Precondition for the use of hybrid additive-thermomechanical technology

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Abstract. Structural-phase state of gradient structures obtained in the course of additive electron-beam production, friction-stir treatment and hybrid additive-thermomechanical technology was investigated by optical and scanning electron microscopy. Characteristic features of defect formation in materials obtained by additive method are revealed. The peculiarities of defects “healing” in additive materials after friction-stir treatment are determined. In tensile tests the mechanical properties of the samples before and after further post-treatment in aluminum alloys are measured.

1. Introduction

At present, the production processes of parts made of heterogeneous metals and alloys are mainly based on the additive method of forming products from different metals [1-4]. In turn, such techniques are based on the melting of metal powders or wire filament and the deposition of molten material on the substrate. Such a process can be carried out in an air environment as well as in a shielding gas or vacuum. Both the electron beam and the laser beam are used as heat sources for melting the material.

But, despite the sufficient versatility of additive production technologies of parts from metal materials, the resulting products have a number of significant drawbacks. The most significant drawback of products obtained from homogeneous metals and alloys is the microstructure of the samples after printing, represented mainly by the cast dendritic structure. This provides quite low mechanical properties of the obtained materials and in some cases requires additional heat treatment after the process of 3d-printing of samples.

At the building of samples from heterogeneous materials, at the expense of fusion forming intermetallic compounds, for example in pair Cu-Al, Al-Ti, strength properties of samples essentially decrease. In this case, the destruction occurs along the boundary of intermetallic-solid solution. Also, when printing heterogeneous materials, for example, the Cu-Al system, due to the higher melting point of copper, its deposition on the surface of the aluminum alloy is limited. Its’ occur due to the excessive melting of aluminum and a high degree of diffusion of aluminum alloy in copper, forming a large proportion of brittle intermetallic compounds in the volume. From the experience of friction-stir welding and friction-stir treatment it is known that intermetallic compounds in the above mentioned metal vapors are formed and under these effects, but, unlike the processes based on the melting of metals, intermetallic layers have a smaller thickness and do not have such a significant impact on the mechanical properties of the resulting products [5-8].
The study of physical processes occurring in the manufacture of samples by technology of additive-thermomechanical influence will allow, in addition to the elimination of a number of negative structural effects in samples with a homogeneous and heterogeneous structure, to form composite metal materials with hierarchical structures due to the alternation of metal layers with processed ultrafine disperse structure and cast undeformed structure. Such composites can be made of homogeneous and heterogeneous metal materials, with a layered or complex three-dimensional structure, with areas with different not only structural-phase composition, but also grain-subgrain structure.

At present, there is no data in the literature on the structural response of materials in the conditions of additive production with thermomechanical treatment of heterogeneous materials, although there is a number of studies on structural changes in the materials obtained by the additive method of friction stir welding and processing [9,10]. For this reason, it is impossible to establish the relationship between the parameters of the process of obtaining the structure and properties of the resulting products by this method. Thus, practical expediency of carrying out works in this direction and fundamental scientific task determine one purpose of the present work. Obtaining these data on the structure and phase composition of the samples and the relationship between structure and properties of heterogeneous materials formed by the hybrid method will allow to obtain products with known properties in advance.

Proceeding from the aforesaid, the present work is directed on studying of structural-phase features of components interaction at additive electron-beam manufacturing and revealing of influence on structure and mechanical properties of the subsequent frictional mixing processing.

2. Materials and methods
The paper studies the processes of materials formation with gradient structure by the method of additive electron-beam production, friction mixing treatment and hybrid method. The samples were obtained on experimental equipment at the Institute of Strength Physics and Materials Science.

Metal wire from Ti-6Al-4V, AA5056, C11000 alloys with a diameter of 1-1.2 mm was used for obtaining samples by the method of electron-beam additive production. Samples were produced by layer-by-layer deposition on the surface of the substrate made of the corresponding alloy at different parameters of beam current, beam voltage, feed rate of the sample or wire. Production of polymetallic samples was carried out with the help of two wire feeders in the chamber, with successive deposition of materials of one filament and another.

Friction-stir treatment of rolled sheet was performed on C11000 copper and polymetallic material from AA5056 and copper alloy sheets, with copper interfering into aluminum alloy to obtain gradient material in the mixing zone. The thickness of the processed sheets was from 2 to 5 mm. For reception of polymetallic system Cu-Al sheets in the thickness of 2 and 3 mm are used.

Hybrid obtaining of materials was made by sequential additive obtaining of materials of aluminum alloy AA5056 by the method of electron-beam production with the following frictional mixing treatment at a depth of 1.8 to 5 mm. The processing was carried out with a standard tool for friction-stir welding.

