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STUDY OF THE INFLUENCE OF ROUGHNESS ON THE MECHANICAL PROPERTIES OF STAINLESS STEEL SAMPLES MADE BY THE LPBF TECHNOLOGY

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ABSTRACT

In the modern additive manufacturing of parts, the LPBF method has become widespread, which implies the technology of laser melting of a metal powder layer, that significantly expands the possibilities for optimizing the geometry of products. For parts manufactured using the traditional method (casting, deformation), it is known that the surface roughness can significantly affect the level of mechanical properties, since protrusions and depressions are stress concentrators. Parts manufactured using additive manufacturing technologies have an increased roughness, but their structural state after manufacturing is significantly different from traditional metal. It is often necessary to operate without subsequent mechanical surface treatment of products manufactured by the LPBF method. In the work the effect of roughness, the presence or absence of mechanical treatment of the working area of the samples on the mechanical properties under static tension conditions was determined. From the analysis of the profilometric curve and microstructure, it was found that samples without mechanical treatment have periodic protrusions, which is related to the texture formed during the manufacture. The average values of the mechanical properties do not differ significantly (less than 6.6 % for various characteristics) depending on the presence or absence of mechanical treatment, but deviations from the average within the sample regarding the values of tensile strength and reduction in area for samples without mechanical treatment are many times larger compared to the interval of value fluctuations within the sample for samples with mechanical treatment.

KEYWORDS: LPBF technology, roughness, stainless steel, mechanical properties

INTRODUCTION

As manufacturing processes continue to improve and develop, the demand for more rapid and less expensive manufacturing processes has led to the development of a number of rapid prototyping (RP) processes. Using additive manufacturing, almost any geometry with variations in size and complexity can be produced with a high degree of accuracy [1, 2]. The main limitation for the manufacture of parts with the methodology of topological optimization applied to them, which may contain internal channels of complex configuration, technological holes and removal of non-working elements to reduce weight, is the complexity of their final mechanical treatment due to their small size (e.g., holes, channels), geometric design features and the inability to bring the tool to a part. These complications necessitate designing of a CAD-model that takes into account and predicts manufacturing processes and features to prevent surface geometry defects in the finished product (e.g., incomplete fusion of holes) that cause their impassability during the process of manufacturing, etc.

Many researchers have considered the issue of final surface treatment of a part [2–5], the so-called post-treatment of parts by chemical, electrochemical and physical effects, which allows achieving the required surface roughness or cleaning as an alternative to mechanical treatment or as an intermediate one before further mechanical treatment. However, it should be noted that achieving the required surface roughness by these methods has a number of disadvantages, which were mentioned in [6–10], namely: loss of geometric parameters in the areas of a part with protruding edges, which is associated with more intensive electrochemical polishing processes in this area [10–11]; the presence of intergranular corrosion formation in the Down-skin areas; insufficient cleaning due to sintering of powder particles in the melting processes in the zone of metal-powder interaction during manufacturing.

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Table 1. Actual chemical composition of 316L steel powder, wt.% [13]

C	Mn	Si	S	P	Cr	Ni	Cu	Mo
0.016	0.78	0.64	0.005	0.008	17.79	12.63	0.04	2.35

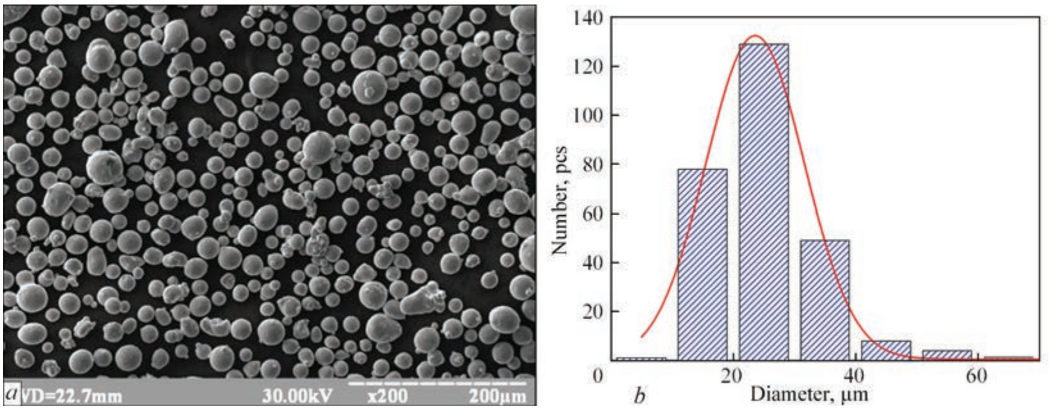

Figure 1. Particles of the source material of 316L powder at ×200 magnification (*a*) and the results of granulometric analysis (*b*) [13]

