L-PBF additive manufacturing simulation of a “cold crucible” in copper alloy

by Nicola Gramegna[1], Antonio Rossi[2]
1. EnginSoft - 2. AddtoShape

Introduction

The TEMART project was approved by Italy’s Veneto Region under the POR-FESR 2014-2020 program under Axis 1 and Action 1.1.4, namely "Support for collaborative R&D activities for the development of new sustainable technologies, new products and services".

The four Regional Innovative Networks (or Reti Innovativi Regionali – RIRs) that participated in the TEMART project, namely M3NERT, EUTEKNOS, VHC and VSL, operate in three different areas of Smart Specialization representing some of the most significant and distinctive domains and industrial sectors in the industry and artisanship of the Veneto region. The region’s four universities, coordinated by the Univeneto Foundation, also participated in the project as partners, making complementary contributions that reflect the specific character of their research and training specializations. As a result, the TEMART project has become highly significant industrially, economically, socially, and culturally. The project involved the development of several case studies concerning the creative use of technologies and processes to produce innovative, competitive, aesthetically pleasing, high quality items. New manufacturing technologies, in particular additive manufacturing (AM) technologies, make it possible to design and produce new shapes with a broad range of materials e.g. polymers, composites, or metallics and even to combine these in the same item/object. As an example, one of the project goals was to integrate different CAE tools into a single intelligent design process for the AM environment. This integration created competitive advantages such as reduced design times with the maximum reduction, for example, in weight and a maximum increase in the part’s functional reliability. With regard to the specific project areas, the case study on crucibles made of refractory metal was a prime example of the reduction in weight and increase in functionality.

After a brief introduction about the implementation objectives of the “cold crucible”, this article describes the virtual approach adopted to design the component and optimize the manufacturing process for CuCr1Zr copper alloy. The partners listed in the acknowledgments played a key role in characterizing the material and fine-tuning the machine parameters for manufacturing the part, which helped confirm the excellent design, and the modelling of the AM process.

Objectives

Officina dei Materiali, a consulting company in the field of materials science and engineering, first launched the idea of next-generation cold crucibles in 2015. The idea quickly gained momentum thanks to the first funded projects which aimed to use simulation software to model the physical phenomena at play during levitative metal melting, and to optimize the technological process of additive manufacturing with pure copper.

The main objective of this study is to demonstrate how additive technologies combined with simulation methods can enable continuous progress in the creation of innovative and efficient products.

The component being studied is a crucible for the controlled melting of metal. Conventional crucibles are usually made of ceramic material with the obvious limitations of high cost relative to service life, and the contamination of the molten metal by the ceramic material itself. Such contamination affects and sometimes impairs the mechanical, electrical, and magnetic properties of many reactive metal alloys.

A "cold crucible", on the other hand, is made of a metal alloy with high thermal and electrical conductivity. This crucible, when suitably cooled and designed, can concentrate its electromagnetic energy to melt the metal contained in the crucible. It does not contaminate the melt in the crucible and also, conceptually, does not use consumables because, if properly designed, it never comes into contact with the molten metal.

Some prototypes demonstrated the cold crucible's potential, but also its limitations compared to production using traditional manufacturing technologies. Furthermore, during validation, some operating efficiency limitations emerged regarding the transfer of electromagnetic energy internally, and heat dissipation.

Using additive technologies enables radically new shapes and geometries to be created. L-PBF (laser powder bed fusion) technology is probably the most versatile of the additive technologies for metal parts in terms of its potential to produce complex geometries in combination with ad-hoc microstructures [1]. More specifically, such technologies can enable the production of more thermally and electromagnetically efficient parts by realizing complex geometries and designing appropriate channels for controlled conformal cooling.

The aspects to consider in producing an object that meets the design specifications as studied and confirmed through the use of additive manufacturing process simulations include optimized complex internal channels, thin walls, and thickness transitions.

Part design for additive processing

In recent years, simulation tools have continuously evolved to support design, or more specifically to complete the virtual workflow of Design for Additive Manufacturing (DfAM), in order to drastically reduce the number of iterative experimental tests, which are very costly and time-consuming. However, there continue to be well-known challenges not least of which are the simulation methods used and the associated computational times. Some of these have been highlighted in the literature by various authors [3]. The main sources of complexity relate to the numerous physical phenomena involved, some of which are difficult to model; the spatial and temporal discretization; and finally, the experimental validation of the results.

