A numerical model to study the temperature and residual stress profiles in hybrid additive manufacturing

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Keywords: Hybrid Manufacturing, Selective Laser Melting (SLM), Numerical Simulation

Abstract. Recently, there has been an increasing interest in hybrid additive manufacturing (HAM) technologies to overcome the limits of conventional and additive manufacturing (AM) technologies. In the case of metals, HAM can be used to combine AM with forming operations. This concept can be applied in both the production of bulk and sheet metal parts. When sheet metal parts are taken into consideration, usually AM technology such as laser powder bed fusion (L-PBF) and direct energy deposition (DED) can be combined with traditional forming operations. L-PBF is preferred when small details have to be applied to the metal sheet before undergoing the forming process. Thus, mass customization can be achieved by using the flexibility of the AM process, its ability to print complex geometries, and the speed of the sheet metal forming process. In this study, a numerical model was developed in order to analyze the influence of the L-PBF process on the metal sheet. The results show how the metal sheet is strongly influenced by the thermal input due to the deposition of the AM part. Moreover, the presence of residual stress can be observed within the metal sheet, which can result in distortion and create problems in the following forming step. The numerical model highlights also the more critical area, in which high-stress concentration is observed.

Introduction

Additive manufacturing (AM), thanks to its characteristic of fabricating parts in a layer-by-layer fashion, allows the production of complex structures with the possibility of creating lightweight structures and multi-functional components [1]. For this reason, AM is widely used in many industrial fields, such as biomedical and aerospace, where customization and complex geometries are usually required [2]. Nevertheless, the spreading of AM in other fields is limited to the large production time and poor geometrical accuracy. Recently, in order to overcome these disadvantages, a new trend of combining AM with conventional manufacturing processes is rising. The combination of AM with conventional manufacturing processes is called Hybrid Additive Manufacturing (HAM), where the goal is to overcome the challenges of both processes by taking advantage of their pros [3]. One strategy that can be used to improve the quality of AM products is combining AM technology with subtractive technology. Usually, when the production of metal parts is considered, Direct Energy Deposition (DED) is combined with the milling operation, which is performed for every layer after the material deposition to obtain a better surface roughness [4]. On the other hand, HAM can be used to shorten the processing time of AM technologies, improve its productivity, and overcome the limitations of traditional forming processes in geometrical complexity. In this way, HAM allows reaching the so-called mass customization [5]. This concept can be applied in both bulk and sheet metal forming by using different AM processes. In the case of bulk metal forming, DED is usually preferred with respect to other AM processes due to its high flexibility. In this case, the forming process is performed before the AM process [6]. When sheet metal forming is considered, instead, Laser Powder Bed Fusion (L-PBF) is usually employed thanks to its superior geometrical resolution. Here, two different approaches can be adopted: 1) sheet metal forming followed by L-PBF, and 2) L-PBF followed by sheet metal forming. Most of the time, the second approach is used because the first one usually requires too complex clamping systems. For the second approach, the metal sheet has to be fixed on the build plate during the L-PBF process. After the end of the printing process, the sheet metal is removed from the platform, and the forming step is performed [7].

Papke et al. [8] investigated the bonding zone between the sheet metal and the AM part. In detail, a Ti-6Al-4V cylindrical geometry was printed on the metal sheet made of the same material as the printed part. The bonding zone was characterized through shear tests and Vickers microhardness. Some works can also be found with more complex geometries, as in [9], where a gear component geometry has been manufactured with the combination of L-PBF and sheet metal forming for 316L. As for the authors' knowledge, a numerical approach in order to investigate the bonding zone in the hybrid process is still missing. Such a numerical model can help in predicting the temperature and residual stress profiles within the AM part and the sheet metal. In this paper, a FEM model was developed in order to evaluate the temperature distribution and residual stress in hybrid additive manufacturing of Ti-6Al-4V. This study's result can help engineering understand the process better and facilitate the design phase by saving time and material.

Numerical model set-up

The FEA commercial software DEFORM-3D™ v12.0 (V12.0, SFC, Columbus, OH, USA) was used to perform the numerical simulation. In the frame of hybrid additive manufacturing, L-PBF was performed on a Ti-6Al-4V sheet metal fixed to the build platform. The thermal and mechanical properties of the metal sheet are presented in Table 1.

