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INFLUENCE OF PROCESS PARAMETERS IN ADDITIVE MANUFACTURING ON THE QUALITY OF PRODUCED METAL PARTS

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Abstract: *The paper presents the results of investigating the influence of different additive manufacturing parameters on the microstructural and mechanical properties of the produced metal specimens. Metal specimens were obtained by additive manufacturing (AM) on the PBF-LB machine in steel quality of X2CrNiMo17-12-2 (steel 316L). Visual examination, microscopic analysis, hardness tests and tensile tests were performed. Significant porosity as well as reduced elongation of tensile specimens was observed in specimens manufactured before parameter correction. After adjusting the process parameters i.e. reducing the laser power, scanning speed and hatch spacing, no porosity was observed. Moreover, improved mechanical properties were obtained, which meet the criteria for conventionally produced steel X2CrNiMo17-12-2 as defined by the standard SRPS EN 10088-3. This shows that the material properties of AM metal parts strongly depend on process parameters. In order to ensure a high quality of AM metal parts, it is necessary to perform material characterization (structural and mechanical testing of specimens) after every parameter adjustment.*

Keywords: *powder bed fusion - laser beam, additive manufacturing process parameters, material characterization, 316L steel, porosity*

1. INTRODUCTION

Additive manufacturing (AM) enables the creation of complex geometries that are often unattainable through traditional manufacturing methods, offering benefits such as reduced part numbers, lightweight structures, and advanced performance characteristics [1, 2]. The market for AM has grown remarkably in the last years, with projections suggesting an increase from approximately $4 billion in 2014 to over $23 billion by 2026 [2].

One of the most prominent AM techniques for producing metal parts is Powder Bed Fusion - Laser Beam (PBF-LB), also referred to as Laser Powder Bed Fusion (L-PBF) and Selective Laser Melting (SLM). This process uses a high-power laser to melt and fuse metallic powders layer by layer, facilitating the creation of intricate and high-precision components [3, 4]. Industries such as aerospace have already adopted PBF-LB for serial production due to its ability to produce parts with high efficiency and material conservation [1, 3].

The process parameters in PBF-LB, including but not limited to laser power, scanning speed, layer thickness, and hatch distance, have a strong influence on the quality of the final product [3, 4, 5]. The mechanical properties of parts manufactured through PBF-LB are highly influenced by these process parameters. Studies have shown that variations in parameters such as laser energy density and scanning strategies can significantly affect the porosity and hardness of the produced parts [3, 4]. For instance, Shin et al. [4] found that optimizing laser energy density is essential to minimize porosity and enhance the mechanical properties of stainless steel 316L parts.

Despite the advancements in PBF-LB, metallurgical defects such as porosity, lack of fusion, spatters and partially melted particles on the parts' surface, cracks,

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balling, loss of alloying elements and residual stress remain challenges that can compromise the integrity of the manufactured parts. These defects arise due to the rapid melting and cooling cycles inherent in the PBF-LB process. [3, 4, 5].

As it was previously shown by Röttger et al. [6], the process parameters optimized and provided by different machine manufacturers can greatly vary from each other, leading to statistically significant variability in mechanical properties and the extent of metallurgical defects in the parts processed by different PBF-LB machines. Effective quality control measures, including process monitoring and thorough material quality investigation after manufacturing, are essential to mitigate these issues and ensure consistent part quality.

2. EXPERIMENTAL WORK

2.1 Material and methods

A commercially available PBF-LB machine was used to produce two identical sets of samples made of stainless steel 316L. For this, two different sets of process parameters were applied – parameter set I and parameter set II – with the respective default scanning strategies. Both parameter sets were as defined by the machine manufacturer and are proprietary information. The adjustments applied to the parameter set II in comparison to the values in the parameter set I were as following: hatch distance was reduced by ~30%, and laser power as well as scanning velocity was reduced by ~10%. Nitrogen was used as the shielding gas in both manufacturing processes, and both processes were performed using the powder from the same metal powder batch. The manufacture process in both trials was conducted as any commercial AM supplier would operate, i.e., according to the user manual instructions of the PBF-LB machine.

