

## Verification of mechanical properties and surface topography of PH1 stainless steel samples obtained by selective laser melting

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### ABSTRACT

Nowadays, additive technologies are used to create physical models, prototypes, samples, tooling, and the production of plastic, metal, ceramic, glass, composite components, and components made of biomaterials. The greatest technological interest is the production of final parts from metal alloys. This paper presents the results of studies of the topography of differently oriented surfaces of PH1 stainless steel samples made using the method of selective laser melting. The surfaces were studied in the plane of construction, perpendicular to the platform, at angles of 45° and 135°. For each surface under consideration, the roughnesses Ra, Rz were determined and a profile was constructed. The findings showed high stability of the topography of the surface layer of the grown material. To confirm the quality of the obtained samples, they were synthesized and tensile tests were carried out. The established characteristics of the elastic modulus, the tensile strength and the corresponding deformations are consistent with the previously determined properties of samples grown using selective laser melting technology and datasheet specifications. According to the results of mechanical tests, the microstructure of the fracture surfaces of the samples was investigated. It is established that the destruction of samples under tension occurs by a viscous mechanism with the implementation of a combination of shear and pit-porous types of destruction. The study of the topography of differently oriented surfaces is carried out – in the plane of construction, perpendicular to it and at angles to the platform 45° and 135°. It is shown that the best surface quality corresponds to two planes – parallel and perpendicular to the plane of the construction platform. The average values of their roughness were Ra ~ 0.6 μm and Rz ~ 4 μm. The quality of the surfaces located at an angle is significantly inferior to the first two. A change in the surface quality depending on the angle of inclination was also observed.

**Keywords:** Metal alloys, Microstructure, Roughness, Mapping, Viscous fracture.

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### 1. Introduction

Today, one of the most promising production tools in modern industry is additive technologies (AT). Additive technologies are used to create physical models, prototypes, samples, tooling, and the production of plastic, metal, ceramic, glass, composite components, and components made of biomaterials [1-6]. The greatest technological interest is the production of final parts from metal alloys used in the aerospace industry, mechanical engineering, automotive, oil and gas industry, electronics, medicine and other industries. Selective laser melting (SLM) is one of the most advanced and popular technologies for 3D printing with metals. When manufacturing products using SLM technology, it is possible to reproduce complex geometric shapes, including internal cavities and channels, and with thoughtful design solutions –

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to achieve a minimum amount of mechanical processing and eliminate expensive tooling. SLM allows manufacturing products with a high level of detail [7-12].

For most power parts, the quality of the surfaces is extremely important, especially under the action of constant loads. [13-18] The destruction of materials, as a rule, begins precisely from the surface for the following reasons: (1) maximisation of stresses at the surface under the action of bending and torsional loads; (2) the development of various types of corrosion processes (chemical, electrochemical, gas, contact, pitting corrosion and fretting wear) as a result of the interaction of the material surface with an aggressive environment. It is known [19-25] that depending on the location of the part in the chamber, the printing mode, the type and the dispersion of the powder, the surface roughness can vary greatly. Studies of surface quality and mechanical characteristics were previously carried out for grown parts made of aluminium alloys [26-31], titanium alloys [32], steels [33-37], and intermetallic alloys [38]. However, they were performed relatively simplistically, considering for the most part only the roughness of the surface located in the plane of the construction platform. This work continues the research [39] and is devoted to studying the quality of differently oriented surfaces of stainless-steel samples obtained by selective laser melting.

Conducting such studies is of significant importance for industrial sectors, in which the method of selective laser melting has found its practical use to improve the mechanical properties and topography of samples of surfaces made of stainless steel. In particular, in recent years, 3D printing technology has become widely used, which allows creating three-dimensional prototypes of physical objects based on computer models created in the shortest possible time. The selective laser melting technique is one of the fundamental methods of this technology, representing the use of laser radiation for the gradual deposition of metal powders. In addition, it is actively and successfully used in the automotive industry, to optimise the topography of the surfaces of parts made of stainless steel [40-46].

