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Characterization of Surface and Bulk Features of SLM Parts

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Abstract. An experiment-analytical procedure based on the building of an object in severe atmosphere resistant steel by SLM is proposed. The complex shape was investigated with the sectioning and laboratory observation of the physical object. The study evidenced the need to get a variable layer thickness to follow double curvature complex shapes. In particular the key variable in the process is the melt bath dimension by which the metal powder assumes by solidification the required global geometry. It was observed that the bath detected mainly in terms of the area of section tends to decrease when approaching to the surface of the physical model where the complex geometry needs to be described. Relationships describing the bath area behaviour and correlations between surface roughness and internal bath dimensions were found and proposed in detail. The surface roughness is highly correlated with the bath area in the zones of the section approaching the surface.

Introduction

The realization of prototypes in the industrial field is very useful since the time to design validation can be effectively shortened. They are very useful for ergonomic, assembly and in service properties evaluation of the part to be definitively realized [1]. When the additive manufacturing is considered, the use of polymer materials allows the verification of the already mentioned characteristics [2] and sometimes they can be used for the definitive in service function. When metallic materials are studied such method requires the due attention since they are very sensitive to manage when the component is realized by layer by layer. The Selective Laser Sintering represents the way by which from the powder the solid state with the desired geometry can be realized. The mechanism operating in the SLS is mainly based on the sintering of particles [3] in which the solid state is given by a surficial fusion welding of them due to laser action. The main disadvantage of such technique is represented by the presence of porosities and of some continuity solutions that could determine a lack of resistance with the need of subsequent post-treatment in particular when intermediate materials are used.

In the Laser Powder Bed Fusion environment (LPBF) the attempt to get the solid physical object in which particles can be joined directly in a stable and tough way is represented by the Selective Laser Melting in which the powder particles are fused each time in a bath where they solidify together. In that way to manage the layer thickness and their number depending on the complexity of the geometry to be realized is really possible. Some authors made researches on the adaptive slicing [4] used as a way to get the best approximation of the surface of the specimen. Even if for metals to get liquid the whole layer represents an enterprise. For that reason the simulation of SLM [5] allows to change the point of view and to consider the additive manufacturing in that field as techniques not only based on layer by layer. Such approach still under investigation is partially reported in [6] where the micro-macrostructure of a specimen realized by SLM is reported. In detail to tune the melted bath sizes allows to avoid the lack of material between adjacent baths, interstitial not melted powder [7] and irregular surface profiles [8] in particular when associated with irregular cavities, porosities, etc.

In the scientific literature many papers concerning powder based additive manufacturing like reported above in the components realization and prototyping fields can be found even if some variables need to be further investigated when complex shapes characterized by high surface finish requirements have to be realized in metallic material. In particular the interconnection between the geometrical and surface characteristics with the bath dimensions and locations.

The present paper aims at studying in depth the relationships between the main dimensions of the baths, of which the physical object is composed at the micro-level, with the surface appearance and geometric features of a heavy atmosphere resistant steel when a complex geometry is realized by SLM. It was observed that in order to follow complex shapes the dimension of the baths in terms of the area in the studied section has to decrease and the layer thickness to be adapted to such requirement during the melting and subsequent solidification processes. The results are reported in detail.

Procedure, Experiment and Characterization by Analytical Modeling

Procedure. An experiment-analytical procedure based on the building of an object in a severe atmosphere resistant steel by means of variable thickness of the layers and on the modeling of the surface and of the bulk in terms of a function of the melt baths sizes taken in the computer aided environment from laboratory section observations is in general proposed. The procedure is reported in Fig.1.

Experiment. The digital model realized in the CAD environment was a solid with maximum planar dimensions of 100x80 mm^2 and an height of the dome equal to 18.75 mm plus a basis of 5 mm. The tridimensional surface obtained by two B-spline curves was translated into STL as reported by the authors in a previous scientific work [2]. After slicing the CLI file was supplied to a 3D LPBF MACHINE where the physical model was realized using a severe atmosphere resistant steel. The thickness of the layer was taken in order to get the desired geometry to the specimen. After SLM the realized metal physical model was slightly surface treated in order to remove residual powder.

In order to get microstructure observations in the specimens obtained after sectioning they were previously grounded, polished and electro-etched in a solution containing at least 10 % of oxalic acid.

