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Selective Laser Melting of Ti6Al4V: Effects of Heat Accumulation Phenomena Due to Building Orientation

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Abstract. Titanium alloy Ti6Al4V is one of the most utilized alloys in the field of additive manufacturing due to the excellent combination of mechanical properties, density and good corrosion behavior. These characteristics make the use of this material particularly attractive for additively manufacturing components with complex geometry in sectors such as aeronautics and biomedical. Selective Laser Melting (SLM), by which a component is fabricated by selectively melting of stacked layers of powder using a laser beam, is the one of most promising additive manufacturing technologies for Ti6Al4V alloy. Although this technique offers numerous advantages, it has some critical issues related to the high thermal gradients, associated with the process, promoting the formation of a metastable martensitic microstructure resulting in high tensile strength but poor ductility of the produced parts. The formation of microstructural defects such as balling and porosity can occur together with the presence of residual stresses that may significantly affect the mechanical characteristics of the component. Specific process parameters and geometries can determine heat accumulation phenomena that result in a progressive decrease in thermal gradients between layers. These heat accumulation phenomena are influenced by the number of layers deposited, but also by the building orientation that, for a given geometry, determines a variation of the deposited surface for each layer.

Introduction

Ti6Al4V alloys are widely used in the aeronautical and biomedical sectors. These sectors often require the production of parts characterized by geometric complexity combined with a low number of pieces required. Additive manufacturing techniques, in this context, are the most suitable to respond to these specificities.

In particular, the Selective Laser Melting technology, which involves the creation of products starting from metal powders deposited in successive layers of predefined thickness, are melted in a selective manner until the completion, layer by layer, of the product, is one of the most used for metal alloys and in particular for the Ti6Al4V alloy considered in this study [1-2].

Many studies in the literature are focused on determining the effect of building orientation on the final mechanical characteristics of the parts produced. In particular, there are numerous studies that, varying the building orientation, usually chosen equal to 0 °, 15 °, 30 °, 45 °, ... 90 ° with respect to the building platform of the additive manufacturing machine on which the pieces are printed, evaluate the changes in mechanical properties of the material in terms of Ultimate Tensile Strength, Elongation to Failure, fatigue Resistance together with changes in material density [3-8].

What we observe, from the analysis of literature results, is that, for a given building orientation, the values of these characteristics are often conflicting, that is, orientations that in some studies show optimal values of mechanical characteristics, in other studies lead to minimum values of the same characteristics.

These different results suggest the presence of factors influencing the effect of the building orientation that can vary even for a given orientation. From this point of view, the studies present in the literature, and those already conducted, have shown that the final characteristics of the samples produced with different orientations depend on the thermal phenomena that occur during the printing process [9-11]. It has been observed that, depending on the specific geometry of the sample and its orientation, the phenomena of thermal exchange with the building platform are more active, leading to a rapid cooling of the sample during the printing process, or heat accumulation phenomena can be activated, leading to a progressive decrease of thermal gradients that determine the thermal exchange in the deposition of subsequent layers.

In this work the occurrence of heat accumulation phenomena has been studied for a fixed geometry of the sample, as the building orientation varies (0°, 45°, 90°), and the effects of these phenomena on the quality of the pieces produced have been highlighted. Geometrical and deposition parameters able to recognize the occurrence of heat accumulation were defined and the quality of samples was investigated by means of tensile strength tests, ductility measurement, micro-hardness tests and density evaluation. In particular, the joint effect of building orientation and specific geometric characteristics of the sample, as the orientation varies, was considered as a function of preferentially active heat transfer phenomena. The above analyses were performed considering orientations for which the presence of the supports required for the sample printing process does not play a key role in active heat transfer processes.

This joint study aims to find an interpretation of the discordant results in the literature about the effect of building orientation on the mechanical properties of the material and the percentage of porosity defects and to producing a synthesis parameter of the thermal effects most active in the printing process, as the geometry of the sample varies, in order to provide a priori information on the characteristics obtained for a given geometry and orientation.

