing on different sub areas is the complex process mechanism of laser powder bed fusion AM. The process itself uses fine powder material in the scale of microns and has the ability to build parts with dimensions more than hundreds of millimeters. During a built job several physical phenomena occur including laser absorption, melting, and solidification. Adding heat transfer mechanisms of conduction, convection and radiation to those physical transformations may lead to numerical problems taking hundreds of hours to compute a 3D model with several layers of real time processing [16]. This challenge is overcome by focusing on different sub areas and conducting simulations on different length scales.

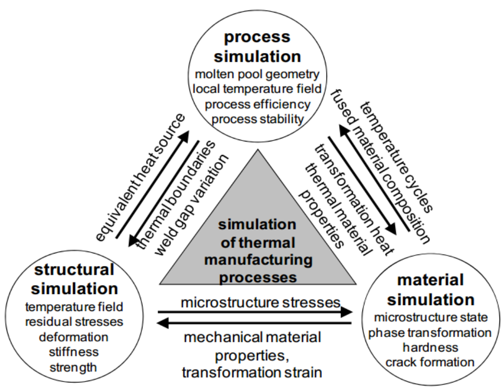


Figure 2. Classification of simulation approaches in thermal manufacturing [15].

The length scales used in laser powder bed fusion simulations are classified in three groups called as micro, meso and macro [17]. Numerical simulations at micro to meso length scale tends to primarily incorporate the full thermo-fluid dynamics of the melt pool with a free surface, which may treat the powder as discrete particles or as a continuum. In terms of numerical solutions, this can be done using self developed finite element, volume or difference schemes [18]. Although micro scale simulations are not common for laser powder bed processes, they can be found for electron beam melting process [19].

On the other hand, macroscopic simulations treat powder bed as a continuum and tend to simulate the process for the full geometry of a workpiece [20, 21]. Various approaches may be adopted for macroscopic simulations including layer based heat sources. The idea behind employing this type of approach is to use a coarser mesh for low computation times. These macroscopic simulations mostly aim to predict residual stresses and distortions on the part geometry.

The length scale of numerical simulations are distinguished according to their physical meaning, and thus according to their level of approximation. The level of approximation varies according to the number of approximations introduced into the model, that is, the number of process parameters that are considered in the modelling and which are correlated directly to the process. The lower the level of approximation, the more computing power and running time are required, and the more the model is complex and flexible [22]. In the scope of this review, micro scale simulations have not been discussed.

3.1. Thermal Simulations

Thermal simulations are used to predict the key characteristics such as heat accumulation and temperature distribution during and at the end of manufacturing processes. Additive manufacturing of metals comprises the main mechanism of solidification after melting or sintering of materials as a result of energy insertion. Heat insertion models can employ different energy distribution principles regardless of whether the applied energy is laser or electron beam.

Analytical and numerical models are used together in order to simulate additive manufacturing processes for macro scale parts. In this respect, employed analytical models are developed on the basis of past welding process models, particularly for thermal simulations.

Among traditional manufacturing methods, welding process is the most similar comparing to additive manufacturing in terms of both moving heat source and addition of molten filler material to the base part. This is the main reason for utilization of welding process models in additive manufacturing.

The very first analytical models for a moving heat source along one axis are represented in two different publications to form the onset of further studies [23, 24]. The initiated models are developed in order to cover Cartesian coordinates for the conduction of heat in a stationary medium [25]. Later on, analytical models are converted to dimensionless form including the travel speed of heat source [26]. Initiatory analytical modeling of a laser application was accomplished for laser welding, adopting the laser as a line source [27]. The last important contribution in the field of analytical modeling was the integration of Gaussian distribution for a moving source at constant velocity [28]. Development of numerical methods has begun following to analytical models by using finite difference technique for the application of various laser processes such as laser welding, laser arc augmented welding, laser surface treatment, and laser glazing [29]. This development led the way to numerical simulations for laser powder bed fusion processes with the first attempts in selective laser sintering process [30].

