Structural evolution of 321 stainless steel in electron beam freeform fabrication

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Abstract. The study of the structural evolution in the specimens of austenitic steel 321 manufactured by an additive method through the melting of a wire material by an electron beam in a vacuum chamber has been carried out using optical metallography, scanning electron microscopy and EBSD analysis. Tensile properties were determined on standard dumbbell specimens. The studies of the structure and properties showed that the 3D-printed samples have a pronounced dendritic structure with a sharp fusion boundary between the substrate and the printed material. The mechanical properties of the specimens are at the level of those cast austenitic steel 321.

1. Introduction
In modern air-space industry it is important to find ways for creating and processing new structural and functional materials intended for various friction units as well as other applications [1-8]. Such developments include developing new processes for joining materials, for example, by means of welding [9-12]. A separate task is to develop tribotechnical materials capable of working in difficult conditions and closed volumes of space- and aircrafts, which requires a sufficient understanding of the processes occurring in friction in the presence of lubrication, and dry and adhesive friction [13-17]. No less important task in producing the air-space parts is to provide a method for manufacturing the complex-shaped parts. The latter is a problem that can be solved by the additive manufacturing.

At present stage, the additive manufacturing of plastic parts or reinforced composites is widely used. Also there are developments of 3D-printers that can print under extreme conditions as those existing for example, under zero-gravity at the space stations. At the same time the additive manufacturing of parts from metallic materials is developed quite poorly.

The most used additive manufacturing processes are based on a powder-bed layer-by-layer deposition of a metal powder with subsequent melting and bonding it to the underlying layer using either laser or electron beam. A similar technology that utilizes wire-feed is of less use. However, the use of this particular technology simplifies the production of the most complex-shaped parts with the presence of a large number of post-processing and modifications in the process of manufacturing parts. With this method of manufacturing parts, the multi-axis machining centers with a tilt-swing table mechanism can used in addition to a large number of other possible devices. Also it is possible to combine the 3D printing process with further multiple processing and obtain details of an even more complex shape and size.
The main difference between the additive manufacturing technology by selective laser fusion and electron beam melting is the necessity of using the vacuum chamber [18-25]. The cost of the laser beam source is higher than that of the electron beam. If it is necessary to use a limited budget for the manufacture of equipment, the option with electron beam technology becomes more acceptable.

Therefore, materials obtained by the electron beam wire-feed additive manufacturing in vacuum are investigated in this work. Stainless steel 321 was chosen as the material for deposition. The main task is to choose the process parameters which ensure formation of a defect-free structure of the specimens.

2. Materials and methods
The 3D-printing of specimens using the electron beam wire-feed additive manufacturing was carried out in experimental equipment in vacuum. Variable process parameters were used including current (mA), voltage (kV), scanning speed (moving the 3D-printer work units) (mm/min), scanning step (mm). Formation of the bulk products was carried out using 1 mm diameter wire of austenitic stainless steel 321. The appearance of the 3D-print area is shown in figure 1. The samples obtained in the longitudinal and transverse direction for the study of the microstructure are shown in figures 2 and 3.

![Figure 1. Appearance of the chamber for 3D-printing.](image)

3. Results and discussion
Figure 2 shows a photograph of a flat specimen №1 obtained from stainless steel 321 wire at accelerating voltage 35 kV, beam current 20 mA, wire-feed rate 10 mm/s, deposition speed 0.2 m/s. The motion along the Z coordinate (i.e., the thickness of the deposited layer) was 0.5 mm. The diameter of the beam sweep is 2 mm, the beam scan frequency is 1 kHz. The width of the deposited track is 2.5 mm. As can be seen from the photograph, the continuity of the sample is not high, i.e. large grooves are located between the trajectories of 3D-printing.

Figure 3 shows a photograph of flat samples №2 (right) and №3 (left). Sample № 2 was obtained from stainless steel 321 wire at accelerating voltage 30 kV, beam current 27 mA, wire-feed speed of 20 mm/s, and a product moving speed with respect to the electron beam 0.2 m/s. The displacement in building direction (i.e., the thickness of the deposited layer) was 0.5 mm. The diameter of the beam spot is 2 mm, the scan is 1 kHz. The width of the deposited tracks is 3 mm. As can be seen from the photography, traces of curvature of the 3D-print trajectory are observed on the surface of the product,
which is caused by an excessively fast wire-feed speed, which nevertheless was completely melted with the underlying layers. Sample № 3 was obtained with the same regimes as sample № 2, but with a lower wire-feed speed 10 mm/s. As can be seen from the photography, this sample has a more regular shape. There is no trace of excess material.

Figure 2. Specimen №1.

Figure 3. Specimens №2 and №3.

Thus the №3 specimen did not contain any significant defects of the macroscopic size. The transition to the specimen № 2 regime entails a breakdown of the structure as a whole, which indicates that the wire-feed rate 20 mm/s is higher than the limit for the given deposition regime.
Figure 4. The microstructure of the specimen formed in the 3D printing process. Transverse to the printing direction (a) and longitudinally to the printing direction (b).

Figure 5. EBSD-map of the specimen’s material obtained by 3D-printing.

As metallographic studies have shown (figure 4), a dendritic columnar structure was formed in the region of 3D-printing. On the panoramic image of the cross section of the product (not shown in the figure), the product/substrate fusion boundary as well as fusion lines between the successively deposited layers are clearly seen. The first layer of the specimen deposited in the 3D-printing process had the smallest thickness (450 μm), which is due to the partial melting and of the substrate material
and mixing with the wire material. The subsequent layers have almost the same thickness (800-900 μm), which indicates on the stability of 3D-printing conditions. In these layers, the thickness of the layer corresponds to the step of vertical scanning along the building direction. The directions of the dendrites’ growth in different layers coincide generally but still gradually deviate by several degrees with each layer toward the direction of motion of the product relative to the beam. Nonmetallic inclusions in the structure of specimens with the absence of macrodefects have not been revealed.

Structural investigations of the specimen’s material using SEM and EBSD analysis (figure 5) show no grain structure texturing under chosen 3D-process parameters. The structure of the metal is represented by rather coarse grains with the mean size in the range 50-80 μm. The material is represented by a structure similar to that of the as-cast steel. The tensile strength of the deposited metal was close to that as-cast metal too (550 MPa).

4. Conclusion

3D-printing of specimens by the electron beam wire-feed additive manufacturing makes it possible to obtain the defect-free fully dense inner structure products having no either inner or surface macrodefects such as non-metallic inclusions or pores. Tensile strength of the specimens after printing is equal to that of the as-cast 321 austenitic steel. No grain structure texturing has been detected. The as-deposited metal structure differs significantly from that of the substrate and separated by the fusion line.

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