# SURFING

## Post-treatments to boost the functionality of additively manufactured parts


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### Executive summary


SURFING is a research project tackling the rapidly growing field of metal Additive Manufacturing (metal AM), which provides design freedom in such a way that traditional technologies cannot achieve. However, metal AM is not free of drawbacks: the quality of the surface and the mechanical performance of AM parts are often not satisfactory for the final destination of use; moreover, a complete comprehension of the effects of all process parameters is still missing. The goal of SURFING is to provide valuable contributions to scientific research on metal AM. The goal is pursued in two ways: writing of a Review Paper regarding the effects of one specific parameter (build orientation) on physical and mechanical properties of final parts; and development of an experimental campaign to investigate the effects of two selected post-treatments on standard specimens. In addition, some effects of building orientation were experimentally analysed. The choice of the technology (L-PBF) and the material (Ti6Al4V) were driven by current market trends. A full characterisation of raw material and specimens before and after the post-treatments was executed, to realise a comprehensive study of the metal AM process. The two post-treatments were chosen between those available on the market, contemplating that they rely on very different operating principles. Both were expected to improve the properties of the final part: the characterization process quantitively evaluated such effect through the comparison of treated and non-treated specimens. SURFING results were consistent, and they confirmed the effectiveness of such treatments. Thus, they are expected to be of interest for final users (i.e., companies leveraging on metal AM) to evaluate applications on their products. These findings also constitute a solid basis for further research on hybrid treatments, different materials and technologies. Finally, SURFING considered the time and costs required for the processes, conscious of the relevance of these aspects in the industrial world.



### Key Words

Metal Additive Manufacturing, Post-treatments, Build Orientation, Ti6Al4V


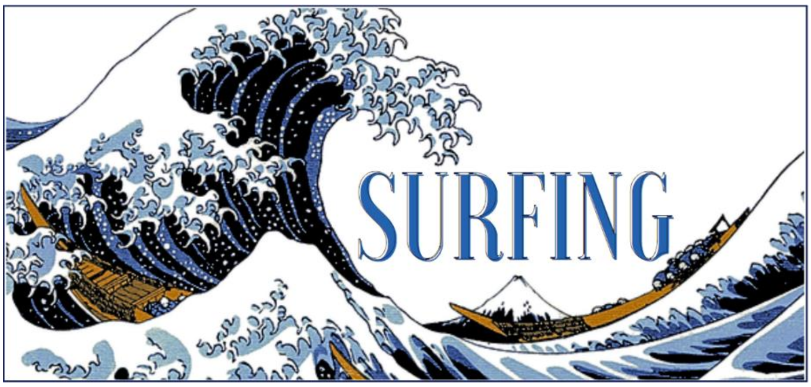


Figure 1: SURFING project logo.

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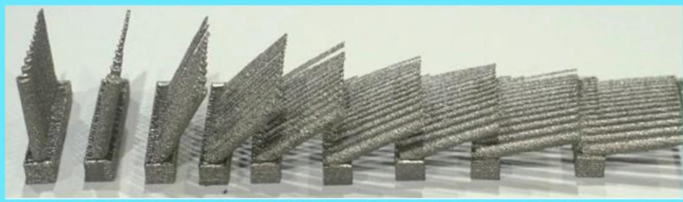
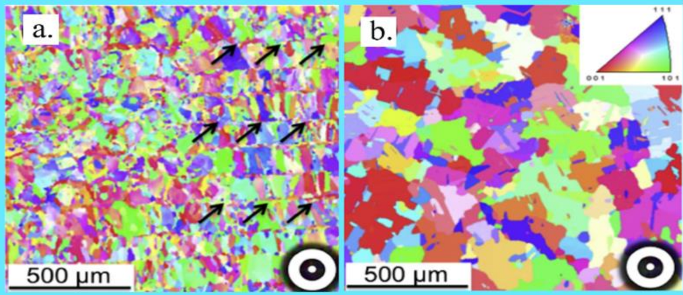
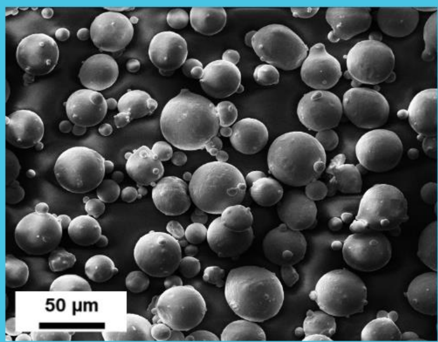
**Build orientation**