This study aims to simulate the L-PBF additive manufacturing process at a macro scale with the goal of determining the residual stresses, distortions and defects related directly to the process itself. The macro-scale simulation uses continuous models in which the material layers are merged into layers of finite elements,

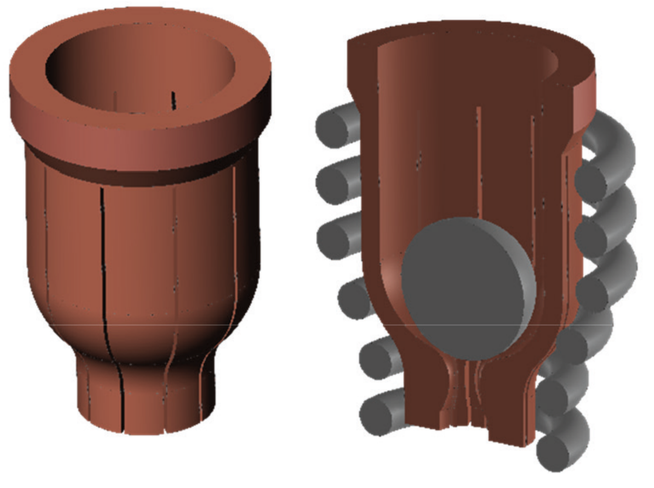


Fig. 1. View of the crucible (courtesy of Officina dei Materiali).

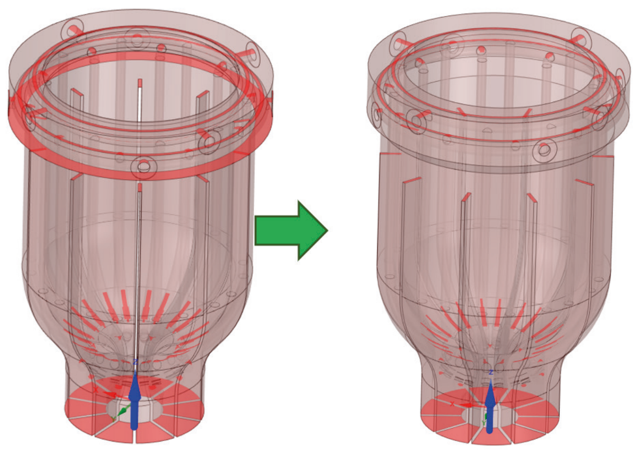
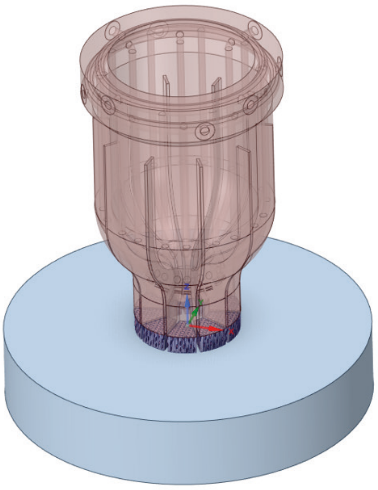


Fig. 2. Geometric analysis of the CAD in terms of a 45° overhang angle relative to the direction of material growth (Z-axis print direction).



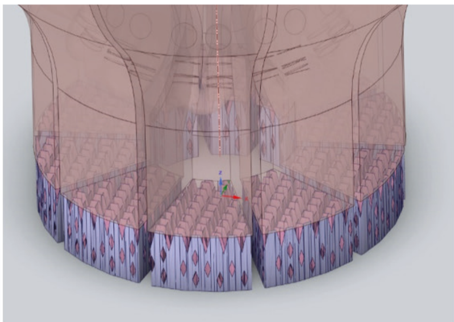


Fig. 3. Support structures built with Ansys Additive Prep for process simulation.

thereby partially foregoing resolution on actual thermal gradients and micro-scale phenomena. Rather than progressively adding material along the laser path, an entire layer is deposited. This only requires the specification of the direction of material accretion and the height of the simulated layer, which greatly reduces the complexity of the simulation setup.

The design of the part required several steps leading up to the analysis of the geometric models in terms of printability by using an analysis of the regions that require supporting structures and that are potentially critical to realize. In Fig. 2, those areas with an "overhang angle" greater than 45° (in red) that require support are highlighted and minimized.

Fig. 3 shows the print setup with the supporting structures that connect the part to the platform.

Simulation of the L-PBF manufacturing process

Similar to conventional welding simulation, the inherent strain approach provides a computationally efficient method to simulate the production of complex metal additive parts on a macroscopic scale. The aim is to predict residual stresses and distortions in the part. This approach simulates a build-up of thermal stress by activating the macro-layers sequentially and applying inherent strain.