For laser powder bed fusion AM processes, heat input is commonly assumed to have a horizontal distribution and a vertical absorption. Since most of the laser intensity is reflected and only a fraction is absorbed [31], heat input is frequently modeled as a surface heat source with a horizontal intensity similar to a bell shaped form (Figure 3(a)). A widely accepted model for such intensity is the Gaussian distribution function [32-35]. Nevertheless, several studies in the literature employs other functions such as Goldak double ellipsoid model [36-37], cylindrical model or modified cylindrical model [38]. The selection of the surface heat source model may change according to scope of the research, and a rough model without distribution will facilitate a rough estimation. For the vertical distribution, power intensity of the heat source is determined by laser absorption coefficient and this coefficient is used as the multiplier with Gaussian distribution function.

Thermal simulations are used to predict several values such as heat input, melt pool depth, melt pool width, temperature distribution and time-temperature history [32-39]. These predictions are useful in terms of defining the optimum process parameters (laser power, laser scan speed, hatch distance) and even more the scanning strategy [41].

On the other hand, developed process models should be validated before using them as predictive simulation tools. It is possible to validate laser powder bed fusion models with various experiments. These validations can be classified in two groups. In the first group, validations are conducted offline. In this regard, built specimens are cut into smaller pieces and after metallurgical preparation, they are investigated with a microscope to measure melt pool depth and width from the microscopic images. Validation is done by comparing experimental results with the simulations (Figure 3(b)). In the second group, validations are conducted with in-situ measurements during process. These comprise high speed inline cameras, photodiodes, pyrometer based systems, infrared (IR) (Figure 3(c-d)) and tomography modules [41]. However there are still some challenges to be overcome for using in-situ measurements. Examples to these challenges include the need for manual operations, machine integration, data capture rates and limited field of view.

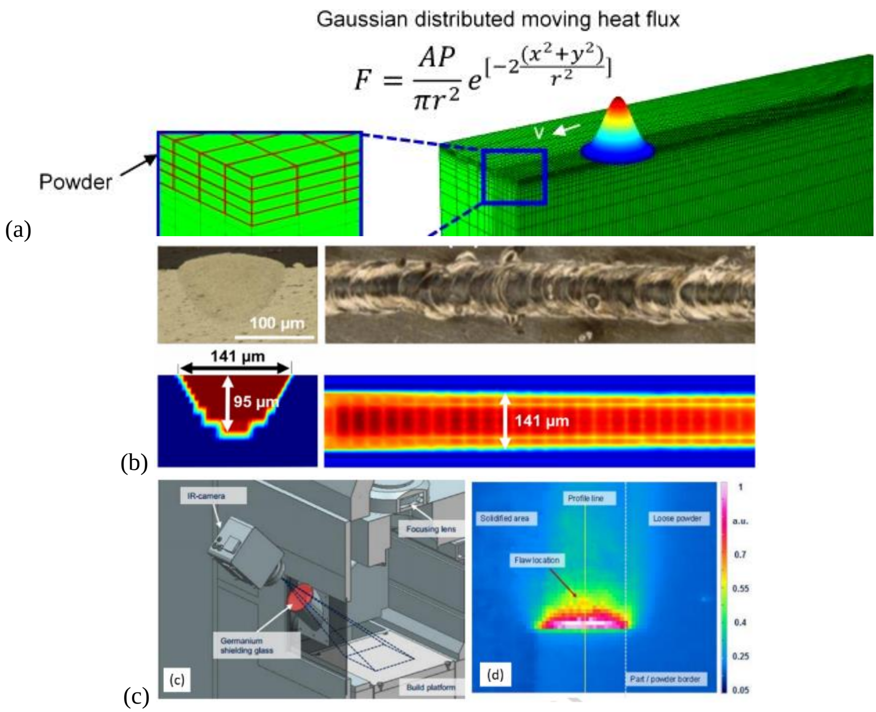


Figure 3. (a) Gaussian distribution [39]; (b) model validation by melt pool dimensions [35]; (c) schematic of equipment set-up with IR camera [42]; thermogram of heat affected zone [42].