**Post treatments**



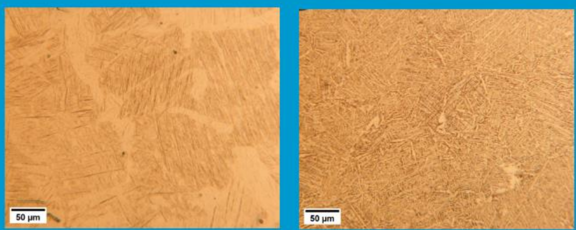

## Design and Production

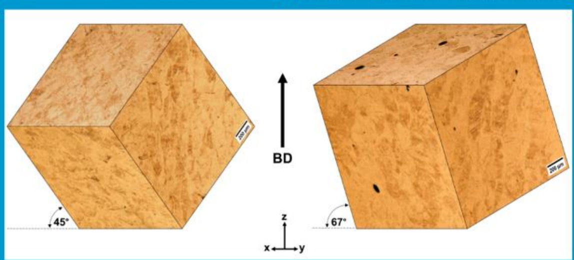





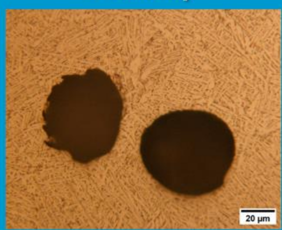
## Experimental Results

### Microstructure

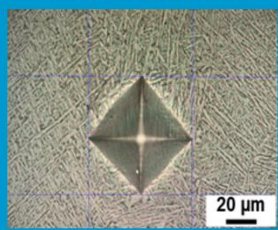




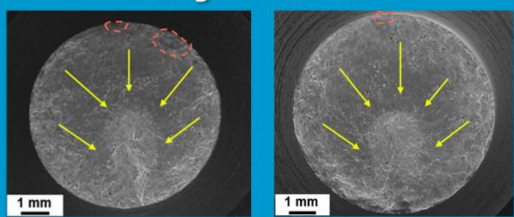

### Porosity



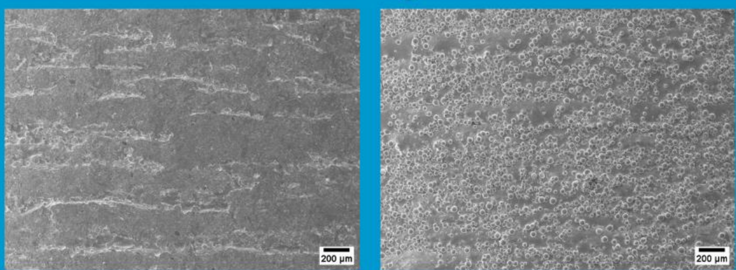

### Micro Hardness



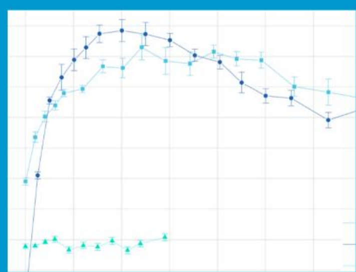

### Fatigue Behaviour




### Surface Roughness



### Residual Stresses



## Project description written by the Principal Academic Tutor

Additive Manufacturing (AM) is an emerging production technology for realising three-dimensional objects of intricate geometries layer-by-layer. It has attracted significant attention due to the possibility of overcoming many design restrictions and simplifying the production of complex geometries. AM has been extensively applied in different technological sectors. For instance, AM is becoming increasingly popular in biomedical applications when patient-specific shapes need to be manufactured. Nevertheless, a key obstacle for the as-built AM parts is their poor surface quality, which originates from the layer-by-layer nature of AM processes and the complex physical phenomena involved, as well as the part geometry, the surface orientation with respect to the build direction, and the design of the support structure. Therefore, their surface and bulk post-treatments can play a critical role in obtaining a controlled, regular, and repeatable surface morphology as well as residual stress distribution in the as-built components to enhance their performance. Thus, the overall objective of SURFING was to develop an integrated chain for the design, fabrication, and post-processing of functional Ti6Al4V parts. In SURFING, to bridge the notable gap between the standard characterisations and in-service performance of real components, the role of geometrical design as well as the surface and bulk post-treatments on the surface and bulk properties, have been assessed and correlated to the performance of AM parts under fatigue loading. Another target in SURFING was to develop the know-how for effective structural design and assessment of metal AM components to design and validate a highly efficient and flexible manufacturing route optimised for different industries. In fact, SURFING addressed the issues related to the high cost of the part, low productivity, lack of standardisation, and insufficient technical knowledge and design skills compared to what is available for traditional materials and processes. Through reduced raw material use, more flexible design and assembly paired with improved functionality of AM components, SURFING findings can contribute to evaluating the economic impact in industrial sectors that can effectively benefit from AM technologies. The SURFING outcomes are scientifically attractive and industrially feasible, leading to the set-up of an integrated manufacturing chain.

## Team description by skill

The SURFING team is composed of five Engineering students, four from PoliMi and one from PoliTo. Each member of the team has a different background (mechanical, mechatronics, automation, biomedical, materials) and this was highly valuable in tackling a multidisciplinary topic as metal AM. The project duration was about 16 months, thus organisation was crucial for reaching goals and different personal competences allowed to assign tasks and to perform them optimally.