Inherent strain is a permanent plastic deformation of the material that subsists in the Heat Affected Zone (HAZ) of the weld, and it is this region which causes the overall deformations and residual stresses.

As this region is an accumulation of various physical phenomena, it is necessary to use a calibration procedure to determine the average total inherent strain, which is only valid for a specific machine model, material and set of process parameters. The accuracy of the material model therefore hinges directly upon the calibration. Such simulations can be conducted with the bare minimum of material property information, that being the mechanical properties at room temperature.

Calibration of the material model

Cantilever beam specimens are now standard for determining inherent strain value as the distortion measurements are simple. Once the test specimens were printed (using the same setup as for the manufacture of the object), they were partially cut from the manufacturing platform near the base, leaving intact the thicker section of the cantilever beam connecting it to the platform. The distortion was measured at three positions (M1, M2, M3) before and after cutting, and the average value was used for the calibration procedure (Figs. 4 and 5).

Essentially, the goal is to identify the calibration parameter (Strain Scaling Factor, or SFF) of the intrinsic strain which matches the measured experimental distortion with the virtual distortion of the simulation.

Process simulation setup

Despite the fact that intrinsic strain values are anisotropic according to the direction of the scanning vectors in relation to the scanning strategy, which is caused by a greater contraction along the scanning direction rather than orthogonally to it,

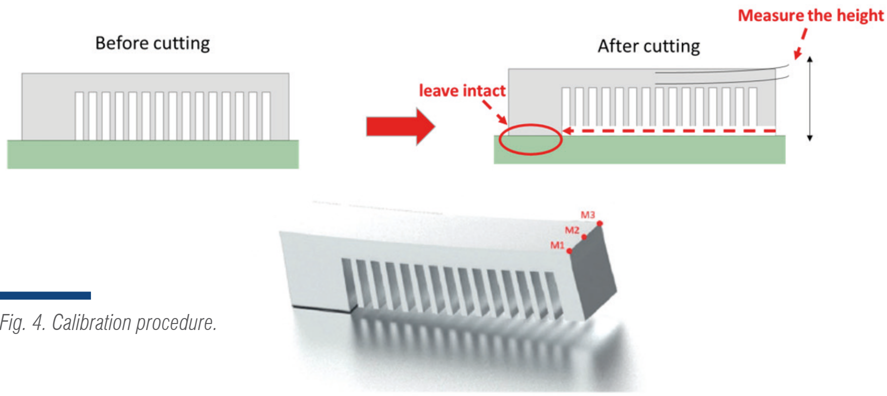


Fig. 4. Calibration procedure.

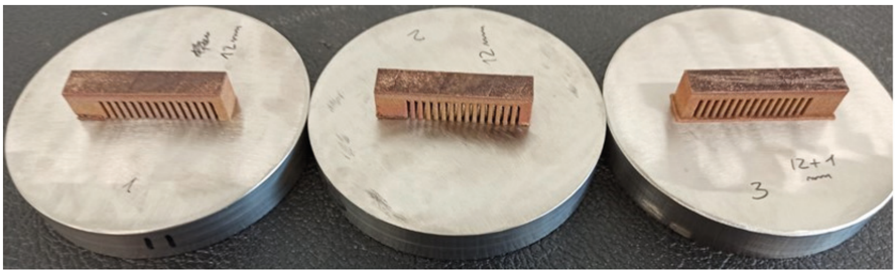


Fig. 5. SLM additive manufacturing specimens for calibration (courtesy of ECOR).

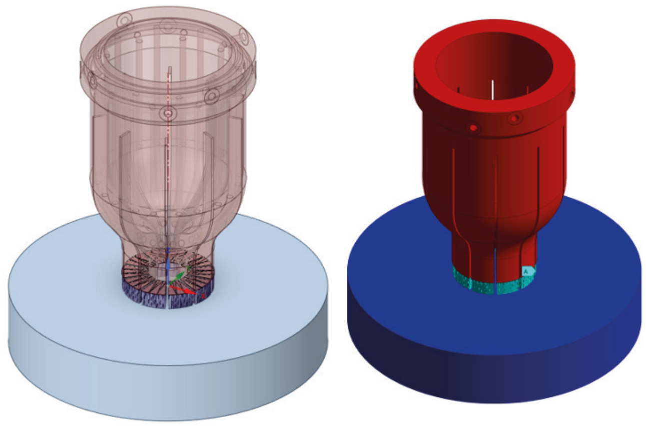


Fig. 6. Setup for manufacturing, and setup in Ansys for LPBF additive process simulation.

they are essentially isotropic when the different powder layers are averaged into a finite element layer that incorporates *n* layers of material (macro-scale approach). The crucible was discretized with tetrahedral FEM (finite element method) elements measuring 0.5mm, which provide a good representation of the geometric features, especially for the cooling channels.