In the field of modern technologies, the considered method of selective melting using laser technologies is one of the most effective production methods. Such methods have become widespread due to the development of technological solutions for accelerated prototyping of parts, since the end of the last century.

Such technologies allow creating prototypes and form models of future parts, fully functional samples, by using the technique of adding material in several layers, followed by their bonding together. Carefully performed studies of the microstructures of these samples allow for the conclusion that their physical and mechanical characteristics are in no way inferior to similar indicators of parts made by casting, while surpassing them in terms of porosity and volumes of third-party inclusions.

Subsequent research in this line would open up additional opportunities in the practical application of selective laser melting methods to improve the physical and mechanical properties of surfaces made of stainless steel, with a view to their further use in various branches of modern industry and technology [47-52].

## 2. Material and methods

The methodology of this study is based on the practical investigation of the properties of surfaces obtained using selective laser melting, while maintaining the specified angles of the samples relative to the platform. In addition, this study used the developments of researchers who considered similar issues as its theoretical basis. Such a combination of materials and methods contributes to the highest quality reflection of the practical results obtained during research and the generation of final conclusions, summing up the entire complex of research work.

A special place in this study is occupied by the efforts of foreign researchers who have studied the problems that make up the subject matter of this research paper and related to it. To obtain the highest quality picture of scientific research and an objective, comprehensive reflection of the information provided, all the developments of foreign authors have been translated into English. Thus, the methodological basis of this study was selected in strict accordance with its stated subject matter and formed to obtain the maximum objective final results. According to the results of the performed scientific experiments, statistical data were generated, submitted in the form of graphic and digital information reflecting the main stages of this study [53-58].

The study considered samples made of EOS Stainless Steel PH1 material by selective laser melting at the EOSINT M270 installation. The main parameters of the technological process: the laser power – 195 W, the laser spot diameter – 100 microns, the scanning speed – 700 mm/s. The samples were grown using supports.

To investigate the mechanical properties, standard ASTM E8 samples were made in the form of blades (Figure 1a) for tensile tests. To investigate the roughness of various surfaces, samples of complex geometric shape were grown (Figure 1b), which represent structurally similar samples with a V-neck under  $45^\circ$ . The number of synthesised samples of each type – 3 [59-65].

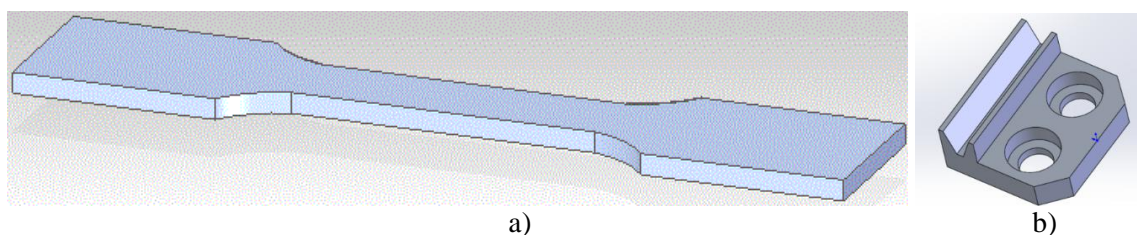


Figure 1. Tensile test sample (a), structural specimen (b)

The main part of the layout of the samples is shown in Figure 2. After printing, the samples were placed together with the platform in a Nabertherm N41/H chamber furnace and annealed at a temperature of  $482^\circ\text{C}$  for 180 minutes [66-69].