Materials and Methods

Dog bone samples (Fig. 1) with different building orientation (0°, 45°, 90°) were fabricated keeping constant other process parameters, namely laser power, scanning speed, hatch distance, scan strategy and layer thickness.

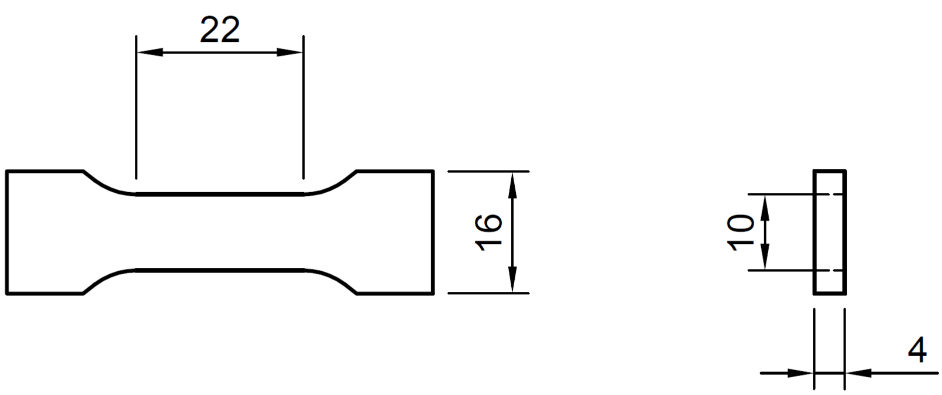


Figure 1. Sketch and dimensions of the dog bone specimen.

The used process parameters are shown in table 1. These parameters are suggested by the SLM Solution Company for the used material. SLM 280 HL machine was used to produce the specimens by the selective laser melting of Ti6Al4V spherical powder provided by SLM Solution Group AG (Lübeck, Germany). In Fig. 2 a SEM image of the used powder, acquired by Phenom ProX Desktop microscope is shown. Particle size distribution was 20-63 µm and mass density 4.43 g/cm3.

Table 1. Process parameters used in this study.

Building orientation	0°, 45°, 90°
Laser power	350 W
Scanning speed	1400 mm/s
Hatch distance	120 µm
Scan strategy	15° rotation between consecutive layers
Layer thickness	30 µm

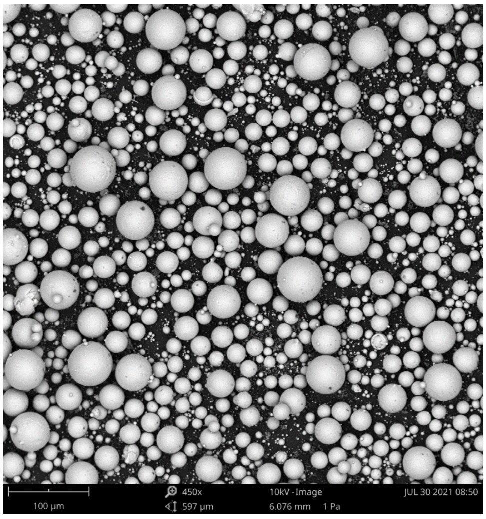


Figure 2. SEM image of Ti6Al4V spherical powder.

The building platform, of the same material of the powder, was preheated to 200° C and the build chamber was filled with argon until the oxygen level is lowered to the 0.1 vol.%. For each case study six repetitions were printed, three were used for tensile test and three for density measurement and microhardness test.

Dog bone specimens were produced as a reduction of Standard ASTM/E8 dog bone shape with a rectangular cross section (10 × 4 mm) and a useful gauge length equal to 22 mm. Quasi-static tensile tests with a loading speed of 1 mm/min were carried out on a Galdabini Sun 5 Universal Testing Machines to observe the mechanical response of the samples.

Microhardness tests with constant load of 500 grams and dwelling time equal to 15 s were performed on a Remet HBV 30, according to ASTM E384, to characterize the surfaces of the specimens.

In order to highlight the variation of the material microhardness values in the different areas of the sample, the useful section of each sample was divided into a grid of areas identified as 1,2,3 and 4, respectively, both for the frontal surfaces of the sample and for the lateral and transversal ones. In particular, in each of these surfaces five microhardness tests were carried out and the overall microhardness value, referred to each individual surface, was obtained as the average value of the above measurements. The used grid for microhardness measurement is shown in Fig. 3.