For parameter set I, three vertically oriented square bars were manufactured in order to investigate the tensile properties. A smaller sample was also manufactured for microstructure analysis and hardness measurement.

The manufactured parts using parameter set II was expanded in comparison to the set I parts by adding three horizontally oriented square bars to the build, in order to investigate the anisotropy of mechanical properties. A schematic of the sample orientation on the base plate is shown in Fig. 1.

Visual examination of the manufactured parts was performed after wire-cutting the bars from the base plate by naked eye and magnifying glass as well as by Leica stereo microscope equipped with DFC 245 camera, and was documented with photographs.

In order to verify compliance with the material designation of stainless steel X2CrNiMo17-12-2 / SRPS EN 10088-1 (equivalent to steel designation AISI 316L) [7], the chemical composition of the manufactured parts was analyzed by Optical Energy Spectrometer (OES) Belec Compact Port.

Hardness was measured by Brinell method (HB 2,5/187,5), according to SRPS EN ISO 6506-1 [8].

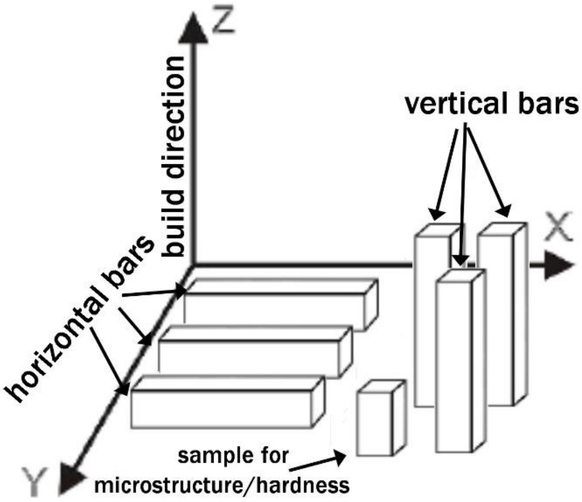

Figure 1. Schematic of the orientation of parts manufactured using parameter set II.

The manufactured square bars were machined to produce cylindrical tensile test specimens. Tensile tests were performed in accordance with SRPS EN ISO 6892-1 [9]. The L_0 length of the short proportional cylindrical tensile specimen was 25 mm at a specimen diameter of 6 mm. The tensile test was performed using a constant speed of 5 mm/min.

In order to examine the microstructure, the appropriate samples were prepared by grinding, polishing and etching using a solution of 65% HCl and 35% HNO_3. The polished and etched surfaces were examined using light microscopy. Microstructure was examined both on surfaces parallel and perpendicular to the build direction.

3. RESULTS

3.1 Visual examination

The lateral surface of the bars manufactured using the parameter set I were visibly rougher than those made applying the parameter set II. Upon looking at the lateral surfaces under the stereo microscope, it was observed that the surface of parameter set I specimens was less uniform, with zones of coarse spherical particles, Fig. 2a. Such coarse zones were not observed at parameter set II specimens, Fig. 2b.