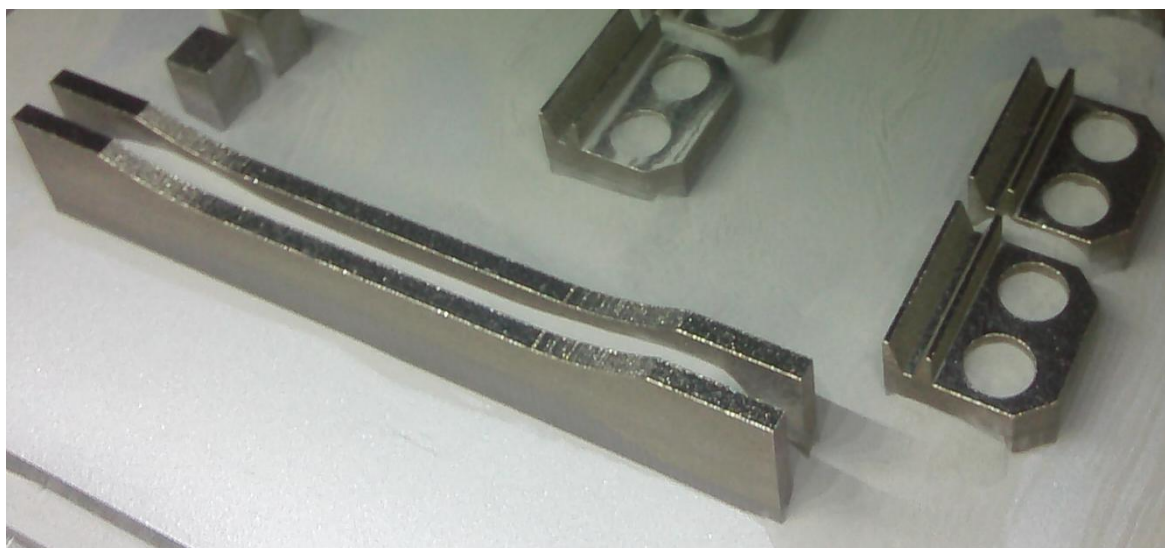


Figure 2. Sample

Mechanical tests were performed on a universal electromechanical breaking machine Instron 5969 with Bluehill® Universal software [70-78]. The loading speed was 1 mm/min. A non-contact video extensometer was used to determine the deformations. All tests were carried out under normal conditions. Experimentally determined mechanical properties were compared with datasheet specifications and previously obtained characteristics [79-83] to assess the quality of synthesised samples. Microstructural studies of samples after mechanical tests were performed using an EVO-40 Carl Zeiss scanning electron microscope equipped with an X-ray energy-dispersion spectrometer X-Max Oxford Instruments. The roughness was determined according to ISO 4287 using a three-dimensional measuring laser microscope OLYMPUS OLS5000. The study was performed on surfaces in the plane of construction, perpendicular to the platform and at angles of  $45^\circ$  and  $135^\circ$  [84-89].

### 3. Results and discussion

*Mechanical properties.* Based on the results of static tensile tests of the samples, diagrams were constructed in the stress-strain coordinates (Figure 3) and compared with the previously obtained results [14] and datasheet specifications (Table 1) [90; 91]. The results of the samples are well correlated with each other, which

confirms the high reproducibility of the SLM method and the quality of the synthesised samples. The Young's modulus was 120 GPa, the ultimate strength – 750 MPa, the relative deformation at break – 37% [92-98].

