

# Deformation uniformity of additively manufactured materials on the example of austenitic stainless steel 321 and copper C11000

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**Abstract.** Structural studies and mechanical tests of additively manufactured samples from AISI 321 steel copper C110000 have been carried out. Mechanical tensile tests of 321 steel show slight differences in the ultimate tensile strength (up to 3-4%) and ductility (up to 10%) of test coupons tested along the material growth direction and along the layer deposition direction. The strength of C11000 copper samples is 9.4% higher in the layer deposition direction, but their ductility is 15.4% lower than that of samples deformed in the growth direction. The strain relief on the surface of the polished gage section of the steel test coupons demonstrates changes in the material structure with small elongated grains along the growth direction of the sample. The deformation relief of copper samples is mainly related to the deformation of large columnar grains stretched in the growth direction.

## 1. Introduction

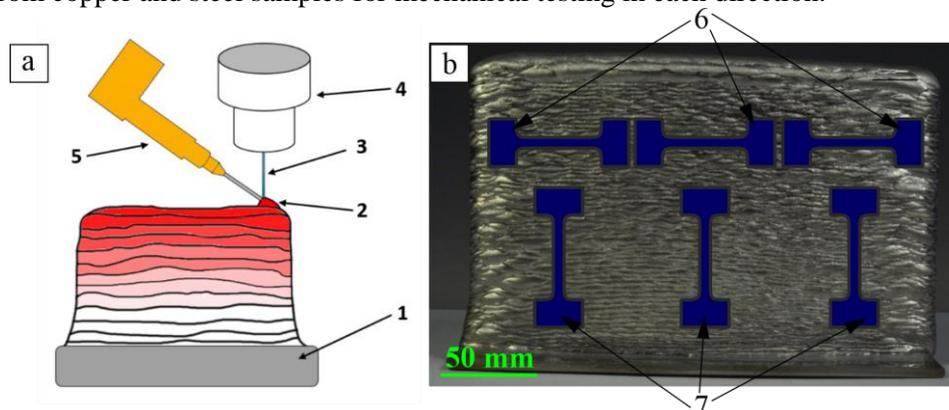
It is known that the process of plastic deformation in the loaded metals and alloys produced by the conventional crystallization from the melt is not homogeneous, and is accompanied by the appearance of localized plastic deformation, the formation of necks [1], Chernov-Lüders bands [2,3], rotation of individual crystal fragments [4], etc. At present, additive manufacturing, which also known as the metal 3D-printing, are being actively developed. This is confirmed by a large number of scientific papers on the selective laser melting of a powder metal (SLM) [5,6], electron-beam additive manufacturing (EBAM) [7], and others. In addition to methods based on melting or sintering of powder particles, there is an active development of wire-based additive technologies using laser, electro-arc or electron-beam heat sources for melting a filament. Since 3D printing of metals has a potential to partially replace conventional manufacturing methods, there is a problem of the influence of new manufacturing processes on both the strength and performance properties of metals and alloys under conditions of different stress-strain state schemes. Due to the rather complex elongated structure directed towards the sample growth, in materials produced using the wire-feed electron-beam additive technology, mechanical properties will also have a certain dependence on the direction of the stress application relative to the direction of the structural components distribution.



The purpose of the work is to study the influence of deformation axis orientation relative to the direction of the sample growth in the shape of a vertical "wall" on the process of plastic deformation under the tension of AISI 321 stainless steel and copper grade C11000, which have significant differences in the structure formed during the electron beam 3D-printing.

## 2. Material and method

Steel and copper samples were manufactured on the experimental equipment [8], designed for the manufacture of products by the EBAM technology in vacuum. The stainless steel AISI 321 wire with the diameter of 1.2 mm was used as a feedstock. The diameter of the C11000 copper wire is 1,0 mm. To melt the wire and ensure the formation of a molten pool, an electron beam heat source was used. The general scheme of the technological process is presented in figure 1,a. In figure 1,b the photo of a wall made during 3D printing with an indication of sample cutting zones in different printing directions is given: along the growth direction (6) and along the layer deposition direction (7). At least 3 test coupons were cut from copper and steel samples for mechanical testing in each direction.



**Figure 1.** Schematic of EBAM process (a), as well as the printed steel sample with the diagram of the cutting positions of samples. 1 – substrate, 2 – molten alloy, 3 – electron beam, 4 – electron beam gun, 5 – wire feeder, 6 – test coupons cut out in the layer deposition direction, 7 - test coupons cut out in the sample growth direction (building direction).