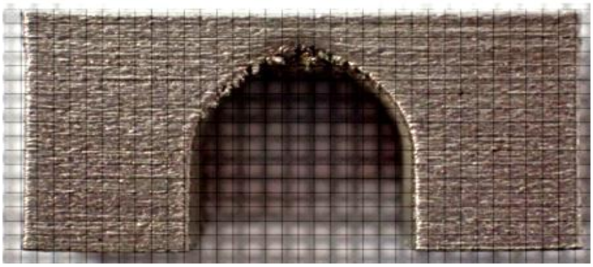
3.2. Mechanical Simulations

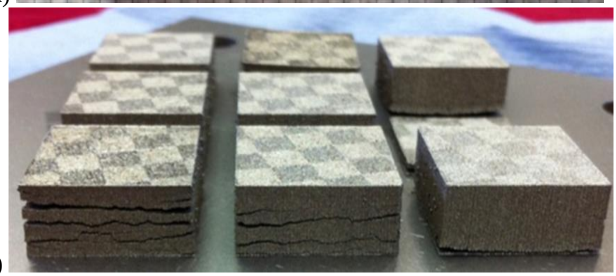
Mechanical simulations are carried out in order to predict deformations and stresses on the parts. The stress field generated during the additive manufacture of metal powders is characterized by several physical processes. These include microstructure evolution, porosity changes, molten pool effects and structural changes, all of which influence the development of thermal and residual stresses [43]. The stresses, also called as Type I residual stresses, vary over large distances [10, 44] and can be observed as deformations on the part revealing significant effects in terms of part dimensions. These deformations can be seen just after cutting the part from base plate (Figure 4(a)) or during the process. The deformations occur during the process may cause the re-coater rub or crash with the built part. Even worse results can be seen such as stress cracking and delamination from base plate (Figure 4(b)).

Due to the above mentioned reasons, the prediction of residual stresses is of significant importance for part quality and also for process performance. Along with the traditional processes such as welding, residual stresses can be calculated using elasto-plastic constitutive models [45]. In this respect, total strain is calculated as the sum of elastic, inelastic and thermal strain components. The major reason of the thermal component is temperature changes and they are proportional with the thermal expansion coefficient of the material. These temperature changes are calculated through thermal simulations and their results are used as inputs for mechanical simulations. These inputs can be made in a sequential manner [46] or multi-physic couplings can be employed in order to facilitate a simultaneous process models [47]. Inelastic component relies on the temperature dependent material properties and strain hardening behavior of the material is needed. This elastic component is derived using two other components. Finally, stress field components are calculated by multiplying strains with stress-strain matrix.

These mechanical simulations are validated using several techniques and these techniques are classified in two categories. In the first category, validations are conducted by comparing part deformations with the simulation results [48]. This simple technique may contain contact or non-contact dimensional measurement methods such as using coordinate measuring machines [47].

In the second category, validations are conducted by measuring residual stresses on the part. Various methods are applicable in accordance with the results of simulations. If the simulation results predict stress values close to the part surface, surface measurement methods of neutron or x-ray diffraction [47, 49] can be used. One other alternative for close to surface residual stress measurement is Vickers micro-indentation technique [50, 51]. Based on experimental correlation between the indentation characteristic parameters and residual stress, the technique requires much work for mechanical preparation. However, it can be preferred because it requires low equipment cost. Subsurface residual stress measurement techniques are useful in terms of the information they provide. With these type of techniques researchers can measure change of residual stress along a certain depth and can validate 3D simulation results. One common technique is hole drilling strain gauge method [52]. This technique involves drilling a small hole in the center of a three grid strain gauge rosette. The strains released by the tested material are acquired for each drilling step and are used to calculate the residual stresses. A further method to have the ability of measuring residual stresses through part thickness is the crack compliance method (CCM) [10]. With this method the part is cut in subsequent small steps using wire electric discharge machine (Figure 4(c)). After each cutting step, the strain is measured at each strain gauge connected to the part's surface at known positions.

(a) 

(b) 

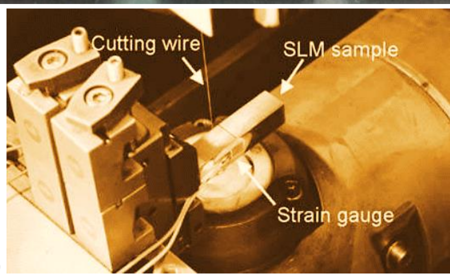
(c) 

Figure 4. (a) Part deformation after cutting from base plate [48]; (b) stress cracking and delamination [53]; (c) residual stress measurement using CCM [10].

