The influence of alloying elements on the formation of the interfacial of a Fe-Cu bimetal produced by wire-feed electron beam additive manufacturing

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Abstract. In the present work, microstructural studies of the Fe-Cu bimetallic sample interface were carried out. The "vertical wall" sample made of different materials – AISI 321 stainless steel and C11000 copper – was produced by the wire-feed electron-beam additive manufacturing. The presence of sharp boundaries between inclusions and a matrix of these immiscible materials was shown. Moreover, the steel inclusions had an intraphase stratification. However, neither between the main elements of the bimetallic compound of Fe and Cu nor between the alloying elements included in the stainless steel composition, the formation of intermetallics was not detected.

1. Introduction
Polymetallic materials are made using two (bimetal) or more metals or alloys (polymetal). The reason for this manufacturing is that many industrial problems cannot be solved using only a single metal- or alloy-based material (monometallic materials). For example, under certain operating conditions, the material must have a high heat transfer rate with a minimal heat loss, as well as resist any form of corrosion in the working environment. Copper has high thermal conductivity characteristics but has a lower corrosion resistance than stainless steel. Thus, compounds of copper and stainless steel are required in the nuclear power industry as one of the important components of vacuum chambers for particle accelerators, and in cryogenic engineering, providing a high electrical conductivity of copper and high mechanical properties of steel. To combine the advantages of stainless steel with copper, a suitable manufacturing process must be applied. However, stainless steel and copper are dissimilar materials with very different thermal, physical and chemical properties. Copper can conduct heat energy up to 10 times faster than steel, which tends to dissipate heat quickly, making it difficult to reach the melting point during fabrication. This is because of the difference in the melting point (Cu – 1085 °C, SS – 1400÷1500 °C) and the heat conductivity (Cu – 401 W/mK, SS – 17÷19 W/mK), so it is difficult to join them for any fusion welding process. In addition, copper has a very limited solubility with the steel in the liquid state, and a copper penetration along the heat-affected zone of the steel can lead to a hot cracking [1]. The Fe-Cu phase diagram contains no intermetallic phases except for a small region of limited solubility between Cu and Fe [2]. Hydrogen readily dissolves in the liquid copper and promotes the formation of pores in the bimetallic interface region [3]. The liquid-phase separation between Cu and Fe is usually observed in laser, electron-beam, and arc welding processes [4]. In this case, the presence of liquid-phase separation leads to the formation of pores and cracks, which negatively affects
the mechanical properties of the finished product. To avoid these problems in the manufacturing of bimetallic products from dissimilar materials, which lead to a loss of quality and reliability of the finished structures, it is necessary to study the laws of structure formation.

Therefore, the purpose of this work is to study the formation of the interface area of a bimetal based on dissimilar materials of AISI 321 steel and pure C11000 copper formed by the wire-feed electron-beam additive manufacturing.

2. Materials and methods

Samples were produced using an experimental equipment for the wire-feed electron beam additive manufacturing of metal products. For the 3D-printing, AISI 321 steel and technically pure copper C11000 wires were used for the samples. The diameter of the steel wire was 1.2 mm and the diameter of the copper wire was 1 mm. The chemical composition of wires is shown in Table 1.

Table 1. Chemical composition of the substrate and filaments used in the wire-feed electron beam additive manufacturing.

| Material | Chemical component (wt. %) |
|----------|-----------------------------|
| Filament |                            |
| AISI 321 | Fe balance to 0.3, Cu 9–11, Ni 17–19, Cr to 2, Mn 0.4–1, Ti to 0.8, Si to 0.12, C to 0.12 |
| C11000  | balance to 0.005, Cu balance to 0.002, Ti –, Si –, C – |

To produce the vertical wall, an alternating strategy of depositing heterogeneous wires was chosen. The steel substrate was fixed on a three-axis water-cooled table. An electron beam was used to form a melting pool. The wire was fed into the melting pool and the vertical wall was 3D-printed by the layer-by-layer material deposition. When using heterogeneous materials with different thermophysical properties for printing, it is necessary to vary low and high values of the heat input depending on the material (Table 2).

Table 2. The wire-feed electron beam additive technology deposition process parameters.

| Material | Deposition speed \( \nu \), mm/min | Current \( I \), mA | Beam sweep, mm | Voltage \( U \), kV |
|----------|---------------------------------|------------------|----------------|------------------|
| Fe       | 250                             | 90 ÷ 48          |                 | 30               |
| Cu       | 600                             | 80 ÷ 45          | 3              | 30               |

The printing parameters were used to adjust the heat input values, affecting the temperature gradient and taking into account the difference in chemical and thermophysical properties of heterogeneous materials. To study the microstructure, samples were cut out of the grown vertical walls using a DK7750 EDM machine. The elemental composition of the bimetallic sample was analyzed using a Zeiss LEO EVO 50 scanning electron microscope with an energy dispersive elemental microanalysis attachment.