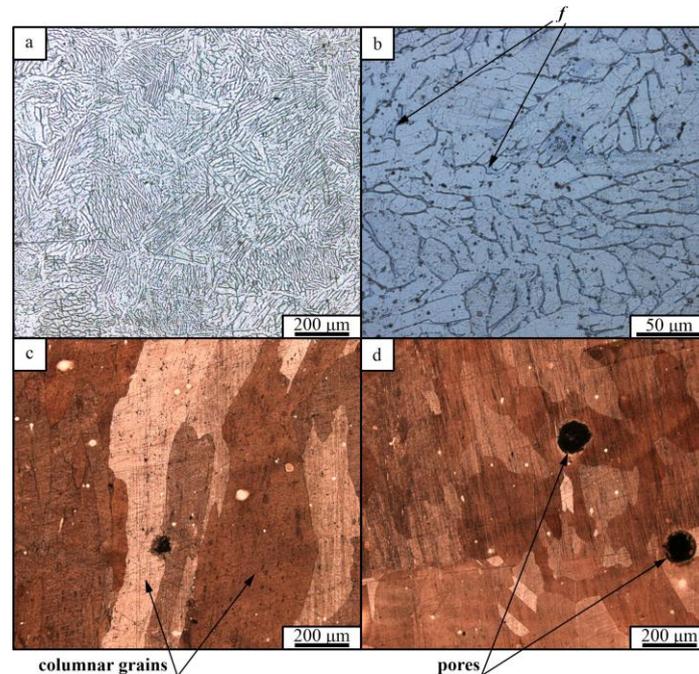
## 3. Results and discussion

A more detailed picture of the wall microstructure is presented in figure 2 at different magnifications. The microstructure is represented by a cast structure with the formation of a well-seen dendritic component. The structure represents the precipitation of  $\delta$ -ferrite in the main matrix of the austenite (f in figure 2, b). Black spots on the images are probably defects that occurred during mechanical surface finishing: grinding and polishing.

The microstructure of copper samples, in contrast to steel ones, is represented by large columnar grains stretched along the sample growth direction (figure 2, c). The grain size in the transverse direction can exceed 300-500 microns, and in the longitudinal direction it can be more than 10 mm, which has also been noted in [9]. Some grains can grow from the lower to the upper edge of the sample. At the same time, there are also inhomogeneities of the grain structure in the sample volume, which are large enough areas with a smaller grain size than in the main sample (figure 2, d). Thus, the grain size in such areas can reach 200  $\mu\text{m}$  and more. Copper samples differ from steel ones also in the presence of defects as pores, mainly of a spherical shape (figure 2, d).

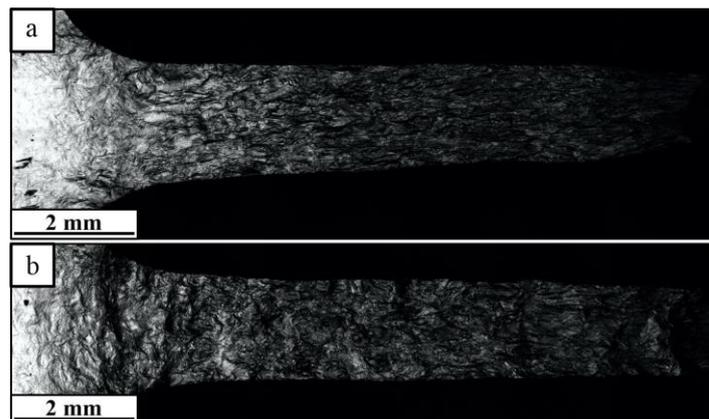
In Figure 3 there are images of AISI 321 steel test coupons after the tensile testing. The test coupon cut along the growing direction (figure 3, a) has fewer plastic properties than the one cut across. The test coupon deformation is characterized by a pronounced "neck" formation at the last stage of the testing process, followed by specimen fracture. This is characteristic of test coupons cut both in the growth direction (figure 3, a) and across it (figure 3, b).

The deformation of copper samples in different directions relative to the growth one occurs with a pronounced dependence of the plastic deformation on the sample cutting direction, which can be clearly seen on the surface of the deformed specimens after the fracture (figure 4).



**Figure 2.** Optical micrographs of the printed wall structure.

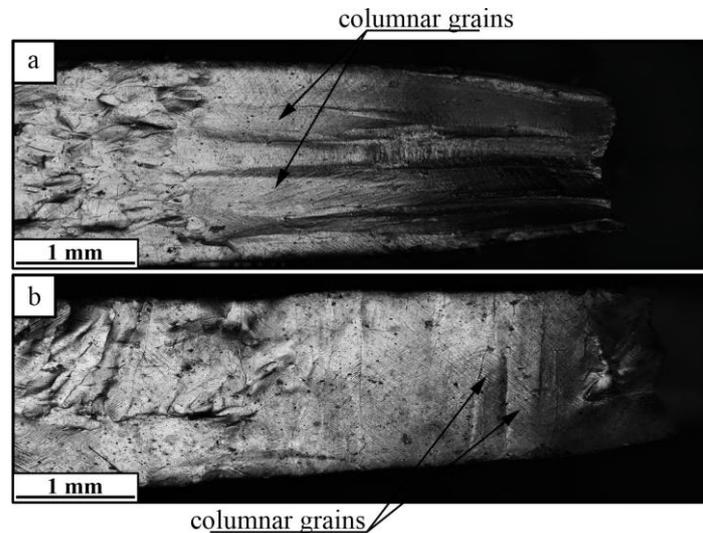
Along the growth direction (figure 4, a), the deformation occurs both in the area with columnar elongated grains and in the area with the fine structure. But the deformation localization and the subsequent fracture occurs mainly in coarse grains with the formation of "neck". In this case, the fracture occurs after reaching the ultimate tensile strength.