The non-linear material used for the calibration procedure was also used to simulate the part (job).

Simulation results

This article describes the important results of the manufacturing configuration considered optimal for manufacturing the CuCr1Zr copper alloy crucible.

The following images of the simulation results show the distributions of distortions induced by the manufacturing process, layer by layer until the end of the process. The thermo-mechanical equilibrium induces a state of residual tension and deformation of the part attached to the base platform by the supports (Figs. 7a and 8a). The same observations, using cross-sectional or external surface views, are made following the detachment of the part from the platform and the removal of the supports (Figs. 7b and 8b).

Preliminary analysis of the results shows that in the as-built condition, i.e. still anchored to the platform, the part is not subject to such distortion as to impair its operational functionality. However, when analysing the distortions after the post-processing steps of

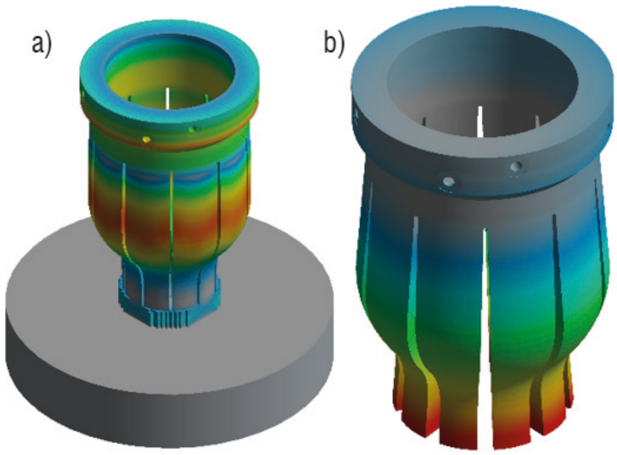


Fig. 7. Part distortions in as-built conditions after process simulation. Left) job anchored to platform. Right) after detachment from platform and removal of supports.

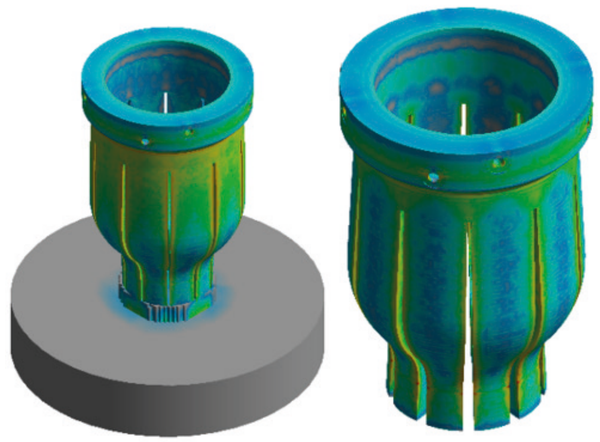


Fig. 9. Stress on the part in the as-built condition after process simulation Right) job anchored to the platform. Left) after detachment of the part from the platform and the removal of supports.

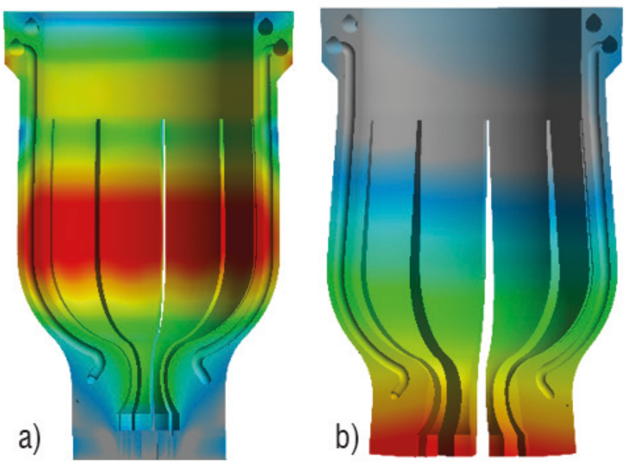


Fig. 8. Cross-sectional view of part distortions in as-built conditions after process simulation Left) job anchored to platform. Right) after detachment from platform and removal of supports.