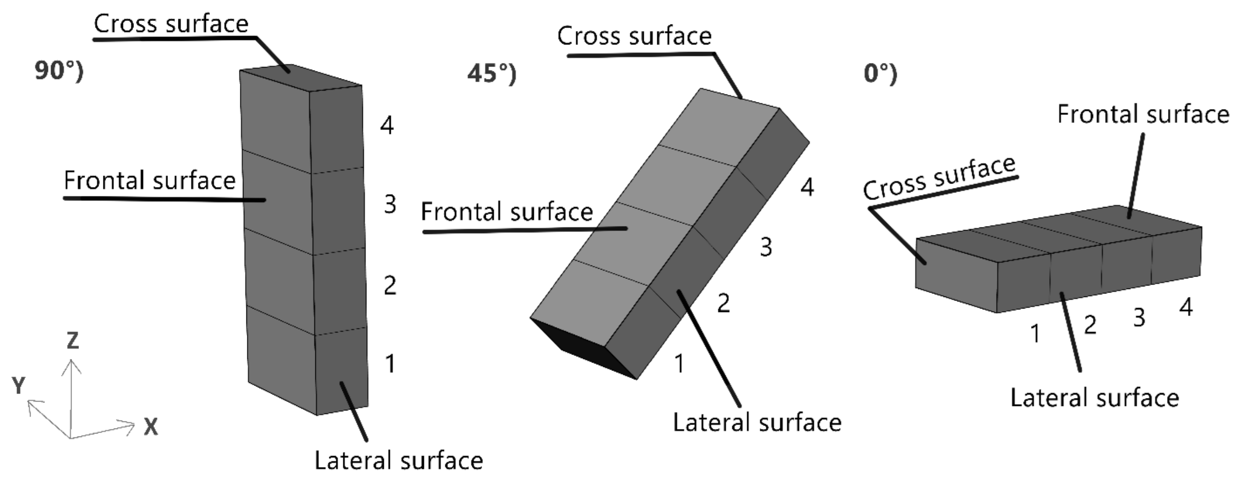


Figure 3. Schematic representation of 0°, 45° and 90° building orientation samples. Sub regions used for the microhardness tests are shown.

In order to evaluate the effect of building orientation on the final porosity of samples, a global evaluation method, using Archimedes' principle at room temperature, according to ASTM B962-08, was used. In this way the density of material was obtained. Each sample was weighed five times in air and afterwards, the same times in water. A Mettler Toledo balance with the accuracy of ±0.1 mg was used to evaluate the mass of the samples.

Results and Discussions

For a clear reading of the results obtained as a result of the tests of mechanical characterization of the samples as well as of porosity, it is first of all necessary to highlight that during the SLM printing process high cooling rates of the single deposited layer occur, leading to the formation of a metastable structure which is the martensite of type α' that normally constitutes the microstructure of the products made with SLM technology. However, it is also necessary to point out that during the SLM process, heat accumulation phenomena can occur [12]. These phenomena are generated by a decrease in thermal gradients as the different layers are made. Recalling also that the heat flows due to dissipation are oriented in the opposite direction to the building direction, i.e. from top to bottom, it is possible to identify two factors that affect the possibility of establishing the aforementioned phenomena of accumulation.

The first factor that affects the phenomenon of heat accumulation is related to the number of layers that are deposited for the overall construction of the piece. This factor is also closely related to the extension of the surface deposited for each layer. Therefore, slender samples tend to present phenomena of heat accumulation, while in the squat samples the thermal exchange with the building platform is more favored and therefore there is no relevant phenomena of heat accumulation. Another factor to be considered is the entity of the volume of material directly below the surface deposited for each layer, and therefore effectively involved in the phenomena of heat exchange from the top to the bottom.

With reference to the previous considerations, in the following the results of the mechanical tests performed in terms of tensile strength (UTS and ETF), microhardness and density are presented. The microhardness, tensile, and density test results for the three building orientations, 0°, 45°, and 90°, are shown in Fig. 4 and Fig. 5 below, respectively.