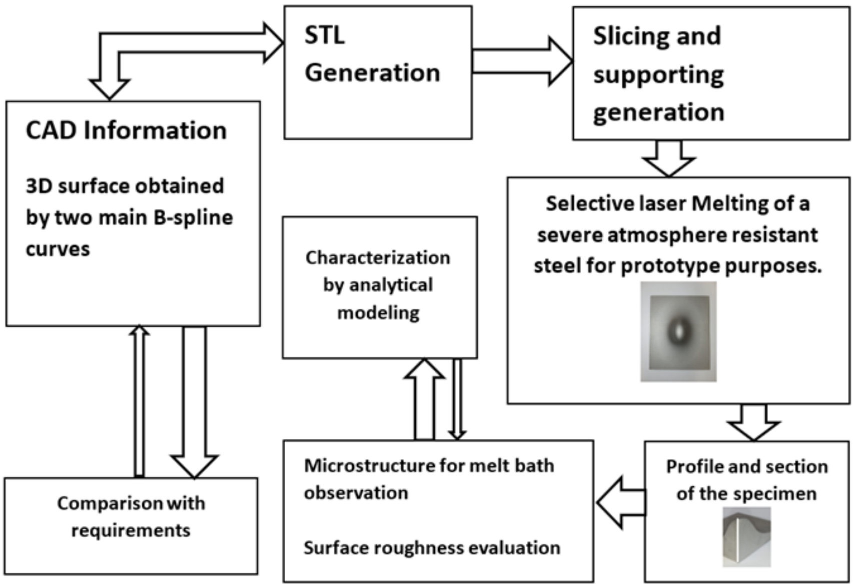

Fig. 1 Methodology for surface vs. internal bath area characterization.

Bath measurement on specimen section. The laboratory observations to get melt and subsequently solidified bath morphologies and layer configuration data and information were performed in the locations of the specimen reported in Fig. 2. The evaluation of the mean area of each bath for each layer was made in the CAD environment using the specified tools for distances and planar surface measurements. The bath sampling was performed both in the subsurface, i.e. the border zone of the specimen immediately below the surface, and in the bulk as far as possible from the border. The white points show the positions of the bath evaluation. The mean values obtained for each zone were obtained.

Surface roughness measurement. The surface roughness Ra was measured on the surface of the specimen by a 2D SCANNING contact rugosimeter. The values were taken along the profile of the specimen defined by the black line in Fig. 2.

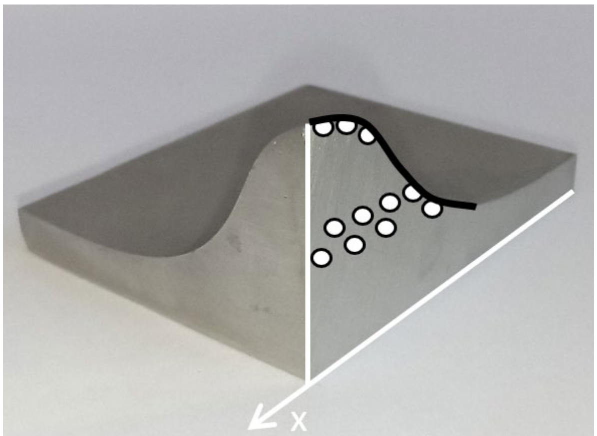

Fig. 2 Position of detected points and profile on specimen for bath dimension and surface roughness evaluation.

Characterization by analytical modeling. The modeling was realized in order to get a type of equation in which the surface and bulk bath area could be analytically described and the external geometry related to the internal configuration of the baths created from the melting of different zones. The model catches all of the melted, re-melted and solidified baths independently of the layer but depending on the volume of each of them and on the proximity grade (surface or bulk) to the external surface complexity of the geometry. The equation obtained is of the type:

$$y = ax^2 + bx + c \quad (1)$$

where y is represents the area or the depth of the bath and x the position along the axis reported in Fig. 2.
The ability to detect the relationship between the surface roughness Ra and the areas or the depths of baths is reported in terms of coefficient of determination R^2.

Results

The sectioning of the specimens shows some different baths inside with different geometry and morphology as reported in Figs. 3 and 4. The layers appear dependent on the global geometry requirements and the baths are made in order to get a lack of material as minimum as possible and to adapt the internal configuration of the material itself to the external geometry. Such particular is evident when the curvature of the physical model is increased, that is for the complex part of the geometry (Fig. 3). In fact, when the curvature increases the bath area tends to decrease. In addition, in such zone the already solidified baths are re-melted each time in order to increase the adaptation attitude of them to describe the complex geometry and to avoid porosities due to the lack of material powder in the nearby of the different baths or not melted powder in the same locations. In such a case the re-melting is operated during the object realization in a given bath and not appears as a post processing similar to that reported by other researchers [9].
The evaluation of the bath characteristics, i.e the area and the depth, allows to quantify and to distinguish those of them very useful for matching requirements. In Fig. 5 values obtained by the digital measurement taken in the computer aided environment are reported for those solidified baths in the zone approaching the surface (named surface) and for those in the bulk (named bulk) following the scheme given in Fig.2.

Fig. 3 Bath distribution in the subsurface of the dome.

