The Formation of Bimetallic Materials by the Electron-Beam Additive Manufacturing

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Abstract. The structure of Cu-Ni system polymetallic materials samples produced by the electron-beam additive technology has been studied. Two types of samples were manufactured: with a smooth and sharp gradient. The separation effect of the nickel alloy from the copper substrate was found in a number of experiments. More intensive heating of the substrate before the first layer was applied, which resulted in the formation of a smoother transition zone from copper to nickel alloy, but did not solve the problem due to uncontrolled diffusion in the molten bath. The use of the multi-wire gradient printing with simultaneous feeding of two filaments allowed to form a smoother transition in the boundary zone.

1. Introduction

The development of additive technologies now allows to produce mono- and polymetallic parts of various shapes, sizes and purposes with properties that are difficult to achieve or cannot be achieved by conventional manufacturing technologies [1-3]. In addition to producing parts from homogeneous materials such as steel, aluminum or titanium alloys [4-8] by additive manufacturing methods, different polymetallic parts of various systems are successfully produced [9-10]. The technology of electron-beam additive 3D-printing with wire filament belongs to the category of the most productive methods for the production of parts from metal alloys [11,12]. Using this method, it is possible to produce gradient materials with a smooth transition from one material to another. In such parts a combination of high tribological properties and a low strength, as well as a resistance in aggressive conditions or a heat resistance and good heat dissipation is possible.

One such polymetallic system is the combination of a copper and austenitic stainless steel that provides a high corrosion resistance of the steel on the one hand and the possibility of heat removal through a copper on the other, making it suitable for the production of containers for the chemical industry [12]. In this system mainly mechanical mixtures of components are formed in the contact zone, without formation of intermetallic phases or solid solutions between main chemical elements.

There are a number of polymetallic systems of the Cu-Al type, allowing to get a complex mixture of solid solutions and intermetallic phases in the contact zone, which makes them applicable for producing tribological layers on the surface of light and strong materials.

Another polymetallic system with the formation of solid solutions in the contact zone without the formation of intermetallic compounds is the Cu-Ni system. Combination of copper and nickel due to their unlimited solubility can be one of the simplest in terms of producing polymetallic samples. At the
same time, this system makes it possible to produce parts withstanding high temperature influences on the one hand, and on the other hand, it makes it possible to produce parts with a high heat dissipation rate due to the copper part. At the same time, by controlling the value of the structural gradient it is possible to increase or decrease the heat dissipation and control the thermal mode of the finished product at the production stage. The purpose of this work is to produce polymetallic samples of the Cu-Ni system with a sharp and smooth gradient in the contact zone.

2. Material and method
The samples were produced at the laboratory equipment for the electron-beam additive manufacturing at the ISPMS SB RAS according to the scheme presented in Fig. 1. The samples with a sharp gradient (1) (fig. 1, a) were obtained by printing with the nickel alloy Cr15Ni60 on the surface of the copper substrate (2). The electron beam (3) was directed through the magnetic focusing system (4) to the printing zone on the wire (6) fed through the nozzle (5), which resulted in the formation of the molten bath (7). Samples with a smooth gradient (8) were produced on the steel substrate surface (9) by the gradient printing with two filaments of copper (10) and nickel (11). The other parts of the printing process are similar to the first scheme. The steel substrate was chosen to change the thermal printing mode and to produce a polymetallic sample of the triple system. The gradient printing consisted of initial printing on a steel substrate exclusively with the copper filament, then adding a filament of the nickel alloy Cr15Ni60 to the molten bath with a subsequent gradual increase in the nickel alloy wire feeding rate and a decrease in the copper feeding.

![Figure 1. Schematic of EBAM process of the printed sample with a sharp gradient (a) and a smooth gradient (b).](image)

After the sample manufacturing, metallographic specimens was cut out longitudinally and transversally relative to the printing direction using a DK 7750 electrical discharge machine. After the cutting, samples were grinded, polished, and chemically etched. Structural studies were carried out on the Olympus LEXT 4100 laser scanning microscope.