The results of studies [7–11] indicate that the roughness level of standard testing samples significantly affects the values of the final mechanical properties. This is even reflected in the standard technical documentation as requirements for the maximum allowable roughness of testing samples. However, it should be noted that this conclusion was made in relation to testing samples made by the traditional manufacturing method. This is mainly associated with the fact that in the technological processes of manufacturing testing samples using the traditional manufacturing method, there may be defects in the form of inconsistencies and inclusions: pores, cracks, carbides, nitrides, intermetallic phases, Laves phases, etc. that have a negative impact on the final mechanical properties, in addition to surface roughness. But, as is known from studies [12], mainly due to the rather high density of samples manufactured by the LPBF technology, namely 99.7–99.9 %, and taking into account the peculiarities of the processes of crystallization and the formation of an unbalanced highly dispersed structural state at high cooling rates, it was found that the conditions of the required roughness can be neglected, since the presence of elevated roughness may not have a significant effect on the final mechanical properties without the presence of a high rate of defects or deviations from the typical structure for parts made by the LPBF technology.

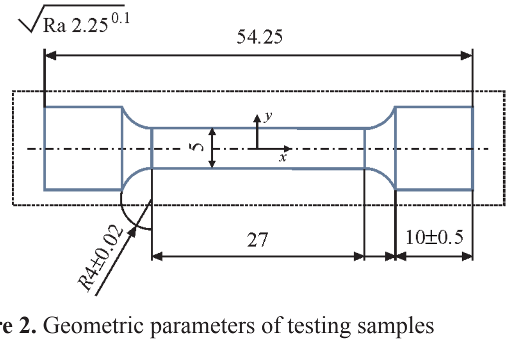

Figure 2. Geometric parameters of testing samples

Based on the above, the study of the influence of roughness on the final mechanical properties is an important issue of materials science in additive manufacturing, since service properties can determine the final operational properties and the life of a part.

THE AIM

of this work is to study the effect of roughness of 316L stainless steel samples made by the LPBF technology on mechanical properties under static tensile conditions.

MATERIAL AND RESEARCH METHODS

In this work, tensile testing samples in the working area without and with mechanical treatment were investigated, fabricated in the Alfa-150D 3D printing machine manufactured by ALT Ukraine LLC with a 150×150 mm printing area equipped with an ytterbium laser with a wavelength of 1064 nm, the protective medium is argon gas circulating in the working chamber.

The samples were manufactured in the vertical direction with a working zone diameter of 5 and 6 mm (with an allowance for subsequent mechanical treatment) and a working zone of 25 mm length. The rational printing parameters that allowed obtaining a density of the finished product of 99.9 % were as follows: thickness of the deposited layer 40 μm, distance between tracks 0.1 mm, power 220 W, beam speed 1070 mm/s, scanning strategy — staggered fields 2.5×2.5 with a rotation angle of 67° relative to the previous layer [13] from metal powder of 316L austenitic steel with the actual chemical composition presented in Table 1, whose particle size analysis is shown in Figure 1. The selected material mainly consists of austenite and is not prone to the formation of