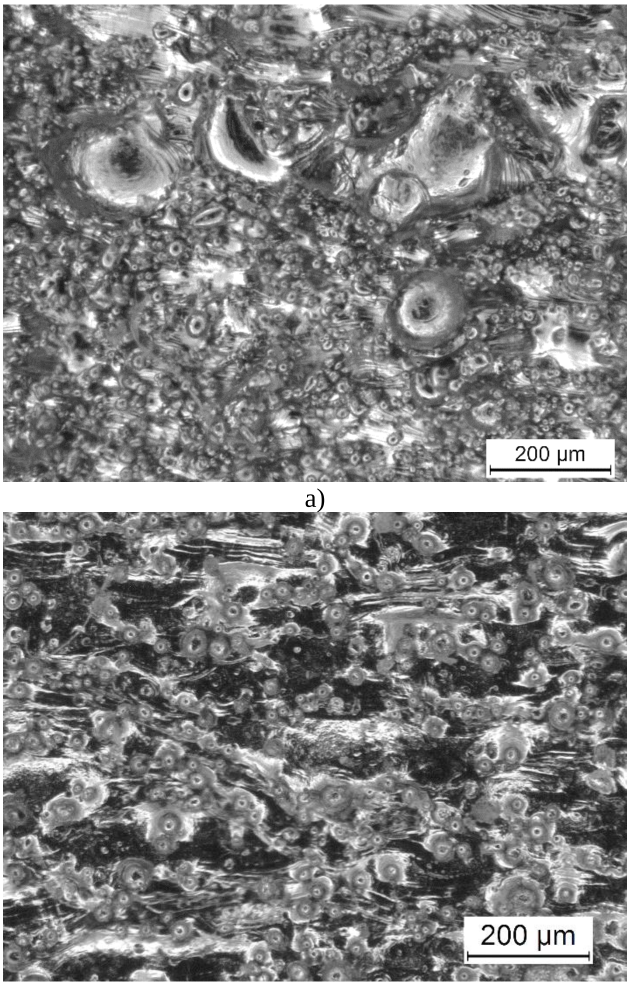

Figure 2. Lateral surfaces of manufactured bars using (a) parameter set I and (b) parameter set II.

3.2 Chemical composition

The chemical composition of the additively manufactured parts is given in Table 1.

Table 1. Chemical composition of the manufactured parts.

Element	*Set I, mass. %*	*Set II, mass. %*
C	0.02	0.02
Si	0.52	0.51
Mn	0.65	0.80
P	0.033	0.044
S	0.004	0.008
Cu	0.21	0.19
Cr	16.73	17.51
Mo	2.44	2.38
Ni	11.20	10.69
V	0.04	0.08
Co	0.07	0.12

Results showed that chemical composition of the additively manufactured parts is in accordance with the chemical composition of stainless steel X2CrNiMo17-12-2 as required by the standard SRPS EN 10088-1 [7].

3.3 Hardness

Results of hardness measurements of the manufactured samples are given in Table 2.

Table 2. Hardness of the manufactured samples, HB

specimen	**Hardness, HB 2.5/187.5**			**average**
set I	216	216	220	218
set II	224	221	226	224

3.4 Tensile properties

The average values of the modulus of elasticity (E), yield strength (YS), ultimate tensile strength (UTS) and elongation (A_5) observed during tensile testing of specimens are shown in Table 3. Characteristic stress-strain diagrams are shown in Fig. 3. The diagrams indicate that the fracture of parameter set I specimens occurs immediately after reaching the maximum force, with almost no post-uniform elongation observed. The values of tensile properties are lower for parameter set I specimens when comparing to the specimens made using parameter set II in the same orientation.

Table 3. Results of tensile tests.

specimen	**E [GPa]**	**YS [MPa]**	**UTS [MPa]**	**A_5 [%]**
set I vert.	172	410	571	28.3
set II vert.	221	508	628	52.6
set II horiz.	247	585	694	44.4

3.5 Microstructure

Upon polishing the samples, pores within the material visible to the naked eye were observed on the specimens made using parameter set I, Fig. 4a. Fig. 4b-c shows the microstructure of the specimens made using parameter set I as polished. Large pores, some of which were up to 500 µm in length were observed, as well as many smaller pores with a length up to 50 µm. Large pores were not observed on polished samples made using parameter set II, instead a small number of fine spherical gas pores was spotted, Fig. 5a.

Fig. 4d-f and Fig. 5b-e show the microstructure of samples made using parameter set I and II, respectively, as etched. On all samples it was observed that the structure on the macro-scale consists of clear solidification tracks, Fig. 4d-e and Fig. 5b-d. On the micro-scale, a fine cellular substructure was revealed, Fig. 4f, and 5e. Instances of grains crossing solidification track boundaries are also noticeable on all analyzed samples, Fig. 4d, and 5d.

On the parameter set I samples it was observed that porosity mostly occurs between solidification tracks in the material. Crack formation starting from porosity and following the solidification track boundary between layers was also observed, Fig. 4d.