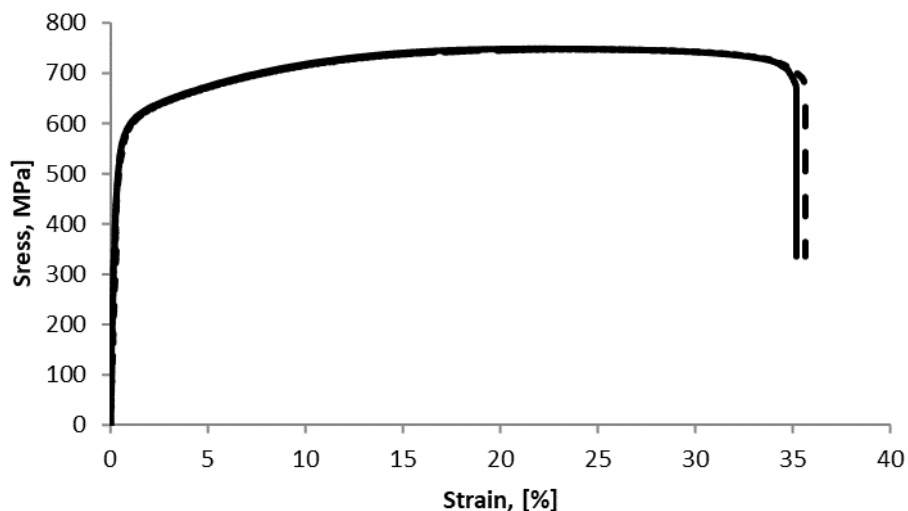


Figure 3. Steel samples test results (dashed line – obtained values, full line – standard values)

Table 1. Samples properties

Characteristics	Unit	Obtained values	Standard values
Young's modulus	GPa	120	116
Tensile strength	MPa	752	748
Ultimate strain	%	37	35

As a result of the tests, the samples were destroyed at an angle of 45° (Figure 4), as in the previous study [14]. The nature of the destruction of the samples is viscous [99-102].



Figure 4. Sample after tensile tests

*Microstructure and roughness.* According to the results of microstructural studies of samples after tensile tests in the vicinity of the fracture surface, the fact of incomplete melting of the initial powder material in the SLM process was established. Round microspheres were present in almost all places of destruction (Figure 5a). The chemical composition of the microspheres (Figure 6), determined by local X-ray spectral analysis, confirmed that they are not sintered particles of the powder used.

It was noted in [103-109] that the nature of the fracture of the samples is brittle-viscous with a significant predominance of brittle fracture. The studies carried out clarified this result and corrected the type of destruction. It is established that the destruction of samples occurs completely by a viscous mechanism with the implementation of a combination of shear-type (shear) and pit-porous-type failures. Shear failure is localised in fairly narrow slip bands and occurs under the influence of shear stresses. Analysis of the fracture surface indicates the generation of flat-bottomed micropores around non-sintered particles and carbide phases. It is possible that their appearance occurs due to the collapse of the dislocation slip bands into a

submicrocrack under the action of shear stresses [110-116]. Given the weak cohesive strength of the "matrix – non-sintered particles" interface, even at the early stages of plastic deformation, it is possible to lose the conjugation of particles with the matrix (essentially, the formation of micropores), which leads to a faster growth of pits (pores) in relatively large microspheres. Thus, as a result of the action of the noted mechanism, shear bands are formed on the fracture surface with the simultaneous formation of a pit relief (Figure 5b) [117-122].