3. Results and discussion
When the single filament of Cr15Ni60 nickel alloy is fed into the printing zone on the C11000 copper surface, samples with a pronounced directional structure and the presence of defects in the contact zone and in the material volume are formed (fig. 2, a-c). In the boundary zone (fig. 2, a, b) on the edges of the samples, there are clearly defined delaminations, which can be caused by the difference in temperature expansion of copper and nickel alloy, as well as the shrinkage direction of a long sample in the shape of a vertical "wall" and the shrinkage direction of the substrate. In the volume of the nickel alloy, cracking occurs along the grain boundaries stretched along the heat dissipation direction (fig. 2, d).
Samples with a sharp gradient showed generally disappointing macrostructure, despite the fact that copper and nickel in the contact zone exhibit fairly good adhesion. The main reasons for the formation of defects are the high cooling rate in the printing zone and a small difference in thermal expansion coefficients (or an uneven thermal impact on the substrate material).

As one of the possible ways to correct this phenomenon, the printing process on a copper substrate with more intense heating of the material during printing has been tested. As a result of the experiments of one layer deposition on the substrate with an intensive beam heating during printing, the structure presented in the figure 3, a was formed. In the upper part of the sample a finely dispersed mixture of dendrites was formed as a result of intensive diffusion of copper into the nickel alloy (area 1 at fig. 2, b, c). Below is the transition zone represented by larger dendrites of copper and the nickel alloy (area 2 at fig. 3, a, d, e). This area smoothly passes into the copper substrate zone (fig. 3,e). In the substrate itself the analysis of a grain enlargement in the structure shows that the length of the heat-affected zone is about 2 mm.

Although the results obtained show the absence of separation and cracking in the samples, they also do not allow to conclude that it is possible to use such a technique due to unlimited diffusion in the contact zone of copper and the nickel alloy. To produce samples with a smooth structural gradient with controlled diffusion of materials during printing, samples were manufactured using the technology of gradient feeding of two filaments described earlier. At the same time, steel 321 was chosen as the
substrate, on which copper was applied with an intensive heating of the substrate to ensure a smoother fusion of the sample and the substrate, and to study the structural regularities of the steel-copper gradient. A typical structure of the samples formed by this method is shown in Figure 4.

![Figure 3](image-url)  
**Figure 3.** Structure of a bimetal sample of the C11000-Cr15Ni60 system produced with an intensive copper substrate melting during printing.

![Figure 4](image-url)  
**Figure 4.** The structure of a copper-nickel polymetallic sample with a smooth gradient.
The steel-copper gradient zone and the copper-nickel gradient zone are clearly distinguished in the sample structure (fig. 4, a). In the Steel-Copper gradient zone, the structure is divided into two parts which are represented by austenite dendrites with copper interlayers and represented by copper containing steel particles. In the predominantly steel region in the large quantity there is the formation of cracks partially or completely filled with copper (fig. 4, b). In the predominantly copper region, the main defects are structural irregularities with the formation of large steel particles or areas depleted in steel.

4. Conclusion
The studies show that during the wire-based electron-beam additive 3D-printing, the formation of polymetallic samples from copper and the nickel alloys is associated with a number of processes occurring at different stages of production. First of all, in the manufacture of samples with a sharp gradient there is a fusion in the boundary zone of the nickel alloy and copper at a shallow depth. Later, when the sample is printed and its gradual cooling occurs a shrinkage, mainly in the printing direction along the length of the sample, which leads to a separation along the edges of the printed material with insufficient adhesion to the substrate. More intensive melting of the substrate due to the control of the beam sweep allows to increase the depth of the gradient zone, but leads to the uncontrolled diffusion of components and an excessive mixing in the molten bath. The production of samples with a smooth transition by using the gradient feeding leads to the formation of irregularities in the contact zone of copper and the nickel alloy. But it also allows to form a polymetallic sample without defects in the form of separation or delamination due to a smooth change in material properties from copper to the nickel alloy. In addition, studies show that by means of layer-by-layer printing it is possible to produce multi-component layered composites with a combination of copper, steel and nickel alloy in a single product.

5. References
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