All the students equally contributed to scientific writing and preparation of deliverables. Everyone participated in the experimental activities, with multiple chances to learn from one another. Thus, the method of work was strictly based on teamwork and collaboration, with no creation of sub-groups. However, some specific contributions can be described:

- S.S. took the role of team leader and she was responsible for communication with Academic Tutors and ASP, organisation of meetings, checking the progress of the activities. She also provided assistance in multiple characterisations.
- F.M.V. had the widest knowledge of materials, metallurgical analysis, and experimental procedures and he managed most characterisation activities.
- C.B. leveraged her experience in mechanics and laboratory equipment to perform specific characterisations procedures on raw material and specimens.
- I.A. supervised the printing and post-processing processes at PoliTo, taking into account process parameters, time and costs.
- N.E.V. went into detail in the analysis of the metal AM market, requirements, and relevance of the results, and he provided assistance in some laboratory activities.

Finally, it is important to recall the value that the support and supervision of highly experienced Academic Tutors and skilled laboratory technicians had for the activities.

## Goal

SURFING is a research project focused on exploring and enhancing the current State of the Art of metal AM. The project primarily concentrates on Powder Bed Fusion (PBF) technologies, which are prominent in both scientific research and industrial production. PBF involves depositing powdered material, layer by layer, and selectively melting it using high-power energy sources like lasers or electron beams. The project aims to contribute with original findings to the field, covering the entire metal AM process, from raw materials to post-processing. This goal is pursued through two distinct approaches: a literature review and the development of experimental activities. In the literature review, the research focuses on a specific parameter that lacks comprehensive guidelines regarding its impact on physical and mechanical properties: building orientation (i.e., the angle between the part's production direction and the printer's baseplate). To address this gap, the project aims to produce and publish a Review Paper on this topic. Concurrently, original experimental activities are designed to investigate the effects of different post-processing techniques on Titanium alloy parts, widespread in AM field for its superior features like the optimal strength/density ratio, biocompatibility, good corrosion resistance, among others, produced through Laser-Powder Bed Fusion (L-PBF). Two post-treatments, Drag Finishing and Stress-Relief heat treatment were selected for examination. The project involves the production and characterization of three sets of specimens in university laboratories, with a focus on their impact on fatigue performance (significant in industrial applications), surface roughness, porosity, and other relevant factors. Moreover, some specific properties such as surface roughness and microstructure were analysed on specimens with different build orientations. SURFING has also considered the costs and times related to processing. These aspects may be useful for a cost/benefit evaluation in an industrial context.