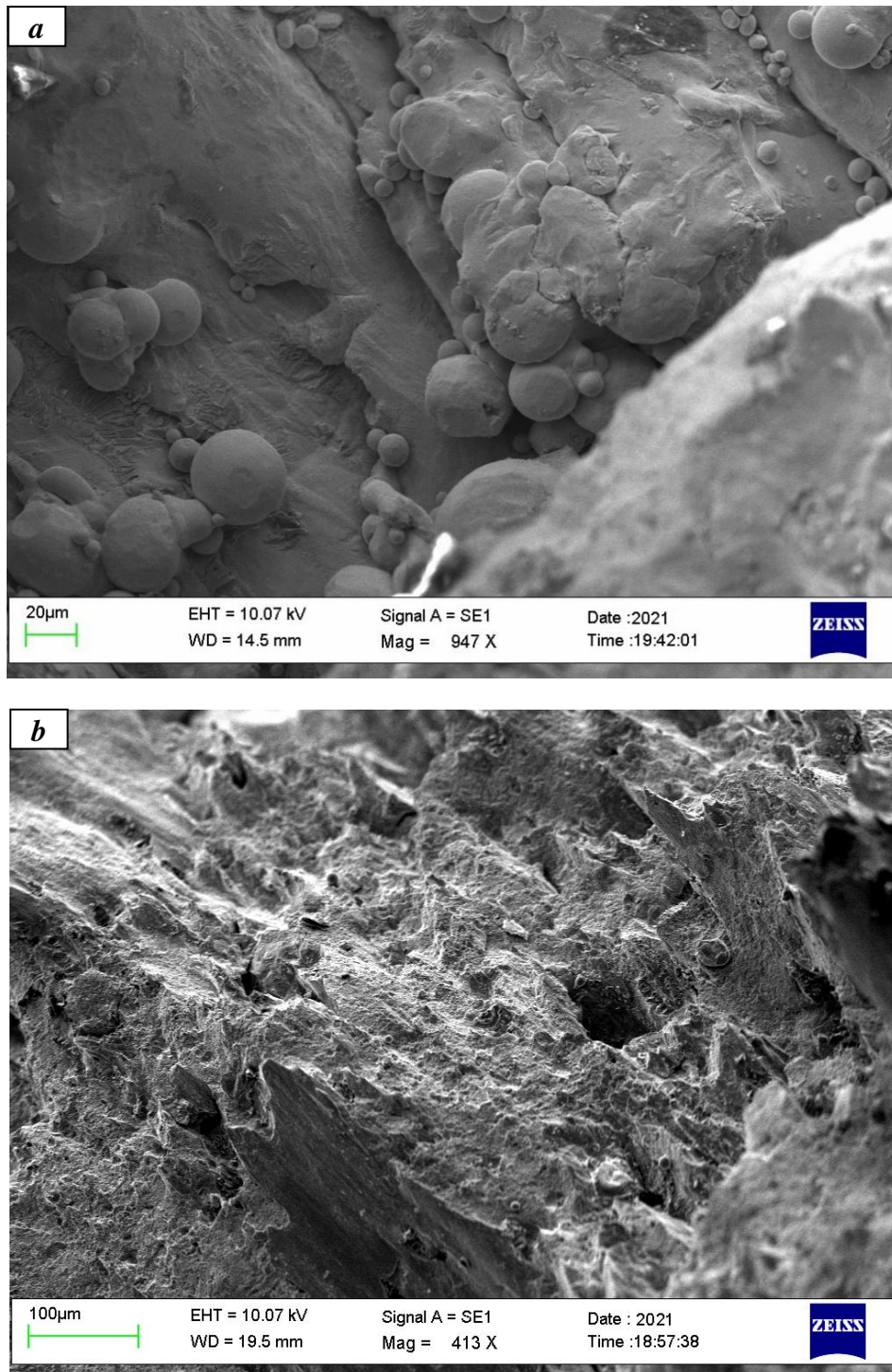


Figure 5. Structure of a macroscopic crack (a) and the structure of the fracture surface according to the shear and pit type (b)