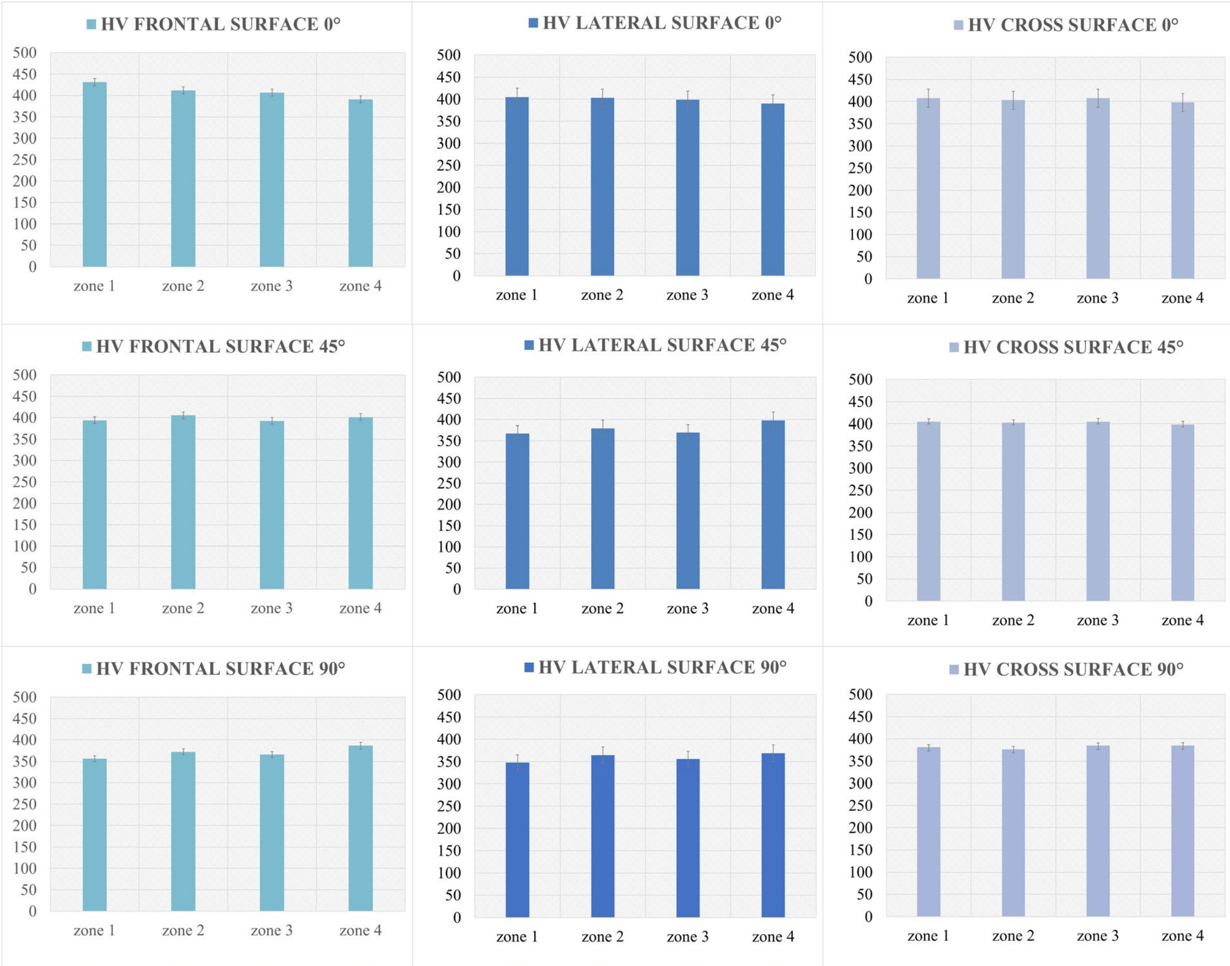


Figure 4. Microhardness test results for the 0°, 45° and 90° building orientation samples.