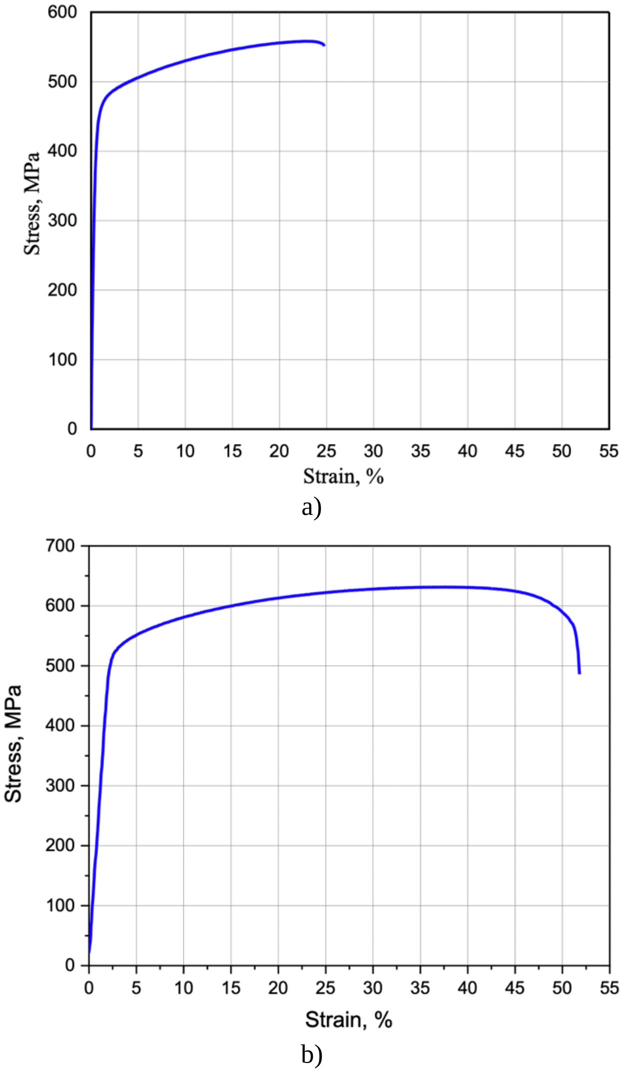

Figure 3. Characteristic stress-strain curves of vertical tensile specimens made using (a) parameter set I, (b) parameter set II.

4. DISCUSSION

The appearance of spherical particles embedded on the lateral surfaces of the set I samples has been attributed to the balling phenomenon. The balling defect arises due to the interplay between surface tension and wettability, which significantly influence the molten melt pool's formation [3]. When individual melt tracks fail to properly coalesce with the substrate, the surface tension causes the molten material to contract into spherical shapes, leading to balling. Additionally, inadequate wetting of remaining solid particles and the underlying substrate, often due to surface impurities, exacerbates this defect. The balling defect is considered as a severe process defect in PBF-LB manufacturing, and often leads to formation of pores, high surface roughness and reduced density of manufactured parts.

Results of chemical composition analysis showed that the composition of the manufactured parts is in accordance with the chemical composition of stainless steel X2CrNiMo17-12-2 as required by the standard SRPS EN 10088-1 [7], which is equivalent to stainless steel AISI 316L. This result shows that the metal powder retained its material designation after the manufacturing processes, indicating that no significant loss of alloying elements because of possible vaporization due to extremely high temperatures right underneath the laser beam occurred.

The hardness of both examined samples is in the range typical for 316L grade steel manufactured by PBF-LB process and is comparable to the hardness specified by the standard for semi-finished products made of this material in annealed condition [10].

Tensile tests showed that the specimens made using parameter set I have poorer mechanical properties than those made using parameter set II. This difference is the highest for elongation (28.3% in comparison to 52.6% for vertical orientation). The values of mechanical properties are significantly reduced in the presence of metallurgical defects, namely pores, cracks or lack of fusion [4, 5, 6]. Therefore, the lower values of the modulus of elasticity, strength, and elongation, as well as the lack of post-uniform elongation of set I specimens, have been attributed to the extensive presence of macroscopic and microscopic defects throughout the material.