4. APPLICATIONS AND CHALLENGES

Although the research on thermal and mechanical simulation of laser powder bed fusion AM processes accelerated within the last years and reached to a certain success, there are still many challenges to overcome. These challenges may be related to various subjects such as materials data and computational performance. Researchers who have tried to overcome these challenges have developed their own methods embracing different tools, assumptions and neglects. This chapter discusses the applications, challenges and the methods of various researchers trying to overcome those.

4.1. Material Data Needed for Simulations

Starting from the first instant of a laser powder bed fusion AM simulation, dozens of material data are needed. These data have to cover several property categories such as optical, physical, thermal and mechanical. Most of these data categories have to include three material forms as powder, liquid and solid. The needed material data is also temperature dependent in order to reflect different stages of process starting from low temperatures and going beyond the melting point. Laser absorption coefficient and density are examples for data under optical and physical categories. Thermal conductivity, specific heat and latent heat are among the required thermal properties. Mechanical properties also include thermal expansion coefficient, elasticity modulus, Poisson's ratio, yield strength and hardening behavior.

Various researchers have diverse approaches acquiring these data. For the liquid and solid material forms, researchers obtain the needed data through experiments [54] or through calculations made with several software packages such as JMATPRO [21]. The experiments used for obtaining the thermal properties include DSC (Differential Scanning Calorimeter) for specific heat and latent heat, and Hot Disk Wire or Laser Pulse Method for thermal conductivity [54, 55]. Most of the mechanical properties are maintained by tensile testing and thermal expansion tests are conducted using dilatometers [56].

The properties required for the powder materials are specific to this process and are obtained in different ways. Among the so called properties, powder density should be considered in a different way comparing to solid or liquid densities. Since these powders are pre-alloyed gas atomized powders mostly having high sphericity and a smooth surface with a negligible quantity of satellites [57], their densities may change depending on whether they are in tapped or apparent situation. The apparent density is the mass of a powder divided by its apparent volume while the tapped density is obtained under standard conditions of tapping. The density during the process is called powder bed density, and its value is between apparent and tapped densities [58].

Although, thermal conductivity and emissivity of powders can be measured using various techniques [59], predictive models are preferred [35, 43, 54, 60] due to difficulties of experiments and temperature dependent data requirements. One of the most employed model [59] for prediction of powder bed thermal conductivity and emissivity uses various attributes such as porosity of the powder bed, thermal conductivity of the skeletal solid and thermal conductivity of continuous gas phase, radiation effects and flattened surface fraction of particle in contact with another particle. There are also other models which calculate contact thermal conductivity of powder particles in detail [61].

4.2. Computational Challenges

Thermal models coupled with mechanical ones can be used to simulate laser powder bed fusion AM, to solve physical phenomena of the process and to predict the effects of different process parameters. While this approach is useful for meso scale problems, it may be computationally expensive for macro scale ones having real part geometries. Among with dozens of temperature dependent material properties, changing boundary conditions of heat input and layer addition makes this computation expensive. The computation time for a real comprehensive model which considers all the factors above is very large and it takes hundreds of hours to compute a 3D model with several layers of real time processing [16]. This computational challenge is overcome by several researchers using different approaches. These approaches are categorized in different classes according to methodology they used, physical assumptions they made and numerical tools they developed.

In the initial development stages of AM simulations, researchers using general purpose FEA (Finite Element Analysis) software focused on layer addition technique. Starting the simulations with a reduced number of finite elements and including them with the addition of each layer was a common method to make the simulations effective. Several researchers used this element birth-and-death technique provided by general purpose FEA software packages such as ABAQUS [62] and ANSYS [63]. Similar approach was also applied to surrounding powder around the part. In this regard, in an example work done with COMSOL [60] software, the powder surrounding the part is not modeled and instead, infinite elements were used. By this way, the number of elements and also the computation time was reduced (Figure 5(a)).