Table 1. Thermal and mechanical properties of the Ti-6Al-4V sheet

Thermal properties	Melting point	1648 °C
	Beta transus temperature	980 ± 4°C
	Thermal conductivity at 20°C	6,7 W/ m°C
Mechanical properties	Yield strength	870 MPa
	Tensile strength	920 MPa
	Elongation	10%

The goal is to simulate the printing process of a Ti-6Al-4V parallelepiped geometry of 15 mm x 10 mm x 5 mm on the metal sheet. A fillet of 1 mm in all the edges was applied to have a smoother transition between the AM part and the sheet metal. In order to shorten the simulation time, a layer-by-layer approach was adopted where the whole layer is deposited simultaneously. The elements affected by the heat source are activated through a search algorithm, which works thanks to the voxel mesh. In this way, according to the deposition strategy (the process parameters being selected), only the elements within the voxel mesh for that particular layer will be activated. Further details about the use of the voxel mesh can be found in [10]. In order to predict the temperature and residual stress profiles on the metal sheet due to the L-PBF process, an area of 60 mm x 60 mm was considered in the numerical simulation. Three geometries were modeled in DEFORM-3D™ v12.0 and designed with Autodesk Fusion 360 (Fig. 1).

The first body (I) is the AM part already described above; the second body (II) is the metal sheet with the dimensions of 60 mm x 60 mm x 2 mm, and the third body (III) is the built plate equal to 60 mm x 60 mm x 25 mm. For each body, a different number of mesh elements were used: 200000 elements for I, 100000 for II, and 30000 for III.

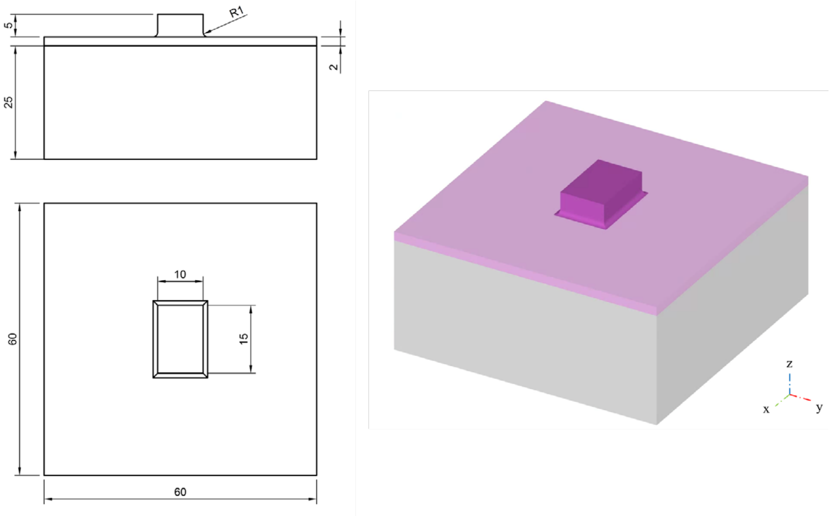

Fig 1. The designed geometries used in this study.

The geometries and the corresponding meshes are reported in Fig. 2. While body III was considered as a rigid material, bodies I and II were modeled as an elastoplastic material to observe the residual stress due to the thermal history they undergo during the L-PBF process.

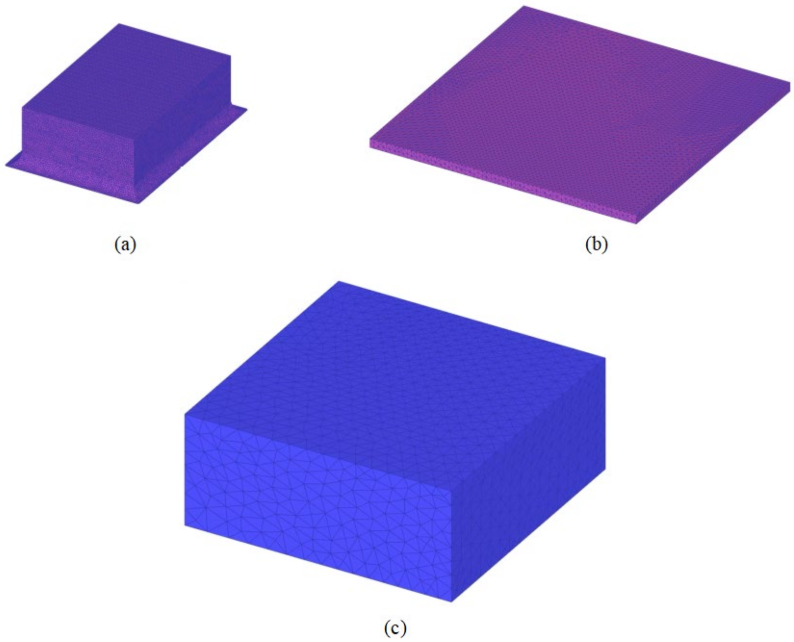

Fig 2. Geometries modeled within the FEA software:(a) meshed body I, (b) meshed body II, and (c) meshed body III.

A voxel mesh dimension of 0.5 mm x 0.5 mm x 0.5 mm was used for the element activation, considering a deposition strategy consisting of laser power of 250 W, scanning speed of 1400 mm/s, hatch distance of 120 µm, and layer thickness of 30 µm.