The samples made with building orientation equal to 0° showed the highest microhardness values, compared to the samples made with 45° and 90° orientations; in fact, microhardness values between a minimum of 390 HV and a maximum of 431 HV were detected. Moreover, the microhardness values detected in the frontal surface were higher than those detected in the lateral surface and cross-sections. In addition to this, a progressive, though small, decrease in microhardness values was observed going from zone 1 to zone 4 of the frontal surface of the samples, while in the cross-sections and lateral surfaces this decrease from zone 1 to zone 4 was very small.

The microhardness trends in both the samples made with 45° orientation and in the samples made with 90° orientation showed an opposite trend from the one observed for the samples made with 0° orientation. In detail, in both cases, increasing microhardness values were found in the transition from zone 1 to zone 4 both in the frontal and in the lateral surfaces, while almost constant microhardness values were observed in the transition from zone 1 to zone 4 in all cross sections. For the samples made with orientation equal to 45°, a minimum microhardness value of 368 HV and a maximum value of 405 HV were measured. For samples made with 90° orientation, a minimum microhardness value of 356 HV and a maximum microhardness value of 387 HV were measured.

Regarding the tensile strength values of the specimens made with the three different orientations, the maximum strength, in terms of UTS, was observed in the specimens characterized by a building orientation equal to 0° (1095 MPa), while decreasing tensile strength values were observed for the specimens made with building orientation equal to 45° (1004 MPa) and 90° (951 MPa), respectively. On the other hand, the result of the tensile tests in terms of ETF showed a moderate ductility for the samples made with 0° orientation (ETF = 7%), while the maximum ductility value was observed for the samples made with 45° orientation (ETF = 9%). An intermediate value of ductility was obtained for the specimens made with orientation equal to 90° (ETF = 8%).

The aforementioned trends of the microhardness values, in the samples made with 0° orientation, denote the prevalence of thermal phenomena for which a rapid cooling of the different deposited layers is active with respect to possible thermal accumulation phenomena that can be established. In fact, the rapid cooling produces high values of microhardness coupled with high values of tensile strength, although it gives rise to low values of material ductility.

In order to understand the microhardness trends, observed for the samples made with orientations equal to 45° and 90°, it is necessary to point out that, for these samples, the transition from zone 1 to the subsequent zones, indicated as 2, 3 and 4, corresponds to a progressive increase in the number of layers deposited one on top of the other. Therefore, the decrease of the microhardness values in the transition from zone 1 to zone 4 is an indication of the establishment of heat accumulation phenomena that prevail over the phenomena of rapid thermal exchange from top to bottom in the opposite direction to the building direction. The ductility values observed in terms of ETF also suggest a prevalence of phenomena that promote a decrease in thermal gradients, as successive layers are made, for specimens made at 45° orientation.

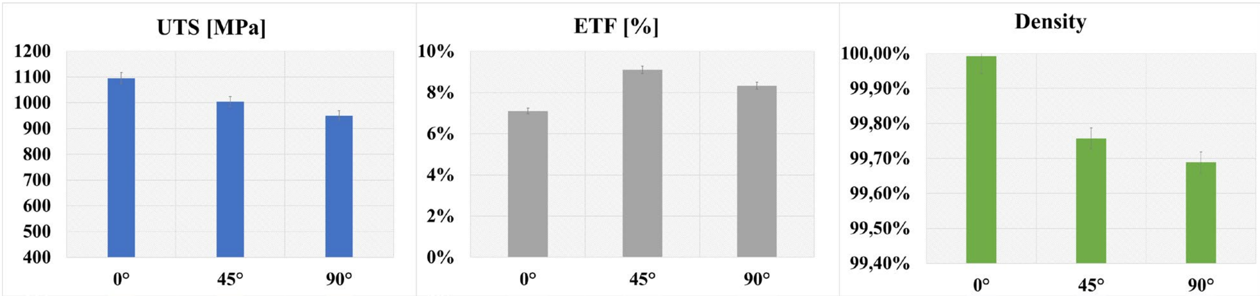


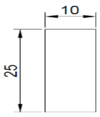
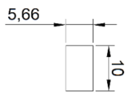
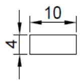
Figure 5. Ultimate Tensile Strength, Elongation To Failure, and Density value for 0°, 45° and 90° building orientation samples.