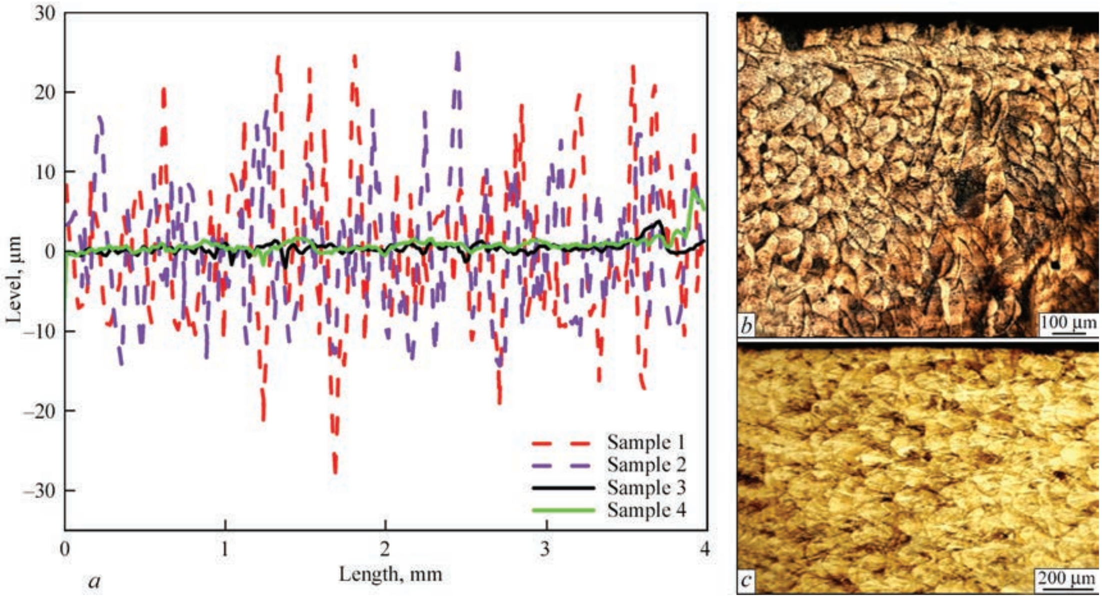

Figure 3. Profilometric surface curves of testing samples (*a*) and microstructure of testing samples 1 (*b*) and 3 (*c*) before tensile tests: 1, 2 — without mechanical treatment; 3, 4 — with mechanical treatment

an intermetallic phase as a result of short-term heating and cooling during heat treatment.

The samples were machined to final dimensions (Figure 2) using a HAAS ST10 lathe; five passes were made in the working area with a tool feed rate of 0.1 mm and a speed of 400 rpm.

Mechanical properties were determined by tensile testing using a standard method in an INSTRON machine. Roughness control was performed by two methods: using a DANA-260 roughness gauge and microstructural analysis in an AxioVert 200MMat optical microscope using specialized software ImageJ.

RESEARCH RESULTS

As a result of evaluating the surface condition of testing samples, it was found that the roughness of samples 1 and 2 without mechanical treatment in the working area was 24.41 μm (R_z) — 6.76 μm (R_α) and 24.56 μm (R_z) — 6.78 μm (R_α), respectively, the roughness of samples 3 and 4 after mechanical treatment was 2.28 μm (R_z) — 0.50 μm (R_α) and 2.26 μm (R_z) — 0.56 μm (R_α), respectively. Figure 3 shows the profilometric curves of the reference surface of 4 mm long testing samples and the surface microstructure of samples before testing.

From the analysis of the profilometric curve and microstructure (Figure 3, *a*, *b*), it was found that samples 1 and 2 without mechanical treatment have peaks at approximately equal distances from each other, which is associated with the texture formed during the crystallization of the base metal and local cyclic heating on the surface. These peaks and areas are the main stress concentrators during loading, which can lead to premature failure. Based on the results of the analysis of the curves of testing samples 3 and 4 (Figure 3, *a*, *c*), it was found that the roughness of these samples is insignificant, the range of fluctuations does not exceed the value of 4 μm. It can be assumed that the mechanical treatment properly levelled the surface of a testing sample without the presence of areas that could be stress concentrators during loading.

As a result of the tensile tests, stress-strain curves were obtained and the main mechanical properties were determined, which are shown in Table 2 and Figure 4.

From the analysis of the determined mechanical properties, it was found that in terms of average val-

Table 2. Results of determining the mechanical properties of samples made of 316 L stainless steel by the LPBF technology with different surface conditions of the working zone

Sample number	Condition	σ_t, MPa	Δ_{av}, σ_t, %*	$\sigma_{0.2}$, MPa	Δ_{av}, $\sigma_{0.2}$, %*	δ, %	Δ_{av}, δ, %*	ψ, %	Δ_{av}, ψ, %*
1	Without mechanical treatment	626.9	–2.3	561.6	–2.8	46.0	–1	66.3	+4,52
2		657.0	+2.29	594.0	+2.72	47.0	+1	60.4	–4,5
Medium		641,9	–	577.8	–	46.5	–	63.3	–
3	Mechanical treatment	677.9	+1.26	587.6	–1.56	43.9	+0.9	65.1	–0,07
4		660.7	–1.28	569.3	+1.57	43.0	–0.9	65.2	+0,07
Medium		669,3	–	578.4	–	43.4	–	65.15	–

Notes. Δ_{av}, $\sigma_t/\sigma_{0.2}$/δ/ψ is the deviation (%) from the average value within the sample.