The results of the tensile testing also showed that the set II specimens prepared from vertical bars have a lower strength, modulus of elasticity and elongation than the horizontal bars specimens. It has been previously established that parts produced by layer-by-layer manufacturing can exhibit an anisotropy of mechanical properties [5]. Defects such as inclusions, oxidations, melting defects and pores are more prevalent at the interface between layers, and act as stress concentrators. In vertically built tensile specimens, these layer boundaries are perpendicular to the loading direction, which causes earlier yielding and lower strength and elongation values in comparison to horizontally built specimens. Nonetheless, it is worth noting that the mechanical properties of both vertically and horizontally oriented set II specimens meet the criteria for conventionally manufactured semi-finished products made of steel X2CrNiMo17-12-2, as defined by the standard SRPS EN 10088-3 [10].

Microstructural analysis revealed significant porosity in the parts manufactured using parameter set I. The irregular shape and large size of these defects indicates that their cause is insufficient fusion, which occurs when the liquid metal does not adequately penetrate the previously solidified layer and results in poor metallurgical bonding [3].

The solidification tracks revealed after etching represent melt pools that were generated by the scanning laser beam during manufacturing. The appearance of grains crossing melt pool boundaries can be explained by formation of new grains by epitaxial growth: the previously solidified layer experiences partial remelting during the melting of a newly coated powder layer; this in turn makes it possible that the new layer solidifies by maintaining the same crystallographic orientation of the nearby grains [5].

The observed formation of a cellular substructure in all examined samples is characteristic for PBF-LB process and is primarily driven by rapid solidification rates and high thermal gradients. These conditions promote the development of cellular dendrites within the microstructure, characterized by fine, columnar grains. This cellular substructure enhances the mechanical properties of the steel by refining the microstructure [3, 5, 6].