The density values measured for samples with 0° orientation were the highest and equal to 99.91%. On the other hand, decreasing density values were measured for samples produced with orientations equal to 45° (99.76%) and 90° (99.69%). These decreasing values denote the activation of lateral thermal flows following the occurrence of thermal accumulation phenomena that reduce the thermal exchange from top to bottom through the volume of solid material below the surface deposited in each layer. Such additional lateral thermal fluxes, through the powder surrounding the sample during the printing process, result in the appearance of lack-of-fusion porosity defects leading to the observed reduction in material density [13].

Following these evaluations, the geometric and deposition parameters useful for identifying the existence of significant heath accumulation phenomena were defined and measured, such as to produce the highlighted trends in terms of mechanical characteristics and density of the material.

The synthesis of the defined and measured parameters is reported in Tab. 2. Specifically, it has been considered that the phenomena of heat accumulation are directly related to the time of surface exposure to the laser, for each deposited layer, therefore it has been evaluated such time ($t_{surface\ exposure\ time}$) as the ratio between the deposited surface (S) and the product between the scan rate and the hatch spacing. The above-mentioned phenomena of heat accumulation are also favoured by a slim geometry of the sample, that is, with a height (H_{max}), relative to the solid material directly below the deposited surface, which prevails over the dimensions of the deposited section. It was then evaluated the ratio between the height of the sample and the extension of the deposited surface in each layer (H_{max}/S). Finally, it was considered that the phenomena of heat accumulation are mitigated in samples characterized by a volume (V) of solid material directly involved in thermal exchange from top to bottom, and therefore directly underlying the deposited surface, is higher. With reference to the above considerations, the HA (Heat Accumulation) parameter has been defined as the product of the factors that favour the phenomenon ($t_{surface\ exposure\ time} \times H_{max}/S$) divided by the value of V, as a factor that hinders the occurrence of the phenomenon.

Table 2. Characteristic geometrical and deposition parameters used in this study.

Geometric and deposition parameters considering the cross-section of the built direction							
Building orientation	**S = deposited Surface for each layer [mm²]**	**Deposited surface geometry**	**V = Volume [mm³]**	**H_{max} [mm]**	**$t_{surface\ exposure\ time}$ = S/(*scan rate × hatch spacing)* [s]**	**H_{max}/S [mm]**	**HA = Heat Accumulation parameter = 1000×($t_{surface\ exposure\ time}$ × H_{max}/S)/V**
0°	250		1000	4	1,488	0,016	0,0238
45°	56,6		160,1	5,66	0,337	0,100	0,2105
90°	40		1000	25	0,238	0,625	0,1488

The above product was also multiplied by 1000 to obtain a significant parameter display for the three different orientations. The trend of the parameters promoting the establishment of accumulation phenomena, as well as the HA parameter are shown, as the orientation of the sample changes, in Fig. 6.

In the above figure it is possible to highlight how the HA parameter, as defined, allows to identify for which geometries the phenomena of heat accumulation that usually affect the mechanical properties of the material producing lower tensile strength and microhardness, coupled with an increase in the ductility of the material, are more active. Specifically, the samples made with an orientation equal to 45° are subject to greater phenomena of heat accumulation.

