On the problem of formation of articles with specified properties by the method of electron beam freeform fabrication

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Abstract. The obtained results show that using an electron beam wire feed process makes it possible to manufacture axially symmetric articles which metal strength is close to that of conventionally made ones. However, it is necessary to optimize the process parameters and thus provide forming the desired microstructure with or without the anisotropy.

1. Introduction
Fast development of additive manufacturing is a global challenge in modern technology progress, which determines provisions for developing and using new advanced, high-productive and competing processes. This work has been focused on developing an electron multibeam additive directed energy wire deposition process and commercial high-productive robotic equipment for manufacturing large metallic components.

This process involves a layer-by-layer deposition of metal by electron beam melting of wire and obtaining then a near-net-shape component (see schematics in figure 1). The advantage of this process is its high deposition rate up to 12 kg/h [1] which is unachievable with other additive processes, for example with a powder additive process [2]. Also it allows making large up to 5000 mm size fully dense and structurally homogeneous components from both refractory and heat-resistant alloys [3]. Extra feature of this process is a feasibility of simultaneous deposition of dissimilar metals and thus forming a composite structure inside a vacuum chamber [4]. Therefore, it excludes any oxidizing of the component.

The project implementation allows filling a commercial niche both in home and abroad markets of equipment and materials needed for high-production additive manufacturing of large complex shape components. Achieving this goal will provide our technological leadership in high-production electron beam additive manufacturing.

The purpose of this work is the development of laboratory 3D-printing equipment and selection of the technological mode of articles producing from stainless steel 321 grade (SS 321). In order to determine the gradient of mechanical properties and the manufacturing quality of thin-wall (<3.5 mm) axisymmetric cylindrical and conical bodies, mechanical compression tests were carried out.

In this paper, a set of laboratory equipment for wire feed electron beam additive manufacturing of metallic components has been developed. Optimal process parameters have been found and used for
manufacturing axisymmetric articles from the SS 321 wire. The structure and mechanical properties of the articles have been studied.

![Figure 1. Schematic of electron beam freeform fabrication (EBF) system components [5].](image)

### 2. Material and methods

The main electron beam deposition parameters are accelerating voltage, beam current, beam focusing distance, beam spot diameter and scanning frequency. The wire feed and beam positioning system are characterized by the wire feed rate and working table velocity with respect to the beam. Determining optimal values of the above parameters and maintaining them during the process are very important for obtaining a high-quality final component.

To reproduce a needed shape of the component it is necessary to program the algorithm of the working table displacements and rotation including the circular interpolation cycles. The programming is performed by coding the control operations (G-codes) which determine the coordinates and velocities of the drive system components.

The coordinate origin is denoted as COP. The forming trajectory onset point is denoted as P.0. This point has its coordinates \((X_0, Y_0, Z_0)\) with respect to the coordinate origin. To start forming the article component it is necessary to change the current position from P.0 to the next point \(t_i\), i.e. move at distances \(\Delta X\) and \(\Delta Y\) along the \(OX\) and \(OY\) axes, respectively. The \(I\) point coordinates will then be \((X_i, Y_i, Z_0)\) since no displacement was along the \(OZ\) axis which will be performed only when forming a new layer.

Specifying the trajectory radius \(R\) and onset (P.0) one sets up the circular trajectory basis with the numerical control system which then calculates a set of points with required sampling frequency and thus determines the deposition trajectory. There is no need in manual generating the trajectory point sets in order to form the needed shape component. Also wire feed rate and working table displacement velocity are entered to the control system.

### 3. Results and discussion

One can see in figure 2(a) article #0 made using the electron beam process from SS 321 wire and process parameters shown in table 1. The poor quality of deposition including the unmelted wire segments and rough surface resulted from using too high wire feed rate as well as non-optimal deposition velocity. Articles #1, #2 and #3 in figure 2 have been obtained using the process parameters (table 1) which differed from those of #0 article by changed deposition velocity.

Article #1 (figure 2b, figure 3) was obtained at 0.1 m/s deposition velocity and showed irregular top edge shape which resulted from excess melting at that low deposition velocity. No unmelted wire segment was observed so that the wire feed rate was at least acceptable value.
Figure 2. General view of cylindrical articles on substrates # 0 (a), # 1 (b), # 2 (c) and # 3 (d).

Table 1. The electron beam wire-feed deposition parameters.

| Articles | Voltage, kV | Current, mA | Wire feed rate, mm/s | Deposition velocity, m/s | Displacement along OZ, mm | Beam spot diameter, mm | Beam scan frequency, kHz |
|----------|-------------|-------------|----------------------|-------------------------|---------------------------|------------------------|--------------------------|
| # 0      | 40          | 15          | 15                   | 0.30                    | 0.5                       | 2.0                    | 1.0                      |
| # 1      | 40          | 15          | 10                   | 0.10                    | 0.5                       | 2.0                    | 1.0                      |
| # 2      | 40          | 15          | 10                   | 0.23                    | 0.5                       | 2.0                    | 1.0                      |
| # 3      | 40          | 15          | 10                   | 0.18                    | 0.5                       | 2.0                    | 1.0                      |

Freeforming the article # 2 was carried out at 0.23 m/s. The article’s surface is rather smooth without any unmelt wire segments or excess melting the edges (figure 2c). This article may be acceptable from the viewpoint of the layers deposited but has curved walls, probably resulted from their insufficient thickness.

Article #3 was obtained at 0.18 m/s (figure 2d, figure 3) and characterized by smooth surfaces without any unmelt wire or excess melting.
Figure 3. Macro- and microscopic images of structure of article #1 in a section perpendicular to the 3D-printing direction.

The mechanical characterization of the articles obtained was performed using compression tests on specimens cut from the articles as shown in figure 5. The Testsystems 110M-10 test machine has been used in the process at ambient temperatures. Table 2 contains mean yield stress values for different specimens tested. It follows from the results that article #3 shows the maximum stable mechanical strength distribution. Article #2 is characterized by minimum yield stress in the direction of deposition trajectory.
Table 2. Mean yield strength values.

| Articles | Mean yield strength, $\sigma_{0.2}$ (MPa) |
|----------|------------------------------------------|
| # 1      | 262 298 269 250                         |
| # 2      | 240 240 301 301                         |
| # 3      | 305 317 315 305                         |

| Specimen cut localization* | 1 | 2 | 3 | 4 |
|----------------------------|---|---|---|---|

*1– along the building direction bottom part, 2 – along the building direction top part, 3 – transversal to building direction bottom part, 4 – transversal to building direction top part

Figure 4. Macro- and microscopic images of structure of article # 3 in a section perpendicular to the 3D-printing direction.
Figure 5. Schematics of the specimens cut off from articles 1 and 2 – specimens cut off along the building direction; 3 and 4 – specimens cut off transversal to building direction, 5 – article, 6 – deposition trajectory, 7 – substrate.

The article #1 (top part) is characterized by the yield strength values higher in the building direction as compared to that of transversal direction. The bottom part metal did not show the anisotropy as above.

4. Conclusion
The compression strength of article #3 was the highest and even higher than that of base SS 321. Articles #1 and #3 had clearly seen fusion interfaces between the successively deposited beads. For a more homogeneous article #2 a high anisotropy of the conditional yield point was observed. Article #1 had high anisotropy of mechanical properties both in the directions of growth and deposition.

It was established that varying the additive process parameters such as wire feed rate, substrate rotation rate one may obtain finally printed components of various microstructure and mechanical characteristics. Manufacturing components with their mechanical characteristics either higher or close to those of base cast metal is also feasible [6]. Moreover, it becomes possible to obtain microstructures of either high or zero anisotropy.

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