Formation Features of Polymetallic Products Obtained by Electron Beam Additive Manufacturing Using Gradient Filament Feeding into the Molten Pool

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Abstract. Samples of functional-gradient materials of the "copper-aluminum" system on a stainless steel substrate were obtained by the method of additive electron beam technology with wire filament. The heterogeneity of the materials structure in different areas of the structural gradient was studied by the method of optical microscopy. Functionally-gradient materials of various compositions with the presence of a smooth and sharp gradient of the structure from copper to copper-aluminum alloy have been investigated. The results indicate the presence of heterogeneities in the composition and structural defects in material.

1. Introduction

Obtaining functionally graded materials from metals and alloys by methods of additive technologies is one of the most urgent tasks at present [1-5]. This is due to the growing need of various industries for obtaining products from materials with significantly different parameters of thermal conductivity, corrosion resistance, heat resistance, etc. [1,3,5]. These combinations can be used to formation of tribological resistant structures on the surface of various metals and alloys, heat removal from hot forging dies, etc. One of the materials with potential applications using high thermal and electrical conductivity in combination with a hardened and wear-resistant surface layer are copper and copper alloys, as well as composite materials based on them. The relevant combinations for such alloys is the combination of copper and composite material of the "copper-aluminum" system in one product, which will allow, due to solid-solution and dispersed intermetallic hardening of the material, to form hardened layers on the surface of copper and its alloys directly in the printing process by adjusting the composition of the polymetallic system. In this case, it is possible to obtain in the surface layer both pure intermetallic layers with high hardness and low ductility, and mechanical mixtures of solid solutions of system components with intermetallic phases. In the first case, it is possible to form structures with high hardness, wear and heat resistance in comparison with the original components, and in the second case - with moderate hardness, wear resistance and relatively high ductility. At the same time, in the products of the first type it seems the most difficult to obtain a defect-free material structure with the absence of cracking or delamination within and at the boundaries of the intermetallic layers. The solution of this problem requires experimental studies to determine the necessary structure of the transition layers, processing parameters and patterns of defect formation depending on the local structure of the samples.
The aim of this work is to obtain polymetallic materials of the copper-aluminum system on a stainless steel substrate by electron-beam wire technology with controlled filament feeding into the molten pool.

2. Materials and methods
Samples were obtained at the experimental setup in the ISPMS SB RAS. Initially an electron beam (1 in figure 1) fed through a focusing system (2 in figure 1) from a source (3 in figure 1) melting a wire (4 in figure 1) introduced into the printing zone from a feeder (5 in figure 1) and molten copper of C11000 grade deposited on the surface of a stainless steel substrate (6 in figure 1). Then, a second filament of aluminum alloy 5556 was introduced into the molten pool with increasing proportion of aluminum alloy feed and decreasing for copper. As a result, layers of mechanical mixtures of copper and stainless steel were formed on the substrate surface by melting the substrate (7 in figure 1), layers of pure copper (8 in figure 1), a gradient layer with a transition from pure copper to a zone of solid solutions (9 in figure 1), layers with a mixture of solid solutions and intermetallic phases (10 in figure 1) and intermetallic layers (11 in figure 1). The thickness of the layers was 5 mm for copper, and 10 mm for the gradient zone. The obtained samples were examined by optical microscopy on Olympus LEXT 4100 and Altami MET1C instruments. The main phases in different sections of the samples were determined using X-ray phase analysis on an X-ray diffractometer DRON-4M. Mechanical properties were investigated by tensile tests of specimens cut from different sections of the polymetallic sample.

3. Results and discussions
The structure of the gradient zone from the substrate to the copper layers is represented by inhomogeneous mechanical mixtures of austenitic and copper fragments (figure 2). Copper is partially penetrated in the substrate due to intensive melting by the electron beam. Steel, as a result of lower density, is mixed in copper to a considerable depth, including in the form of large fragments. Significant structure defects are practically not distinguished in this case. In the mixed steel fragments in the copper matrix there is a penetration of copper particles.

In contrast, in the structure of the copper-aluminum gradient, the formation of defects is noted in quite large numbers (figure 3). The most significant of the defects are pores and cracks (figure 3, a). The most optimal is the formation of mixed interlayers (figure 2, b). The formation of structures containing intermetallic phases is presented by a dendritic structure with intermetallic particles between the dendrite axes (Figure 3, b). In this case, no defects in the form of cracks or delaminations are observed.
Figure 2. Area of structural gradient from steel substrate - to copper layers of the sample

When approaching the area of intermetallic layers, the formation of large fragments of intermetallide of various types is observed, in a smooth transition from the solid-solution layers - to intermetallic layers not exhibiting a tendency to crack formation, even in the presence of significant heterogeneities of structure (figure. 4). In this case, the heterogeneity in the structure of the layers is due to the uneven structure of the molten pool, the different density of copper and aluminum alloy and the high rate of crystallization of the metal in the printing process.

Figure 3. Structural gradient zone from copper layers to intermetallic layers

Studies using X-ray diffraction analysis show that near the substrate in the gradient area with a mechanical mixture of copper and γ-Fe, with a slight mixing of α-Fe. In layers of pure copper, at a sufficient distance from the substrate, no impurities are detected. Layers with the predominant presence of solid solutions do not reveal the presence of intermetallic phases. In layers with a mixed structure, the formation of intermetallic phases of two groups, Al$_4$Cu$_9$ and Al$_{13.892}$Cu$_{6.10808}$, is noted. In the near-surface intermetallic layers it can be noted additionally the content of intermetallic compositions AlCu and AlCu$_3$.

The highest mechanical properties in the samples are characteristic of the area near the substrate, where the steel mixed into the material of the copper layers leads to an average ultimate tensile strength of 350-360 MPa (figure. 5). In the material of the copper layers the ultimate tensile strength is significantly lower and averages 200-205 MPa. In layers with a predominantly solid solution structure the ultimate strength is on average about 280-290 MPa. The reduction of the ultimate tensile strength to the values of 175-185 MPa is characterize the layers with mixed structure with the content of intermetallic phases and solid solutions. The lowest ultimate tensile strength is characterize for a surface layer and makes 90-100 MPa, thus, due to presence of residual quantity of solid solutions of copper and aluminum in this layer it is still possible to mark plastic behavior of material at deformation. The
presence of steps in the graphs of the copper-aluminum system is associated with the destruction of brittle intermetallic phases.

Figure 4. Heterogeneities of the structural gradient area from copper layers to intermetallic layers

4. Conclusion
The conducted studies show that using the method of gradient smooth feeding of the material into the molten pool by electron beam additive technology it is possible to obtain functionally graded products of the copper-aluminum system with the formation of intermetallic layers of complex composition on the surface. The structural heterogeneities in the gradient area on the one hand are quite significant both in the transition from substrate - to copper, and from copper - to surface, but, despite this, they do not reveal the formation of delamination or cracking in the structure. The formation of extended transition interlayers between layers with a solid-solution and intermetallic structure prevents the formation of defects in the materials. In the layers with the coarsest structure and the presence of the hardest intermetallic phases a decrease in the ultimate tensile strength occurs, while in the main volume of the material the mechanical properties remain at a sufficiently high level.

Figure 5. Mechanical properties of graded polymetallic material in different layers

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