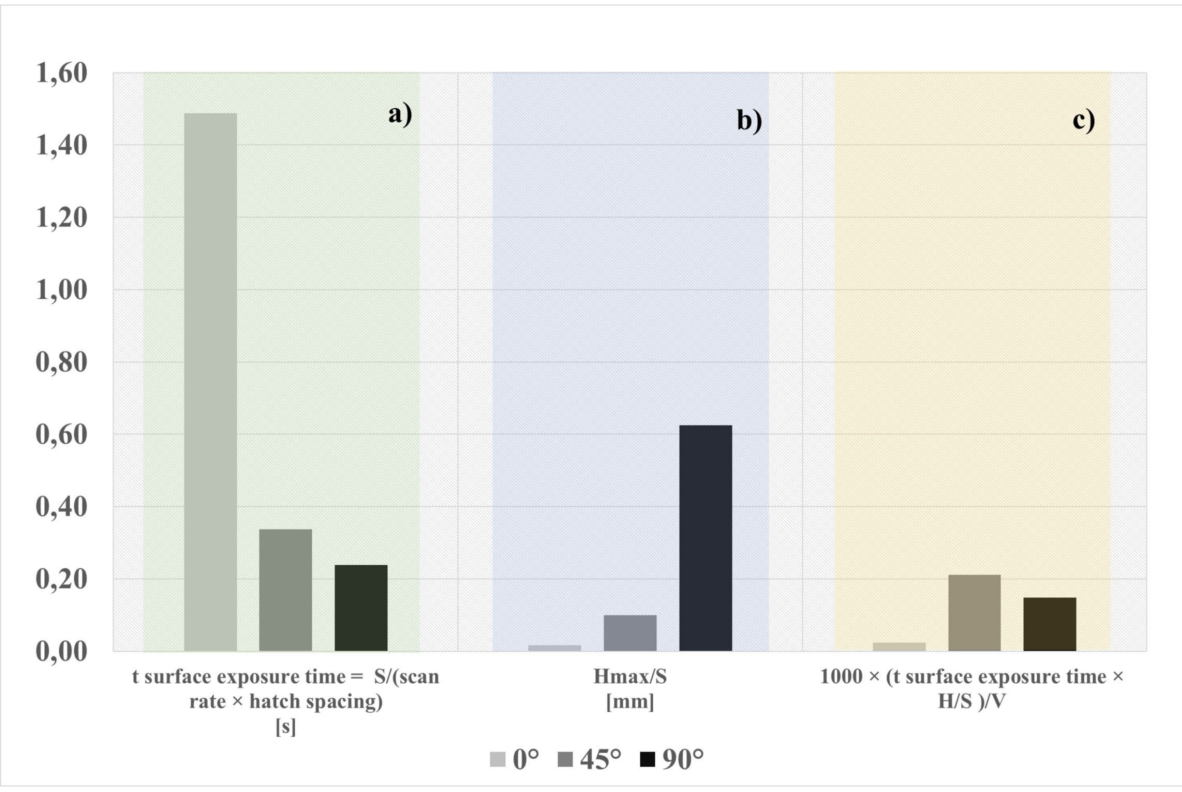


Figure 6. Heat accumulation parameters for 0°, 45° and 90° building orientation samples. a) $t_{surface\ exposure\ time}$ parameter, b) H_{max}/S parameter, c) HA parameter.

Significant heat accumulation phenomena, although less than in the previous case, are also present in the samples made with 90° orientation. For the samples produced with orientation equal to 0° only marginal effects of heat accumulation have been found.

The HA parameter, as defined, therefore allows the identification of the occurrence of heat accumulation phenomena both when the geometry of the sample and its orientation vary.

Conclusions

In the present work, the effect of building orientation on the mechanical properties (UTS, ETF and HV) and density of the specimens made with the three orientations equal to 0°, 45° and 90°, in the case of samples for which the presence of the supports does not significantly influence the active thermal exchanges during the deposition process of the successive layers, was studied. The main key findings are reported below:

- The microhardness, UTS and ETF values, in the samples with 0° orientation, denote the prevalence of a rapid cooling of the different deposited layers respect to heat accumulation phenomena.
- The trends of mechanical characteristics (UTS, ETF and HV) and density for the samples made with orientation equal to 45° and 90° correspond to the occurrence of heat accumulation phenomena that prevail over the phenomena of rapid thermal exchange from top to bottom in the opposite direction to the building direction.
- Geometric and deposition parameters useful for identifying the existence of significant heath accumulation phenomena were defined and measured. The defined Heat Accumulation parameter (HA) allows to identify for which geometries are more active the phenomena of heat accumulation that usually affect the mechanical properties of the material producing lower tensile strength and microhardness, coupled with an increase in the ductility of the material. In the present case the samples made with an orientation equal to 45° showed greater heat accumulation phenomena.

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