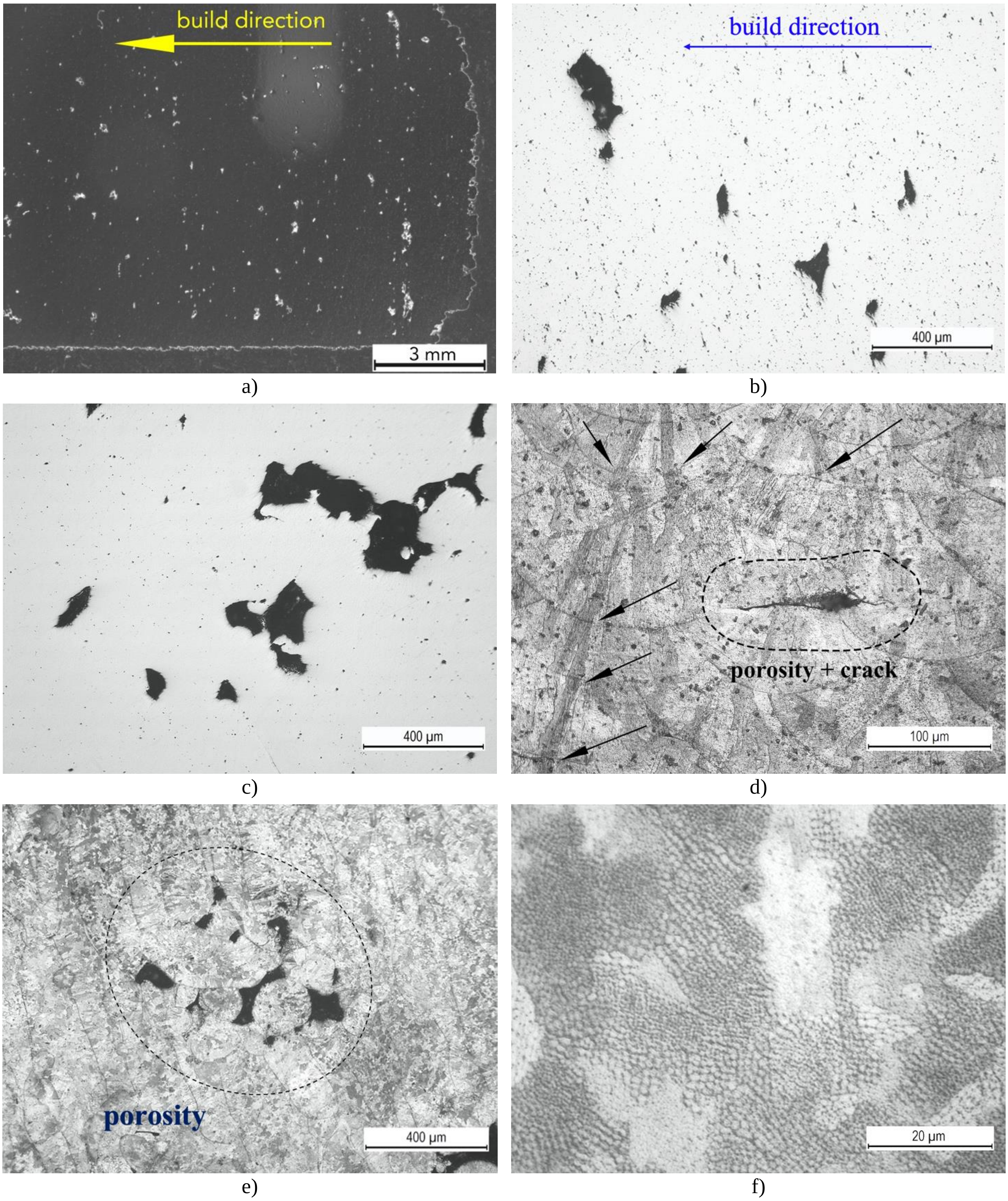

Figure 4. (a) Polished set I sample, as observed under stereo microscope. White areas represent macroscopic pores within the material. (b-c) Microstructure of the set I sample as polished. Observed are surfaces (b) parallel and (c) perpendicular to the build direction. Large and small pores are visible as dark spots. (d-f) Microstructure of the set I samples as etched. Observed are surfaces (d) parallel and (e) perpendicular to the build direction. Epitaxial grain growth is marked with arrows. (f) Cellular substructure revealed at higher magnifications.