## Understanding the problem

Despite the numerous advantages offered by metal AM, several challenges are still open in the field. Particularly, the quality of the surface and the mechanical performance of parts immediately after production (i.e., as-built condition) are often not satisfactory. Thus, manufacturing parameters must be carefully tuned, and post-processing of the part is often necessary to meet the final requirements to produce reliable parts for specific industrial fields that demand maximum quality and precision. Thereafter, despite the continuous growth in scientific research on the topic, a full comprehension of all the influencing factors and their correlations is still missing. Raw materials suppliers, machinery producers, and final users would highly benefit from solid scientific results on the outcomes of such technology, and more consolidated knowledge of the overall process is needed to bring awareness and foster metal AM.

For instance, a sufficiently comprehensive understanding of the effects of building orientation on the final physical and mechanical properties of the parts produced by metal AM is still missing. Building orientation relevance in this field is crucial since the parts produced often reveal very intricated geometries, with sections printed in directions other than vertical or horizontal. Even though many research papers have been published in recent years, there is still a lack of agreement on its consequences in properties such as manufacturability, dimensional accuracy, porosity, microstructure, static and fatigue strength, fracture toughness, corrosion and wear resistance, among others. Indeed, it is hard to establish a common standard knowledge on this parameter.

In addition, a wide range of post-treatments is available but just a few specific guidelines to select the best ones in defined manufacturing routes have been shared among the scientific community, particularly because metal AM comprises an extensive variety of different technologies and materials. Therefore, studying and comparing the benefits of different post-treatments on a specific metal AM technology and material is worth the effort and could be useful for part producers focused on specific sectors where metal AM is becoming relevant. Furthermore, an analysis of the associated costs and production times for this specific production routes could also bring more attractiveness to adopt this innovative technology.

## Exploring the opportunities

Metal AM has significant advantages over traditional manufacturing techniques such as larger design freedom, ease of customization and lower material waste. On the other hand, there are some technology limitations: long production times and not satisfactory surface quality and mechanical properties immediately after production. This causes the need to perform additional post-treatments procedures to achieve the required features. Thus, costs and times of the overall process in some cases are not competitive in the market compared to the traditional ones. Furthermore, in the current state of the art there exists some ambiguity regarding how certain parameters affect the final properties of the piece. This constitutes a lack of a structured, shared knowledge and so an opportunity for SURFING to fill this gap.

## Generating a solution

Once understood the opportunities in the field, two parallel paths were chosen in order to maximize the impact of the project in the metal AM R&D area.
Firstly, we decided to write a structured review paper addressing how the build orientation affects the key mechanical characteristics, in particular manufacturability, geometrical accuracy, porosity, roughness, microstructure, static/tensile strength and fatigue strength. Build orientation was chosen since it was seen to be one of the parameters with higher impact on the final characteristics, so it is a crucial aspect to investigate. This first part aimed to fulfil the need of a comprehensive summary on the effect of building orientation in metal AM, making it accessible for everyone doing research in the field.
The second path was strictly experimental with the goal of creating a strong basement on which are the effects of some post-treatments on standard specimens produced by Laser-Power Bed Fusion (L-PBF) using a Titanium-6Aluminium-4Vanadium (Ti6Al4V) alloy. More in detail, two different types of post-treatments were analysed: the first one is a mechanical post-treatment (called drag-finishing) which works on the surface properties in order to improve the mechanical strength of the specimen. The second one is a stress-relief heat treatment, that has the same objective, but it acts on the internal stresses in the specimen without changing the surface features. Both the post-treatments applied were effective in enhancing the mechanical performance of the specimens analysed, in particular for what concerns the fatigue behaviour. Among the two, the stress-relief treatment demonstrated the best improvement. Furthermore, the investigation about the effects of the build orientation on surface roughness evidenced worse surface quality in inclined specimens with respect to vertical ones.
In addition to the strictly technical analysis, it was possible to do an initial time-cost analysis to evaluate the feasibility of applying the selected post-treatments.