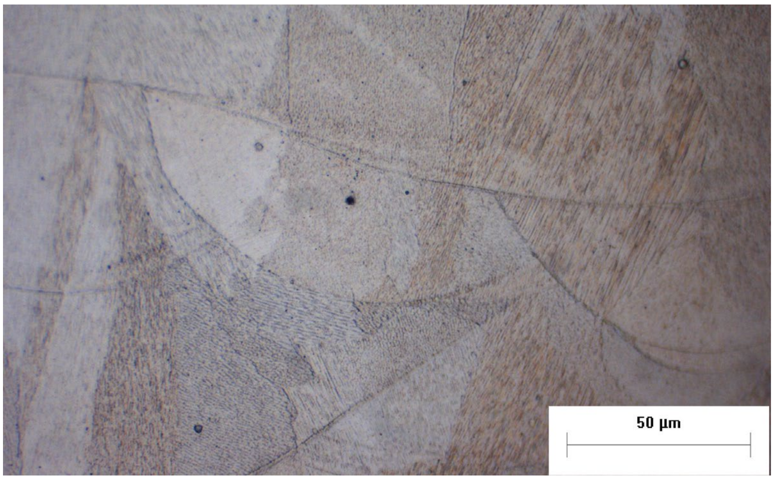

Fig. 4 Bath distribution in the bulk of the specimen.

The area values of baths in the proximity of the surface are lower than those detected in the bulk of the physical model according to the detected rule high curvature- low bath volumes. In particular, the values at the bulk tends to increase due to the position of detections as can be seen in Fig. 2. In fact the detection points in that case are in the deepest bulk of the model. This means that high productivity is preferred. The curve of the surface points plotted both in the connection (positions 1 and 2) and at the dome (positions 4,5 and 6) reveals that high curvatures need to be realized and consequently low values of the bath area need to be supplied.

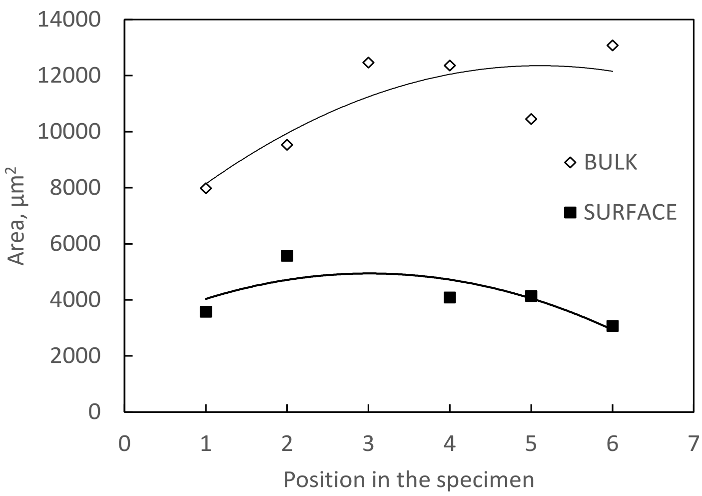

Fig. 5 Area of bath versus position in the specimen.

In Fig. 6 the study was performed approximatively on the same solidified baths in terms of their depth. The obtained values and related curves for both the bulk and surface appear represented as similar in the trend even if those got for bulk are higher in value than those for surface. The similar trend is attributed to the melting strategy followed for building. It consists in the increase of bath areas that means high depths for the bulk while for surface high depth is in general due to the re-melting approach.

For both the area and the depth of the baths the interpolation of the obtained data got the following equations.

The areas of the bulk baths along the specimen can be described by:

$$y = -249{,}88x^2 + 2552{,}6x + 5835{,}9 \quad (2)$$

where y is represented by the area and the x represents the position like reported in Fig.2.

The areas of the surface baths can be described by:

$$y = -224{,}75x^2 + 1353{,}2x + 2906{,}5 \quad (3)$$

The depth for bulk can be described by the following:

$$y = -7{,}0889x^2 + 37{,}782x + 58{,}093 \quad (4)$$

While the depth of surface bath is represented by:

$$y = -5{,}3797x^2 + 31{,}255x + 25{,}089 \quad (5)$$

By them the distribution of the bath volumes inside the metal physical model can be effectively described and reproduced without lack of material or continuity solutions. Such methodology could be very useful for tuning the building stage of subsequent similar models.

The main effect of the bath dimension at the surface is still under investigation but it can be represented by the shape got by the external geometry of the model and then by the values of the surface roughness.

In Fig. 7 the correlation between surface roughness Ra and the bath area is reported through a determination coefficient R^2 equal to 0.82 stating that the given sizes are strictly related to each other. In Fig. 8 the same behaviour when the depth of the bath is concerned is not expected for the already explained reasons. In fact, the R^2 got for Ra and the depth of bath is equal to 0.64 evidencing low correlation.