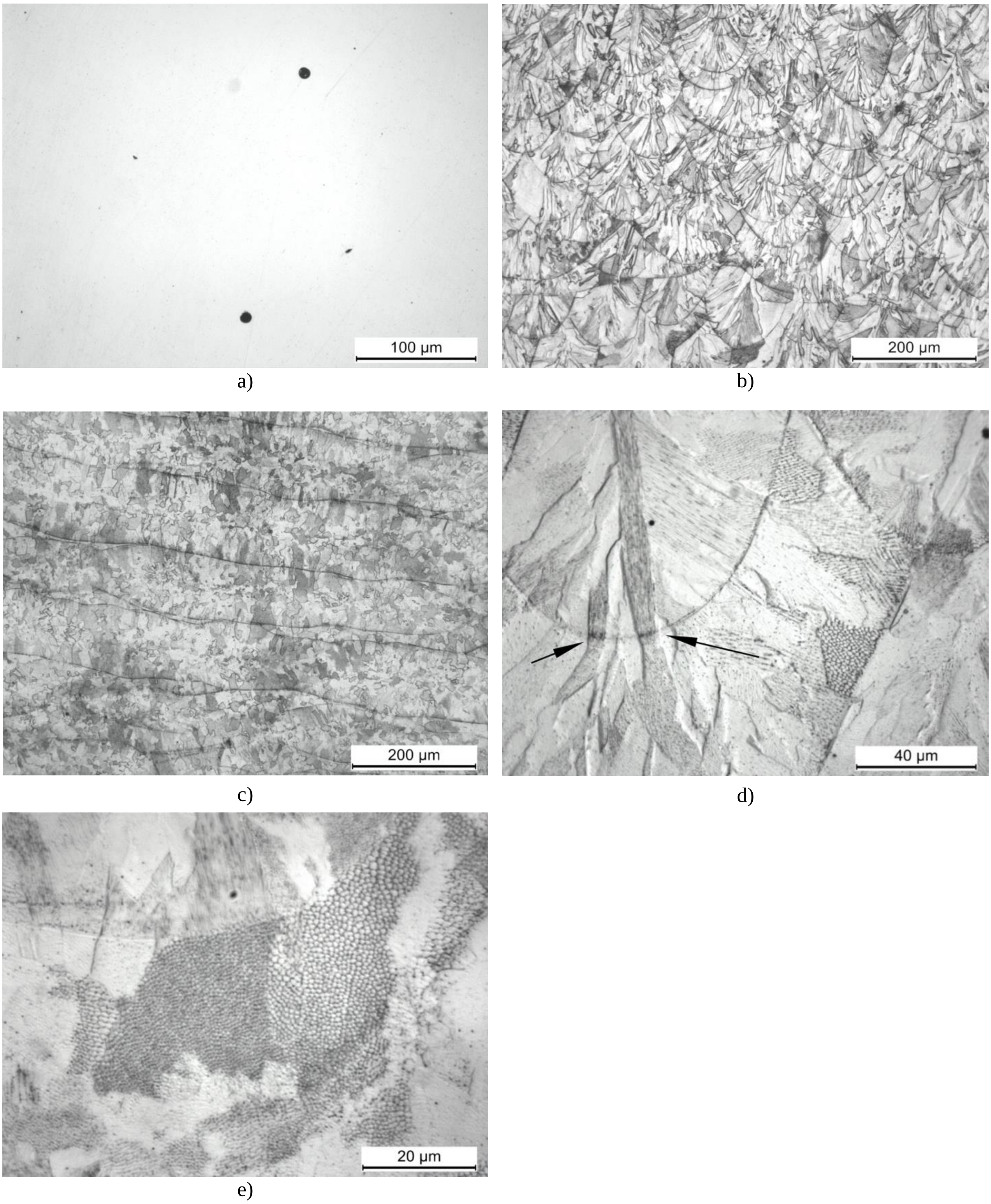

Figure 5. (a) Microstructure of the set II samples as polished, observed on a surface parallel to the build direction. The dark spots represent small gas pores. (b-e) Microstructure of the set II samples as etched. Observed are surfaces (b, d, e) parallel and (c) perpendicular to the build direction. Epitaxial grain growth is marked with arrows. (e) Cellular substructure revealed at higher magnifications.

It was observed that the porosity in set I samples mostly occurs between solidification track layers, which as discussed previously is intrinsic to the layer-by-layer manufacturing process. In the set II samples, no insufficient fusion defects and only a very small amount of gas pores were detected, and their presence is considered to not have a significant impact on the material quality.

5. CONCLUSION

This study highlights the significant impact of process parameters on the quality of stainless steel X2CrNiMo17-12-2 (AISI 316L) parts fabricated using Powder Bed Fusion – Laser Beam (PBF-LB). Key findings include:

1. The balling defect, considered a severe defect in the PBF-LB process, is observed in samples produced using parameter set I. This defect contributes to high surface roughness and possibly to porosity.

2. Chemical composition analysis confirmed the retention of alloying elements in the manufactured parts, ensuring compliance with the required material designation of stainless steel X2CrNiMo17-12-2.

3. Samples made using parameter set I exhibited poorer mechanical properties, particularly elongation, compared to those made using parameter set II. This reduction is due to the presence of metallurgical defects such as pores, cracks, and lack of fusion defects.

4. Anisotropy of mechanical properties was observed, with vertically built specimens showing lower strength, modulus of elasticity, and elongation than horizontally built specimens.

5. Significant porosity due to insufficient fusion was found in parts manufactured with parameter set I, while set II samples showed minimal defects, indicating better overall quality.

In conclusion, parameter set II demonstrated a significant improvement in mechanical properties and reduced defect prevalence compared to set I. It was shown that additive manufacturing of metal components using process parameters provided by the machine manufacturer does not guarantee defect-free parts. Material characterization (including microstructural examination and mechanical testing of specimens) must be conducted after setting up the AM machine and after each parameter optimization in order to ensure high-quality AM metal parts. Optimizing PBF-LB process parameters is crucial for minimizing defects, ensuring material integrity, and achieving desired mechanical properties in metal components. Future research should focus on further refining these parameters and exploring advanced post-processing techniques to enhance the performance and reliability of PBF-LB-manufactured parts.

Acknowledgement

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