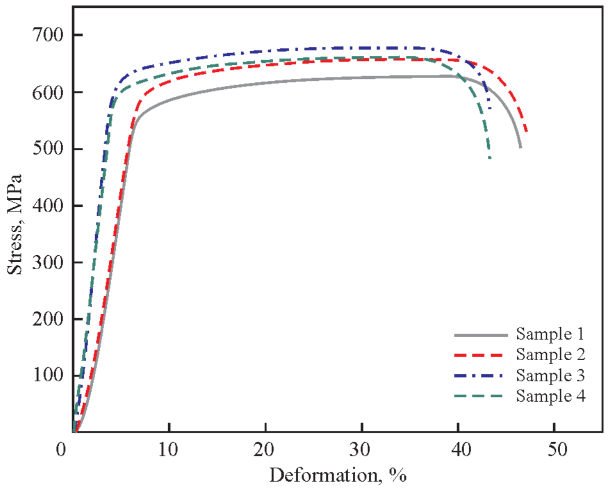

Figure 4. Stress-strain curves of 316 L stainless steel testing samples made by the LPBF technology with different surface conditions of the working zone: 1, 2 — without mechanical treatment; 3, 4 — with mechanical treatment

ues of samples 1 and 2, which were tested without preliminary mechanical treatment of the working zone, they have lower values of strength characteristics, namely: tensile strength — 641.9 MPa and yield strength 577.8 MPa, i.e. by 4.09 and 0.1 %, respectively, compared to samples with mechanical treatment of the working zone, namely: 669.3 and 578.4 MPa, respectively. However, it should be noted that the average values of the ductility indices varied in different directions: the average values of relative elongation (46.5 %) of testing samples 1 and 2 are 6.6 % higher, and the average values of reduction in area (63.3 %) are 2.8 % lower than the average values for samples 3 and 4, namely, relative elongation — 43.4 % and reduction in area — 65.15 %. These results for the ductility characteristics, namely: relative elongation and reduction in area are mainly associated with the opening and elongation of high roughness zones, as noted in [14–16].

The comparative analysis of the mechanical properties of testing samples 1 and 2 showed that samples which did not undergo the stage of mechanical treatment after manufacturing, have a deviation from the average value of ±2.5 % of the tensile strength and yield strength within the sample, and testing samples 3 and 4 have a deviation from the average value of ±1.4 %. From the analysis of deviations in the ductility characteristics, namely relative elongation from the average by groups, it was found that testing samples 1 and 2 without mechanical treatment have a spread of values in the range of ±1 %, while testing samples 3 and 4 have a spread of values in the range of ±0.9 %. As for the reduction in area, it was found that samples 1 and 2 have a range of deviations from the average of ±4.51 %, and samples 3 and 4 — ±0.07 %. Thus, it can be concluded that the average values of mechanical properties do not change significantly depending on the presence or absence of mechanical treatment, but it should be noted that the deviations from the average values of tensile strength and reduction in area for samples without mechanical treatment (1 and 2) in the middle of the sample are much larger compared to the range of fluctuations within the sample for samples with mechanical treatment (3 and 4).

CONCLUSIONS

1. It has been found that samples of 316 L steel made by the LPBF technology using rational technological parameters at a powder working layer thickness of 40 μm have a roughness of 24.41–24.56 μm (R_z); 6.76–6.78 μm (R_a); the surface profile has peaks at approximately equal distances from each other, which is associated with the texture formed during the crystallization process and local cyclic heating of the surface.

2. A comparative analysis of the mechanical properties determined on 316 L steel samples made by the LPBF technology revealed that the strength characteristics of samples with a working zone without mechanical treatment in the state after manufacturing have lower average values (tensile strength and yield strength are 4.09 and 0.1 % lower, respectively) compared to the average values of these characteristics determined on similar samples with mechanical treatment of the working zone. The average values of the ductility indices changed in opposite directions: the values of relative elongation of samples without mechanical treatment were 6.6 % higher, and the values of reduction in area were 2.8 % lower than the average values for similar samples with mechanical treatment.

3. The analysis of the mechanical properties of 316 L steel samples determined after tensile tests, which were manufactured by the LPBF technology, revealed that the spread of values within the sample relative to the average value of the yield strength and reduction in area is insignificant (1.0–2.5 %) regardless of the presence or absence of mechanical treatment. However, the deviations from the average values of the tensile strength and reduction in area for samples without mechanical treatment within the sample are many times greater compared to the range of fluctuations within the sample for samples with mechanical treatment.