The obtained results allow to get and to relate the surface roughness on the most complex surface parts of the model with values found by other authors in [10, 11] for planar surfaces obtained without post surficial treatments for increasing surface finish taking into consideration some overlays required.

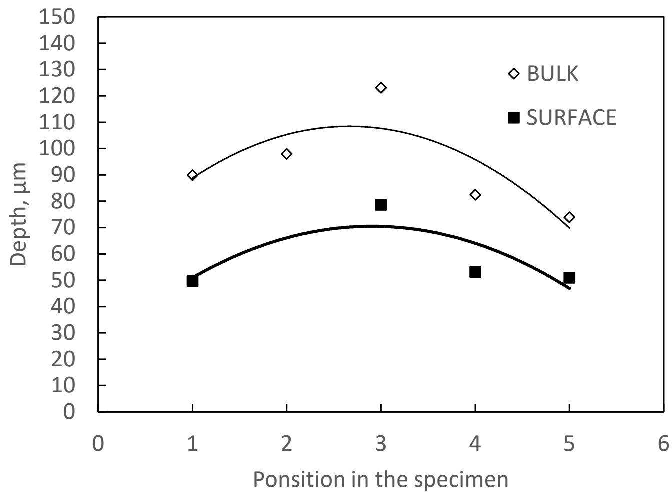

Fig. 6 Depth of bath versus position in the specimen.

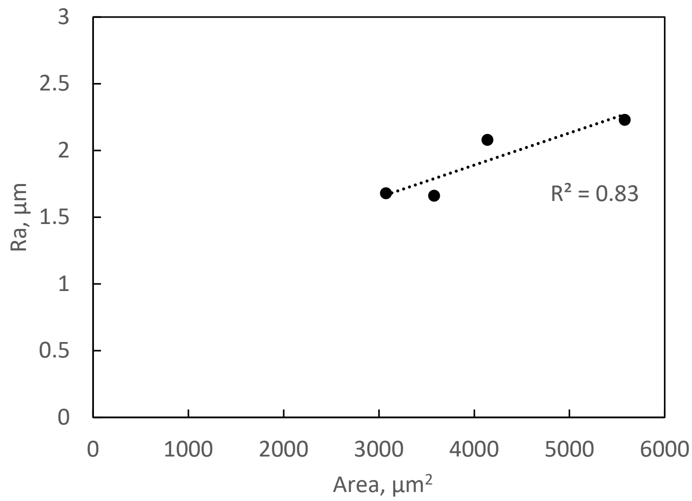

Fig. 7 Correlation between surface roughness and bath areas.

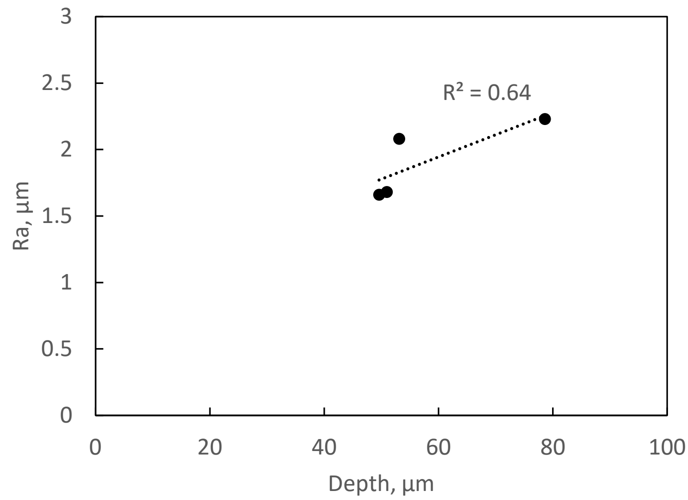

Fig. 8 Correlation between surface roughness and bath depths.

Summary

An experiment-analytical procedure based on the building of an object in severe atmosphere resistant steel by SLM is proposed. In order to get the complex shape of that the key variable is represented by the melt bath dimensions. By the specimen section observation the melt bath dimension, evaluated in terms of the area and of the depth, and by the surface roughness detection it can be stated that:

- The fixed layer thickness does not represent the real key variable of the process
- The surface complex shape can be effectively followed with decreasing the subsurface melting baths area and using a re-melting technique during production in order to limit the presence of voids and improve the adaptation to the required geometry independently of the material
- The bulk of the physical model can be rapidly built using bigger melt bath areas
- The models to describe the relationship between the complex shape and the bath volumes in terms of their area and depth versus position are given making possible their use for similar model realization in a faster way
- An high correlation is found between the surface roughness and the melt bath areas at the surface.
- The correlation does not arise when the melt bath depth is considered because this variable does not depend only on global dimension of them but also on the re-melting approach followed and applied on baths approaching the surfaces.

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