Researchers also employed assumptions and neglects in order to reduce simulation times. One simple approach is to neglect the contribution of radiation as a source of heat loss [16, 34, 43, 64]. A further step may include applying the heat source as a whole scan vector (Figure 5(b)) or even on a whole layer [65]. Although this may not reflect the real thermal situation, it is reported that it shows good convergence with the mechanical results in the form of residual stresses and distortions [65].

Drastic reductions in simulation times need special methods which cannot be utilized using general purpose software packages. For this reason, special techniques are developed and today they form the basis of various dedicated commercial AM simulation software. An important highlight among these techniques is the applied plastic strain method [66]. This method uses high resolution model of the transient thermo-mechanical analysis and calculates plastic strain tensor components and the equivalent plastic strain. Later on obtained plastic strains mapped to complete part. As a result final distortions are estimated (Figure 5(c)). Due to the nature of this technique and the use of inherent strains, simulation results need to be calibrated by simple experiments such as manufactured cantilever beams. Today similar techniques are used in commercial AM simulation software packages AMPHYON and SIMUFACT ADDITIVE.

Besides physical assumptions and methodological developments, numerical improvements can also be used for time efficient simulations. In this regard, two different methods are mesh coarsening technique [37] and feed forward dynamic adaptive mesh refinement and derefinement [67]. Both methods have similar objectives and update element sizes according to time dependent conditions. In this regard, the element sizes become smaller for the active powder layer or for the instant coordinate of the laser spot (Figure 5(d)). Today similar techniques are used in commercial AM simulation software packages CUBES (acquired by AUTODESK) and 3DSIM (acquired by ANSYS).

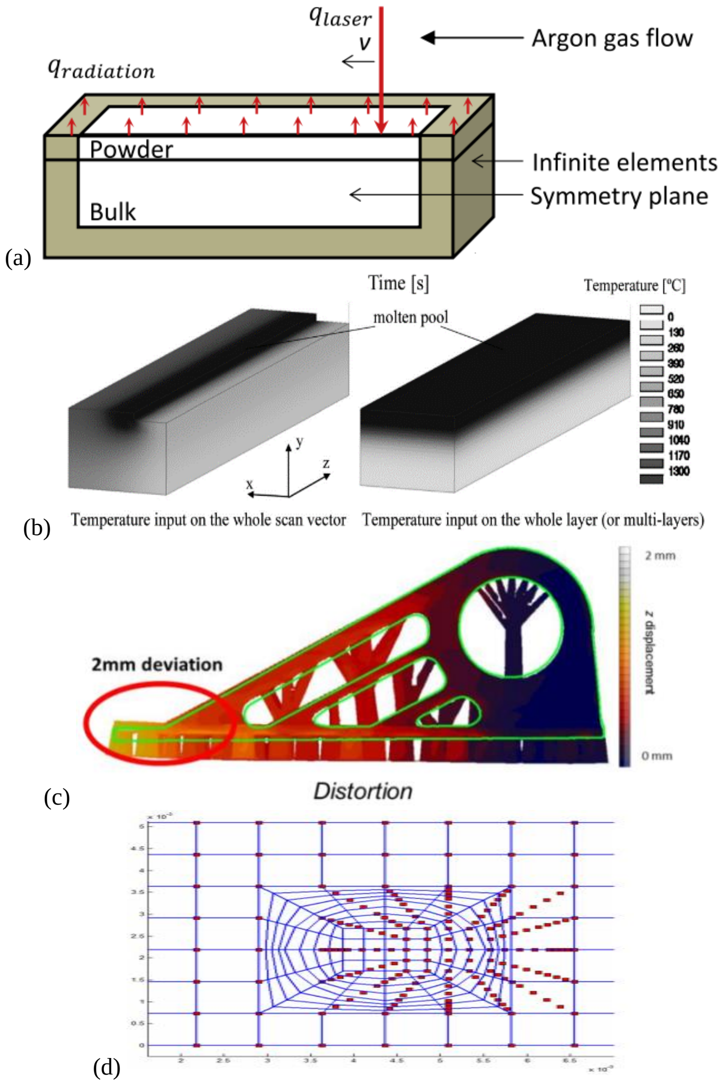


Figure 5. (a) Schematics of infinite element approach for surrounding powder [60]; (b) schematics of vector and later heat source [65]; (c) simulation results after using applied plastic strain method [66]; (d) feed forward dynamic adaptive mesh refinement [67].