REFERENCES

1. Khakbiz, M., Simchi, A. (2019) Optimization of powder injection molding process parameter for production SS316/TiC composite for biomedical application. *J. of Advanced Materials and Technologies*, 7(**4**), 1–10. DOI: https://doi.org/10.30501/jamt.2019.84282
2. Adjamskiy, S., Kononenko, G., Podolskyi, R., Badyuk, S. (2022) *Implementation of selective laser melting technology in Ukraine* [in Ukrainian]. Kyiv, Naukova Dumka. DOI: https://doi.org/10.15407/978-966-00-1856-3

3. Gu, D., Meiners, W., Wissenbach, K., Poprawe, R. (2012) Laser additive manufacturing of metallic components: Materials, processes and mechanisms. *Int. Mat. Rev*., **57**, 133–164. DOI: https://doi.org/10.1179/1743280411Y.0000000014
4. Wong, K.V., Hernandez, A. (2012) A review of additive manufacturing. *ISRN Mech. Eng*., **4**, 1–10. DOI: https://doi.org/10.5402/2012/208760
5. Brackett, D., Ashcroft, I., Hague, R. (2011) Topology optimization for additive manufacturing racket. http://utw10945.utweb.utexas.edu/Manuscripts/2011/2011-27-Brackett.pdf.
6. Gong, H., Rafi, K., Gu, H. et al. (2015) Influence of defects on mechanical properties of Ti–6Al–4V components produced by selective laser melting and electron beam melting. *Mater. Des*., **86**, 545–554. DOI: https://doi.org/10.1016/j.matdes.2015.07.147
7. Ashby, M., Mehl Medalist, R.F. (1983) Mechanical properties of cellular solids. *Metal. Transact. A*, **14**, 1755–1769. DOI: https://doi.org/10.1007/BF02645546
8. Lu, T.J., Stone, H., Ashby, M. (1998) Heat transfer in open-cell metal foams. *Acta Mater*., 46(**10**), 3619–3635. DOI: https://doi.org/10.1016/S1359-6454(98)00031-7
9. Evans, A.G., Hutchinson, J., Ashby, M. (1998) Multifunctionality of cellular metal systems. *Progr. Mater. Sci*., 43(**3**), 171–121. DOI: https://doi.org/10.1016/S0079-6425(98)00004-8
10. Adjamskyi, S.V., Kononenko, G.A., Podolskyi, R.V., Badyuk, S.I. (2023) Prospects for the application of electrochemical polishing of scaffold samples manufactured by additive technology. *Aviaciino-Kosmichna Tehnika i Tehnologiya*, **4sp2**, 76–81 [in Ukrainian]. DOI: https://doi.org/10.32620/aktt.2023.4sup2.10
11. Adjamskyi, S.V., Kononenko, G.A., Podolskyi, R.V., Badyuk, S.I. (2021) Study of electrochemical polishing efficiency of variable section samples with different roughness of steel AISI 316L, manufactured by technology of selective laser melting. *Aviaciino-Kosmichna Tehnika i Tehnologiya*, **2**, 66–73 [in Ukrainian]. DOI: https://doi.org/10.32620/aktt.2021.2.08
12. Herzog, D., Seyda, V., Wycisk, E., Emmelmann, C. (2016) Additive manufacturing of metals, *Acta Mater*., **117**, 371–392. DOI: https://doi.org/10.1016/j.actamat.2016.07.019
13. Adjamsky, S.V., Kononenko, G.A., Podolskyi, R.V. et al. (2023) Mechanical properties and microstructure of the 316L steel produced by different methods. *Powder Metallurgy and Metal Ceramics*, 62(**7–8**), 436–444. DOI: https://doi.org/10.1007/s11106-024-00405-9
14. Ronneberg, T., Davies, C.M., Hooper, P.A. (2020) Revealing relationships between porosity, microstructure and mechanical properties of laser powder bed fusion 316L stainless steel through heat treatment. *Mater. Des*., **189**, 108481. DOI: https://doi.org/10.1016/j.matdes.2020.108481
15. Yu, C.-H. (2022) *Anisotropic mechanical behaviours and thin-wall effects of additively manufactured austenitic alloys*. Linköping: Linköping University Electronic Press. DOI: https://doi.org/10.3384/9789179293154
16. Yu, C.-H., Peng, R.L., Lee, T.L. et al. (2022) Anisotropic behaviours of LPBF Hastelloy X under slow strain rate tensile testing at elevated temperature. *Materials Sci. and Eng.: A*, **844**, 143174. DOI: https://doi.org/10.1016/j.msea.2022.143174

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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