3. Results and discussions

The grown vertical wall has no defects, the layers are uniform throughout the entire height of the product (Figure 1 a). This suggests that the printing parameters are optimal for producing samples from heterogeneous materials with the number of layers for each being 10 ones [5].
The macrostructure of the additively manufactured bimetallic product made of stainless steel and copper shows the presence of a pronounced boundary when changing the wire filament feed from steel to copper (Figure 1 b). Along the boundary, no crack-type defects are detected, indicating the complete layer deposition. At the same time, the shrinkage pores that normally form when layers are deposited are also absent. The boundary between the dissimilar materials has a curvilinear shape, and specifically is curved toward the end faces of the vertical wall. This observation is associated with a slight spreading of the copper filament during the growth, due to the lower melting temperature compared to the steel filament one. At the same time, the curvilinear boundary does not affect the macro- and microstructure features of the Fe-Cu bimetal. Figure 2a shows that the boundary has an irregular thickness of 35-45 µm, decreasing to a thin interface.

This is associated with an insignificant misalignment of the wire from the center of the electron beam spot. A similar filament runout is allowed during the growth of thin vertical walls, except in the case of the formation of macro-defects in the form of significant thickening and streaks on the edge area. On both sides of the interface, there are inclusions observed: in the copper region – Fe-Cr-Ni ones, in the steel region – copper ones (Figure 2b). Furthermore, the interphase boundaries of steel inclusions and copper particles are sharp, and there are no transition regions. However, the detailed analysis of the microstructure showed (Figure 3) that there is no formation of intermetallic compounds neither between Fe and Cu, which agrees with the literature data [2], nor between the alloying elements included in stainless steel.
Figure 3. SEM images of the interface area of Cu-Fe bimetal fabricated by the wire-feed electron beam additive manufacturing.

It is shown that near the wide boundary there is phase separation, and near the narrow boundary, there is a homogeneous macrostructure with large copper inclusions. At a distance of 30÷35 μm from the boundary, the influence of elements included in the used filaments is eliminated and the chemical composition of additive steel (Table 3, region 1) and additive copper (Table 3, region 8) corresponds to the initial chemical composition presented in Table 2. However, the width of the boundary (Figure 3b) shows that there are two distinct phases in the iron-enriched region: a dark phase with Cr content of about 4 weight % and a light phase with Cr content of about 10 weight %. This does not disagree with the conditions of iron phase transition according to the Fe-Cr-Ni ternary diagram [6]. Immediately near the analysis threshold, the chemical composition of regions 5 and 6 differs from the initial composition of the filament, forming a mechanical mixture of Cu and Fe, alloyed with elements of Cr, Ni, and Ti. But at a distance of 15÷17 μm from the border the composition tends to the initial one. As for the formation of copper inclusions in the steel matrix, it also contains elements related to stainless steel. The copper penetrates the intergranular space of the steel, which in turn re-melts, creating a separation of the two immiscible materials. The delamination that occurs during the application of the wire filament to the melt bath in the liquid state is observed. In the area where the copper particles form, secondary phases have formed that contrast with the copper and austenitic steel. These inclusions have areas that are enriched in Cr and depleted in Ni, as shown by the mapping results.

Table 3. Elemental analysis of interface boundary bimetal’s in Figure 3

| Elt. | Area | Ti | Ni | Fe | Cr | Cu  |
|------|------|----|----|----|----|-----|
|      |      |    |    |    |    |     |
| Conc., wt. % |      |    |    |    |    |     |
| 1    | 0.2  | 18.6 | 69.6 | 9.2 | 2.4 |
| 2    | 0.0  | 16.7 | 68.8 | 4.9 | 9.6 |
| 3    | 0.2  | 17.8 | 60.8 | 10.6 | 10.6 |
| 4    | 0.6  | 8.7  | 23.2 | 2.6 | 64.9 |
| 5    | 0.2  | 17.7 | 66.7 | 4.1 | 11.3 |
| 6    | 0.0  | 5.1  | 16.5 | 1.4 | 77.0 |
| 7    | 0.4  | 2.5  | 7.7  | 0.4 | 89.0 |
| 8    | 0.1  | 0.3  | 1.0  | 0.0 | 98.6 |

4. Conclusion
The Fe-Cu bimetallic product formed by the wire-feed electron beam additive manufacturing has a sharp interface area. Inclusions of various shapes and sizes of steel and copper are observed near this area. At the formation of inclusions, there is a pronounced boundary with the matrix, and as a consequence, there are no conditions for the formation of intermetallic compounds. However, the steel inclusions have a
non-uniform composition: in some areas, there is an enrichment in Cr and depletion in Ni, which is explained by the presence of a phase separation.

Acknowledgments
The work on the sample production was performed according to the Government research assignment for ISPMS SB RAS, project FWRW-2019-0034. The reported structural studies of bimetal were funded by RFBR according to the research project No 20-32-90173.

References
[1] Mai T A and Spowage A C 2004 Mater. Sci. Eng. A 374 224-233
[2] Tan C, Zhou K, Ma W, Min L 2018 Mater. Des. 155 77-85
[3] Chen S, Huang J, Xia J, Zhao X, Lin S 2015 J. Mater. Process. Technol 222 43-51
[4] Le T N and Lo Y L 2019 Mater. Des. 179 107866
[5] Osipovich K S, Gurianov D A and Chumaeovsky A V 2021 IOP Conf. Ser.: Mater. Sci. Eng. 1079 042089
[6] Franke P and Seifert H J 2011 Calphad 35 148-154