**Figure 3.** Images of steel test coupons fractured during the static tensile testing: a - specimen cut in the vertical direction (the wall growth direction); b - specimen cut in horizontal direction (the layer deposition direction).

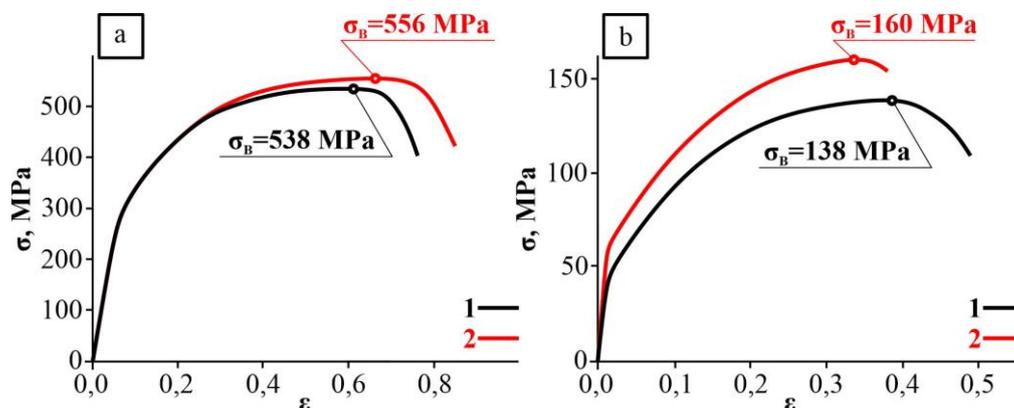
In samples cut out in the layer deposition direction, the deformation develops mainly in large grains as well. Despite the presence of the structure heterogeneity, the fracture occurs in the region of the large grain structure (figure 4, b). The pores clearly visible in the structure of metallographic specimens were

not observed on the surface of test coupons and their influence on the process of plastic deformation was not evaluated.



**Figure 4.** Images of copper test coupons fractured during the static tensile testing: a - specimen cut in the vertical direction (the wall growth direction); b - specimen cut in horizontal direction (the layer deposition direction).

The process of the steel 321 deformation under tension (figure 5, a) develops in 3 main stages. These include the stage of elastic deformation, the stage of plastic flow with parabolically changing stress values and the stage with high and slightly changing stress values preceding the neck formation and the test coupon fracture. This is true for both types of test specimens. In this case, at the elastic deformation and parabolic stages, the differences are small or absent completely. The largest differences are characteristic at the last stage of deformation, the duration and stresses of which are higher for specimens cut along the layer deposition direction (see Figure 3). The difference in plasticity was ~10 %. The average value of the ultimate tensile strength of samples cut out in the growth direction is equal to 540 MPa, and for samples cut out in the layer deposition direction, it is equal to 557 MPa. The average values of the relative elongation until the “neck” formation for both directions are 61,5 and 68,0 %, respectively. In this way, in samples from the 321 steel, the influence of the strain direction on the ultimate tensile strength not exceed 3 – 4 %, and on the ductility, not more than 10 %.



**Figure 5.** Tensile curves of steel 321 (a) and copper C11000 (b) steel samples: 1 – specimen cut in the vertical direction (the wall growth direction); 2 - specimen cut in horizontal direction (the layer deposition direction).

The plastic deformation of copper samples before the end of the elastic deformation stage also has no pronounced differences from the strain direction relative to the growth direction (figure 5, b). Upon the transition to the plastic deformation, the differences in the stress-strain curve between these types of samples begin to increase. Samples cut in the layer deposition direction have the greatest strength of 157.0 MPa. Samples cut in the growth direction have an average value of 142.2 MPa. The ductility of samples cut in the growth direction is equal to 39%, and in the transverse direction, it is about 33%. Thus, the strength of specimens in the direction transverse to the growing direction is higher by 9.4%, and the ductility is lower by 15.4% than for specimens deformed in the growing direction.

#### 4. Conclusion

In the present work, the samples from steel 321 and copper C11000 produced by EBAM method have low differences in mechanical properties during plastic deformation, which is confirmed by tensile diagrams. The analysis of the test coupon surface after fracture shows quite significant deformation relief changes caused by the deformation mechanism along and across the grains elongated in the growth direction. Changes in mechanical properties in tests of both materials performed at different strain directions show lower values of the ultimate tensile strength during testing in the direction of the sample growth. The ductility during deformation along the growth direction of steel is lower, and during the deformation of copper, it is higher than for similar test coupons cut in the layer deposition direction. Thus, the studies show that in the additively manufactured samples made of copper or steel under conditions of tensile testing in different directions, the strength and ductility undergo changes by up to 10-15%, and for steel with a less pronounced growth direction, changes in mechanical properties are less than for copper.

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