Fig. 10. Cross-sectional view of the stresses on the part in the as-built condition after process simulation Left) job anchored to the platform. Right) after detachment of the part from the platform and removal of supports.

removing the part from the platform and removing its supporting structures, a substantial increase in distortion can be seen. This indicates that heat treatment to relieve residual stresses and avoid subsequent distortions is necessary to obtain a component that deviates as little as possible from the nominal geometry.

The maximum value in terms of residual stresses exceeds the fracture stress but is limited to very narrow areas and is due to the peculiarities of certain mesh nodes. Further investigation is needed to verify the above observations.

Remarks and conclusions

The TEMART project's intended objectives were successfully achieved in this industrial case where the virtual approach to the design of the copper alloy crucible made it possible to produce the object successfully at the first attempt (right first time). The first prototype's material density and final shape matched expectations.

By designing the component according to DfAM (Design for Additive Manufacturing), the geometry was studied from the perspective of the production process, allowing us to identify the potential critical areas during the design phase even before producing the part, and therefore determine how to modify them. The process simulation made it possible to predict tension and deformation values in order to assess the component's compliance with the design specifications and to take countermeasures in the event of non-conformity thus eliminating the iterative process in the field.

Upon completion of the project in early 2021, the first example of a new-generation cold crucible designed to melt metals and metal alloys with a high melting point was produced and tested. Internally, the shape of the funnel and the number of cuts were optimized to produce a gradual variation in levitating force (in order to accommodate alloys of different densities) while retaining a conveniently sized nozzle for tapping melt that can be controlled electromagnetically; the production by additive manufacturing adhered faithfully to the optimized complex shape.

Apart from numerous advantages over traditional crucibles, the new crucible demonstrated a considerable energy-saving capability, reducing the power consumption required to melt metals by a factor of 3-4 compared to traditional cold crucibles.

Addtoshape was created in 2022 from a meeting between Seitron, an industrial production company that has operated on Italian and foreign markets for over 40 years, and Officina dei Materiali.

Addtoshape was established on the foundations of Seitron's strong spirit of innovation and modern industrial production capacity, Officina dei Materiali's decades of experience in national research facilities, and a registered patent (no. 102021000024227 (filing date 21/09/2021)) protecting the new-generation crucible. Seitron, ever attentive to the evolution of technologies and to the challenges posed by new processes and new markets, has decided to take on the adventure offered by additive metal manufacturing of pure copper, in order to support the production of new-generation cold crucibles.

Acknowledgements

We would like to thank the M3NET Consortium, project leader of the TEMART ("Tecnologie e materiali per la manifattura artistica, i beni culturali, l'arredo, il decoro architettonico e urbano e il design del futuro" or technologies and materials for artistic manufacturing, cultural heritage, interior design, architectural and urban decoration, and the design of the future) project and all the project partners – with particular reference to Officina dei Materiali, Ecor International, and the Department of Industrial Engineering (DII) of the University of Padua.

For more information:
Antonio Rossi – Addtoshape
antonio.rossi@addtoshape.com

References

[1] C. Meier, R. W. Penny, Y. Zou, J. S. Gibbs, and A. J. Hart, "Thermophysical Phenomena in Metal Additive Manufacturing by Selective Laser Melting: Fundamentals, Modeling, Simulation, and Experimentation", *Annual Review of Heat Transfer*, vol. 20, no. 1, pp. 241–316, 2018.

[2] BSI Standards Publication, BS EN ISO / ASTM 52911-1:2019 *Additive manufacturing - Design Part 1: Laser-based powder bed fusion of metals,* October 2019.

[3] W. J. Sames, F. A. List, S. Pannala, R. R. Dehoff, and S. S. Babu, "The metallurgy and processing science of metal additive manufacturing", *International Materials Review,* vol. 61, no. 5, pp. 315–360, 2016.

[4] L. Bertini, F. Bucchi, F. Frendo, M. Moda, and B. D. Monelli, "Residual stress prediction in selective laser melting: A critical review of simulation strategies", *The International Journal of Advanced Manufacturing Technology,* vol. 105, no. 1–4, pp. 609–636, Nov. 2019.

About Addtoshape

Addtoshape designs and manufactures, through additive manufacturing, innovative windings in pure copper for high performance electric motors. Complex geometries, otherwise not achievable with traditional, round or flat copper wire, are now achievable without limits, allowing maximum freedom of expression in terms of shape, function and performance. Despite large-scale production capacities and high efficiency achieved by traditional windings, the growing pressure from environmental policies is pushing the electric motor sector to a leading role in the fight to reduce global greenhouse gases. To achieve this, it is necessary to reduce the carbon footprint of electric motors by further increasing their efficiency and power density.