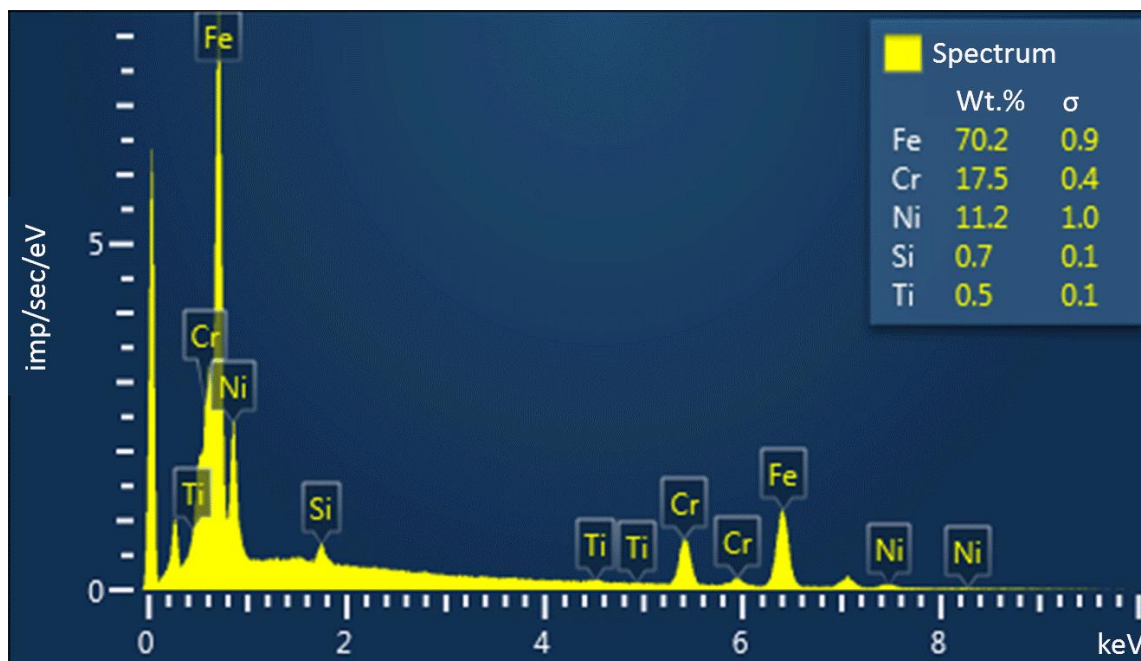


Figure 6. Data from the micro-X-ray spectral analysis of the microsphere

One of the obtained samples of the same type for the study of surface quality is shown in Figure 7. The surface topography and the roughness measurement trajectories for each sample type are shown in Figure 8. For each surface variant, the study was carried out on three samples in three areas. During the roughness measurement, the arithmetic means of the absolute values of the profile deviations within the base length Ra and the average absolute value Rz were determined. The results of roughness measurements for each of the surface variants are summarised in Table 2. The data analysis showed the stability of the surface quality for each of the considered options [123-126].



Figure 7. Sample for the study of the surface

Table 2. Results of roughness measurements

Characteristics	Unit	flat	perpendicularly	45°	135°
Ra	μm	0.561-0.695	0.574-0.645	0.778-1.204	1.387-1.645
Rz	μm	3.405-5.024	3.425-4.136	4.018-6.425	10.321-14.847