4.3. Case Studies for the Effect of Process Parameters

Numerical simulations of laser powder bed AM processes can be used to understand the effect of different process parameters. In this respect, thermal simulations are useful for understanding the effect of basic process parameters of laser power and scan speed [40, 54, 68-69]. The results of these simulations give insight about the shape and size of the melt pool as well as temperature distribution. The dimensional features studied are melt pool depth and melt pool width. Most of the researchers agreed that the melt pool dimensions increases with the increasing laser power

(Figure 6(a)) and decreasing scan speed [40, 54, 68]. Some of the research for thermal simulations revealed that scan strategy is as important as process parameters and can effect temperature distribution drastically [70]. It has shown that parallel scanning strategy has some drawbacks while spiral scanning is difficult to generate for non-convex domains. Preferable alternatives presented are paintbrush or chessboard scanning strategies (Figure 6(b)).

Although mechanical simulations are basically used for understanding the residual stress and distortions of the parts, these need to be used more effectively. In this regard, in-process distortions for complex geometries should be considered in much detail and process parameters along with the build direction should be optimized in order to avoid any crashes of the part with re-coater. There is also a clear gap for detailed simulations of support structures, which hitherto considered as single type or moreover with fewer geometrical features. Experimental studies revealed that support structure type, geometrical features of supports and also the dimensions of those features are important in terms of avoiding part distortions and effecting the separation of support while post-processing (Figure 6(c)) [71]. Within the current state-of-the-art there are just a few simulation studies considering the support structures in detail [72, 73].

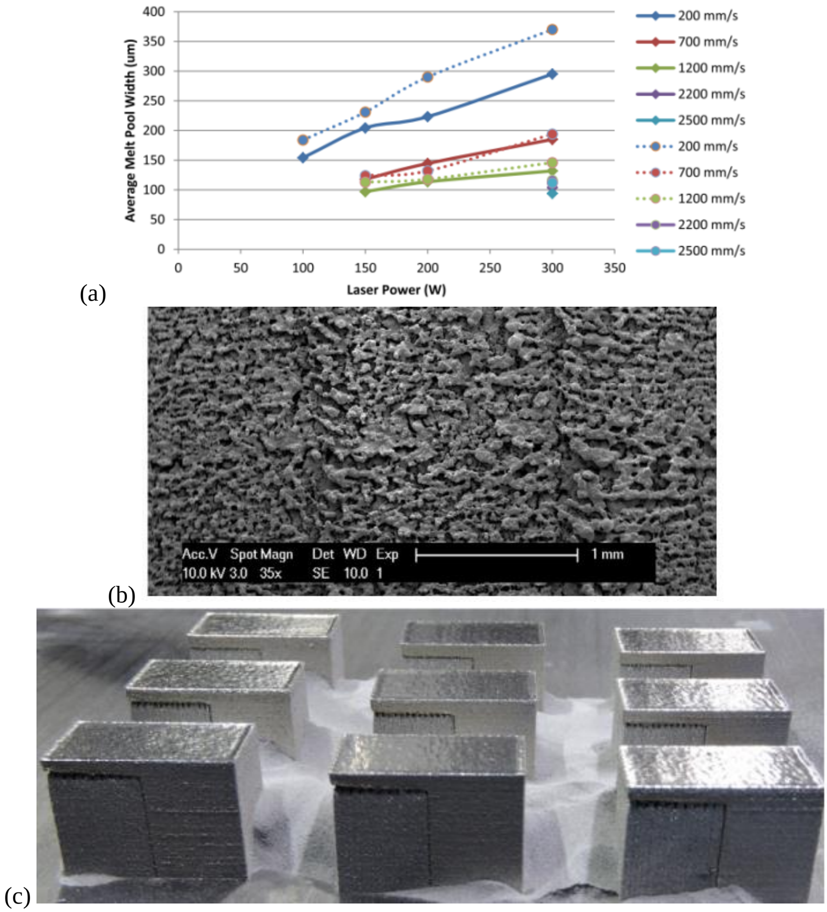


Figure 6. (a) Effects of laser power and scan speed on melt pool width [54]; (b) micrographs of chessboard scanning strategy [70]; (c) separation of support structures from the part [71].