Sticking conditions were applied between I-II and II-III during the simulation of the L-PBF process and the cooling phase, where the residual stresses will develop. The build chamber temperature was set at 40 °C, while the temperature of II and III was set at 200°C.

Only convection heat exchange with argon was considered in the numerical model using $h_{conv} = 1$ W/m^2 °C, simplifying the computational complexity. A Newton-Rapson iteration coupled with a MUMPS (MUltifrontal Massively Parallel Sparse) solver was used to solve the thermomechanical problem. The simulation was carried out with a 12th Gen Intel (R) Core (TM) i9-12900 2.40 GHz processor.

Results and Discussions

The FEM model was used to analyze the temperature and residual stress profiles on the AM part and the metal sheet following the L-PBF process. In order to simulate the printing process, a voxel mesh dimension of 0.5 mm x 0.5 mm x 0.5 mm was used. This will result in a number of voxel mesh elements of 30, 20, and 10 along the x, y, and z directions, respectively. Since the height of the AM part is 5 mm, the layer thickness is 30 μm, and the voxel mesh element along z is 10, the computational layer will include about 16 real layers. In this way, it is possible to simulate the L-PBF process with a low computational cost. In detail, using a 12th Gen Intel (R) Core (TM) i9-12900 2.40 GHz processor results in a simulation time of 39 min and 15 sec (2355 total seconds). The temperature distribution predicted with the numerical simulation at the end of the L-PBF process is shown in Fig. 3.

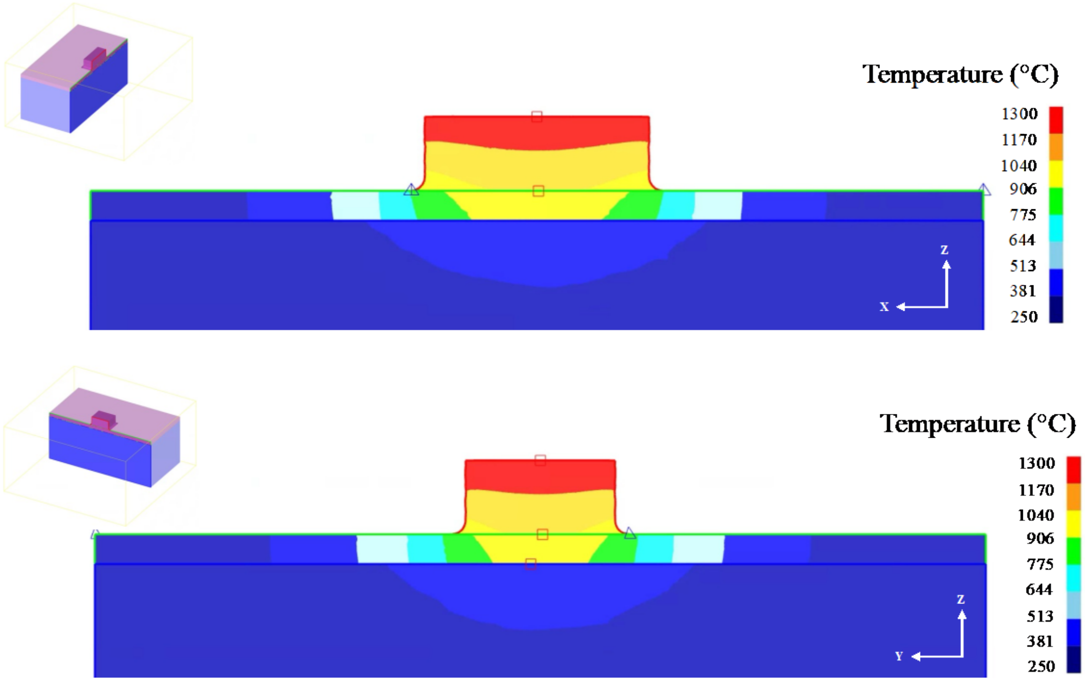

Fig 3. Temperature profiles along the longitudinal and transversal cross sections effectuated with two different planes, XZ and YZ, respectively.

It can be observed how the heat exchange between the AM part and the metal sheet is preferred with respect to the build platform. Near the bonding zone, the metal sheet is strongly affected by the thermal input, which melts the metal powder during the scanning of the new layer. In that area, it is possible to reach about 1000°C. The temperature along the metal sheet will decrease up to 400°C a few millimeters away from the printed part. This can be seen in both the longitudinal section (XZ plane) and the transversal section (YZ plane). The thermal history will be responsible for residual stresses during the cooling phase. In Fig. 4 the residual stresses σ_x and σ_y are presented. Strong residual stresses in the middle of the metal sheet can be observed.