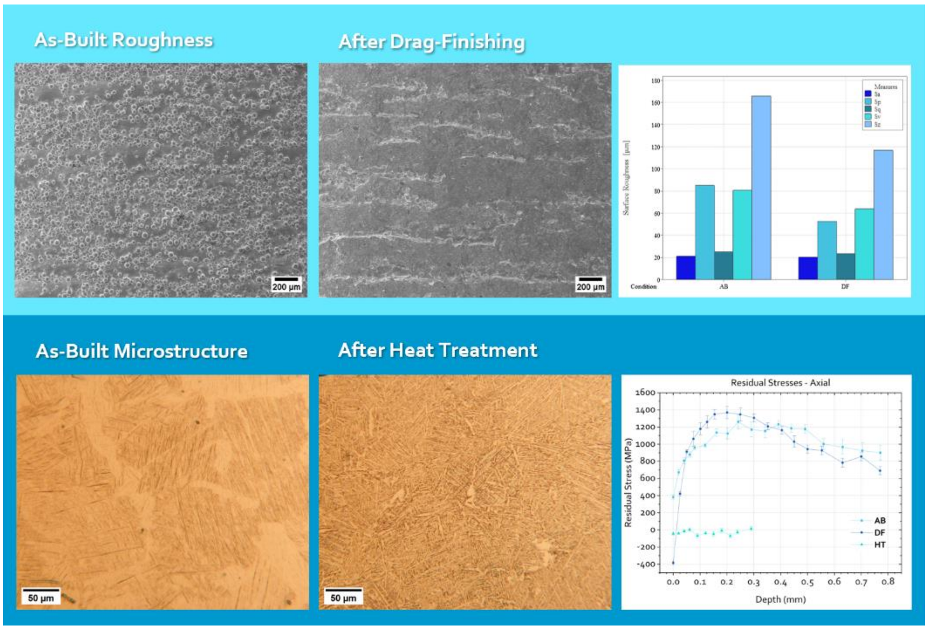



Figure 2: Overview of the effect of the post-treatments applied.

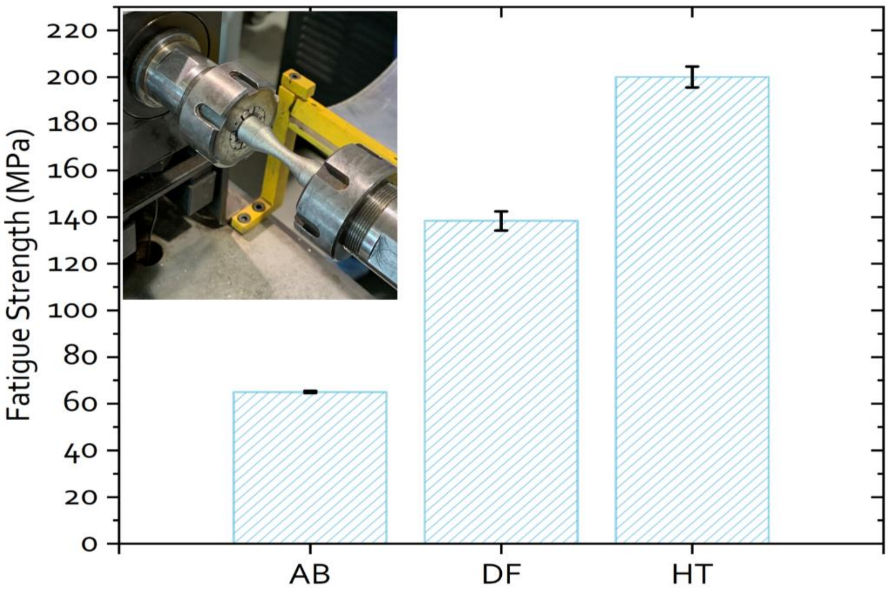


Figure 3: Results of the fatigue tests carried out in the different conditions analysed.

In conclusion, the outcomes of this project contribute to enhance the awareness of AM processes by the diffusion of solid experimental results. Moreover, they constitute a very solid basement for any researcher who wants to investigate more in-depth on this area.
Some further developments could be the analysis of other metal AM technologies, such as Electron-Beam Power Bed Fusion (EB-PBF); the study of other post-treatments, in particular hybrid ones (as a combination of the ones previously described), considering the relationship between performance, cost and time. Finally, this feasibility evaluation can be extended to specific components in order to provide companies using metal AM a competitive manufacturing route.

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