4.4. Trends and Future Perspectives

Since numerical simulations of additive manufacturing is relatively a new topic within various engineering disciplines, research and scientificl efforts are still in progress. In this regard, the transformation between recent studies and ongoing research may determine the next steps, trends and thus future perspectives. These research efforts may broaden their focus to diverse areas. These include changing of modeling techniques, application of unused material properties to modeling, trying to predict new results and phenomena, introducing new additive manufacturing processes and materials, and even more coupling additive manufacturing processes with other manufacturing methods within the scope of modeling research [74-80].

From laser powder bed additive manufacturing simulations perspective, notable trends are changing of modeling techniques, application of anisotropic material properties to modeling, and trying to predict new results or phenomena. Recent studies show changing of pure finite element models by enriched analytical solutions may offer benefits in terms of computational costs [74]. Or application of integrated process–structure–property modeling frameworks may allow capturing of more details with the same or less computational cost [75]. Application of anisotropic material properties to modeling is a further aspect to be highlighted within future perspectives. In this regard, small number of studies exist to employ anisotropic material flow within simulations, but it is obvious that inclusion of anisotropy in simulations is benefical in terms of convergence between simulations and experiments [77]. Figure 7 shows tensile specimens and multi-axial loading samples used for inclusion of anisotropy to numerical simulations of laser powder bed additive manufacturing.

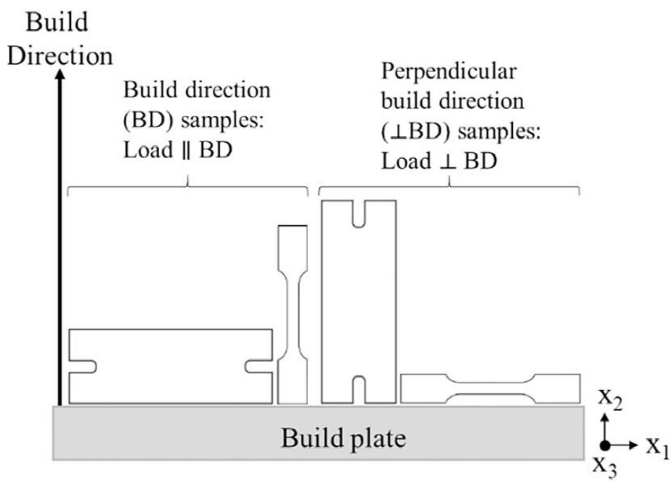


Figure 7. Schematic of sample orientation for tensile and multi-axial loading tests [77].

5. SUMMARY AND CONLUSIONS

This paper has focused on the numerical simulations of laser powder bed fusion additive manufacturing. It presented the process mechanism of laser powder bed AM, physical phenomena taking place during process, classification of modeling techniques, thermal simulations, mechanical simulations, application related subjects and challenges. Various studies compared according to assumptions they made, material data they used, methodology they utilized and software they employed. A summary of the paper highlights is listed below:

- Process modeling is an expanding practice in order to predict residual stresses and thus part distortions for additive manufacturing of functional metallic parts.

- Additive manufacturing modeling approaches are structured on the basis of the sub areas material, process, and structure. The length scales used in laser powder bed fusion simulations are classified in three groups called as micro, meso and macro.

- Thermal simulations are used to predict the key characteristics such as heat accumulation and temperature distribution during and at the end of manufacturing processes, while mechanical simulations are carried out in order to predict deformations and stresses on the parts.

- Different validation methods can be used in accordance with simulation results.

- Numerical simulations of laser powder bed fusion AM have challenges with the needed material properties and computational performance.

- Computational challenges are overcome by several researchers using different approaches. These approaches are categorized in different classes according to methodology they used, physical assumptions they made and numerical tools they developed.

- Along with general purpose FEA software, dedicated software were also developed for AM simulations.

- These numerical simulations can be used to understand the effects of different process parameters thermally and mechanically.

- Simulations need to be used more effectively to include further details such as complex geometries and support structures.

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