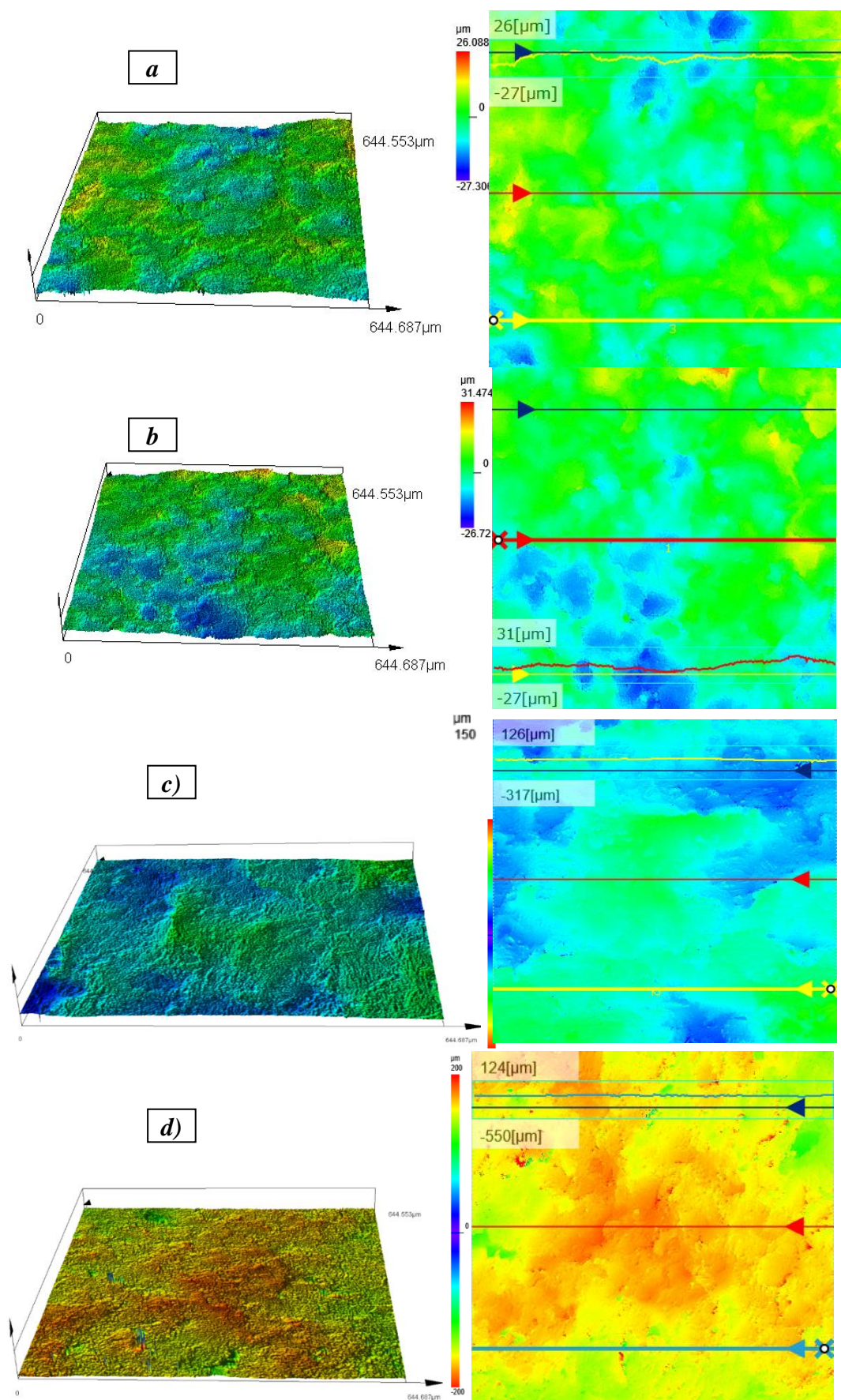


Figure 8. Investigated surfaces: left – surface topology; right – trajectory along which the roughness was determined: *a* – flat, *b* – perpendicularly, *c* – at an angle 45°, *d* – at an angle 135°

#### 4. Conclusions

The results of studies of the microstructure and mechanical properties under tension of PH1 stainless steel samples grown by selective laser melting are presented. The obtained mechanical characteristics were compared with the datasheet specifications characteristic of this kind of material. It is shown that the obtained results, taking into account the error, are identical to the properties of standard samples. It is established that the destruction of samples under tension occurs by a viscous mechanism with the implementation of a combination of shear and pit-porous types of destruction. Shear failure is localised in fairly narrow slip bands and occurs under the influence of shear stresses. Analysis of the fracture surface indicates the generation of flat-bottomed micropores around non-sintered particles and carbide phases. It is possible that their appearance occurs due to the collapse of the dislocation slip bands into a submicrocrack under the action of shear stresses. Given the weak cohesive strength of the "matrix – non-sintered particles" interface, even at the early stages of plastic deformation, it is possible to lose the conjugation of particles with the matrix (essentially, the formation of micropores), which leads to a faster growth of pits (pores) in relatively large microspheres. Thus, as a result of the action of the noted mechanism, shear bands are formed on the fracture surface with the simultaneous formation of a pit relief.

The study of the topography of differently oriented surfaces is carried out – in the plane of construction, perpendicular to it and at angles to the platform 45 and 135°. It is shown that the best surface quality corresponds to two planes – parallel and perpendicular to the plane of the construction platform. The average values of their roughness were  $R_a \sim 0.6 \mu\text{m}$  and  $R_z \sim 4 \mu\text{m}$ . The quality of the surfaces located at an angle is significantly inferior to the first two. A change in the surface quality depending on the angle of inclination was also observed.

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