The maximum value of the predicted residual stresses is around 900 MPa, such residual stresses can lead to distortion after removing the metal sheet from the build plate and can affect the mechanical response of the metal sheet. These residual stresses must be considered because, in the sheet metal HAM process, the metal sheet will undergo other metal forming operations.

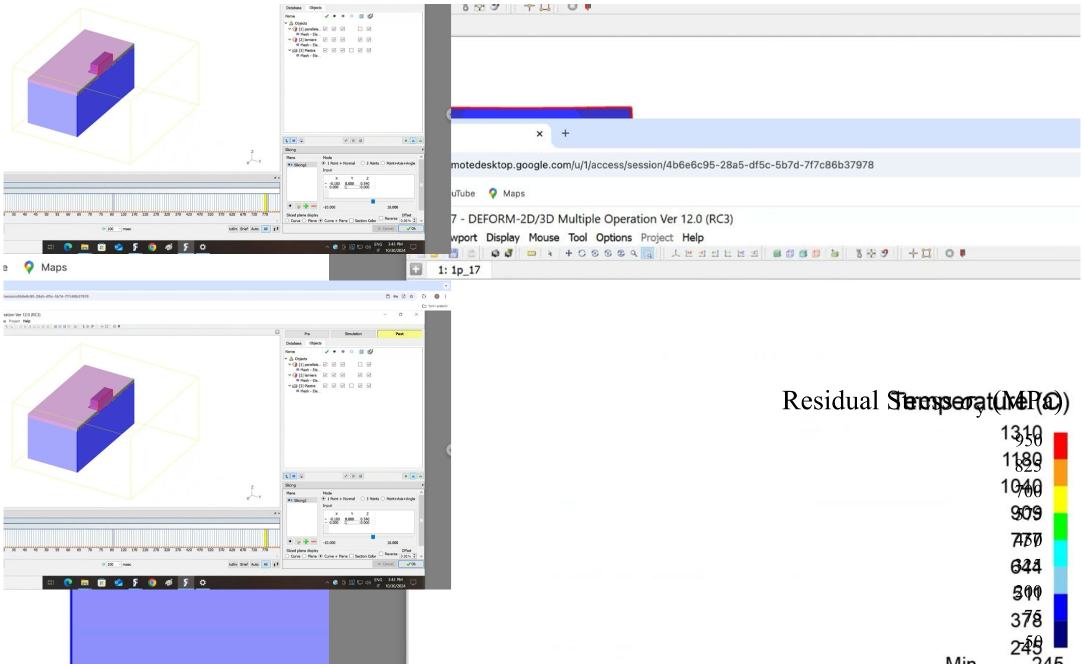

Fig 4. Residual stresses σ_x and σ_y along the XZ plane.

From the numerical simulation also, the distribution of the effective stress was analyzed (Fig. 5). It is worth noting that the most stressed area is the one near the edges of the AM part even if 1 mm fillet were applied in order to have a smoother transition and avoid stress concentration. This means particular attention must be paid to these areas where the AM part and the metal sheet can be detached.

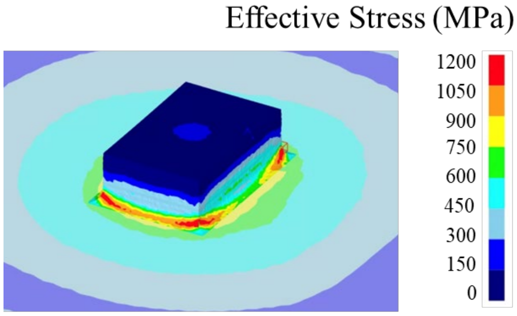

Fig 5. Effective stresses due to the L-PBF process and the cooling phase.

Conclusions

A commercial software, DEFORM 3D v.12, based on the finite element method, was used to simulate the deposition of a parallelepiped geometry on a metal sheet during the L-PBF process of Ti-6Al-4V alloy. The main finding of this study can be summarized as follows:

- The deposition of the AM part strongly influences the metal sheet temperature profiles, a temperature of about 1000°C can be observed at the core of the metal sheet and decrease up to 400°C a few millimeters away from the AM part.
- The metal sheet's thermal history leads to large residual stress, especially below the AM geometry, where high temperatures were detected at the end of the L-PBF process.
- The residual stresses σ_x and σ_y can result in distortion in the XZ and YZ planes after the removal from the platform. This has to be considered in the case of HAM, where the AM processes will be followed by a forming process.

- Particular attention must be paid to the corners in which delamination between the AM part and the metal sheet can occur due to the high-stress concentration.

Acknowledgements

Part of this study was carried out within the activity of project using Italian MUR funds: “Aluminum Low Impact Circular Economy (ALICE)”, funded by the European Union - Next Generation EU, Mission 4 Component 1, Project: P2022WN727, CUP: B53D23027330001 PRIN 2022-PNRR.

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