After printing, samples for optical and scanning metallography were cut out using the electrospark method. The research was carried out using optical and scanning electron microscopy on the Olympus LEXT 4100 laser scanning microscope and Zeiss LEO EVO 50 scanning electron microscope.

3. Results and discussion
The materials produced by the electron-beam additive production method have a structure similar to that observed in a standard metallurgical foundry. Metal in the printing zone is represented by a typical dendritic structure with elongated in the direction of heat dissipation. In the process of products formation there is a formation of rough wavy morphology on the surface, correlating with the layering of the material structure. In the internal volume of the material pores and heterogeneity of the structure
of different sizes are formed. The elimination of such defects is possible only in case of different post-treatments after manufacturing of parts.

At additive obtaining of details from heterogeneous metals and alloys with the limited solubility and propensity to formation of intermetallic phases in structure the complex multiphase structure, and special distribution of chemical elements and specific kinds of defects is formed (Figs. 1 and 2). At non-uniform cooling and heterogeneous distribution of chemical elements in the structure of the sample cracks of different structural and large-scale levels are formed (Fig. 1). In the case of mismatch of the parameters of the electron beam leading to non-fusing of the wire, it is possible to introduce wire into the material of the melted substrate. In this case, a defect is formed, for example (when printing copper-titanium samples), in the form of introduction of pure copper in the resulting material, with the formation of large areas of formation of intermetallic materials of different compositions around it (Figs. 1 and 2). Also, the formation of heterogeneous distribution of intermetallic phases in terms of size and volume fraction in the sample material (Fig. 2) can be referred to as defects.

**Figure 1.** Structure of the polymetallic sample of the Cu-Ti system with defects obtained by the method of electron-beam additive production.

**Figure 2.** Inhomogeneity of the polymetallic sample structure of the Cu-Ti system, obtained by the method of electron-beam additive production.
In polymetallic materials, which are not prone to the formation of intermetallic phases and do not have mutual solubility in the solid state, for example, as copper and austenitic steel, a mechanical mixture of system components with different concentrations is formed in the boundary zone. Pore formation and inhomogeneities of both grain structure and phase composition are possible in the structure. The use of two gradient wires from two different feeders in the same melt bath at the same time allows the structure to be aligned and the resulting material structures to be controlled during printing.

![Figure 3. Structure of the boundary zone of a Cu-Fe system polymetallic sample obtained by electron-beam additive production.](image)

From the conducted works on manufacturing of samples by the method of additive electron-beam production it is possible to draw a conclusion about heterogeneity of structure, formation of defects of various type, the form, the size and irregularity of a surface of received samples. Part of the above mentioned defects can be removed by normalization of the parameters of the sample production process. The other part cannot be eliminated at normalization of parameters, for example, low durability of the received materials in comparison with sheet rolling, heterogeneity of structure, large-crystal structure, etc. For this reason, the formation of a homogeneous structure of the surface layer or internal volumes in the material obtained by the additive electron-beam technology, it is necessary to use different post-treatment.

The formation of ultrafine disperse materials by friction-stir has been actively developed over the past decades. This method is based on the friction-stir process, which is also used for friction stir welding of different metals and alloys. At frictional processing the tool under the influence of axial force at the certain frequency of rotation at the expense of frictional heating is introduced into the sample, after that there is a progressive movement of the tool in the warmed up material and formation of the recrystallized finely dispersed structure in a mixing zone (Fig. 4). Despite the heterogeneity of the processed material structure in the thermomechanical affected zone, this technology allows to produce materials with high mechanical properties and homogeneous structure. The heterogeneity of the structure of the thermomechanical affected zone can be removed by multi-pass treatment.

At formation of materials by a method of frictional mixing processing from heterogeneous metals and the alloys on the basis of the metals testing at mixing the intensive phase interactions including mutual dissolution of components of system, formation of secondary phases, solid solutions or intermetallic compounds, the structure in a zone of mixing is formed more difficult type. In the
structure there is a pronounced layering with alternating layers of initial components and intermetallic compounds formed on their boundaries (Fig. 5).

![Structure of copper sample C11000 after friction-stir treatment.](image1)

**Figure 4.** Structure of copper sample C11000 after friction-stir treatment.

![Structure of a polymetallic sample of the Cu-Al system obtained by friction-stir treatment.](image2)

**Figure 5.** Structure of a polymetallic sample of the Cu-Al system obtained by friction-stir treatment.

At intensive diffusion of system components, it is possible to form intermetallic phases with complex structure and high heterogeneity of structure in different directions (Fig. 6). In a number of cases, during the formation of materials of such systems as Cu-Al, the material overheated with the destruction of the sample structure and the melting of aluminum alloy material. At the same time, by regulating the parameters of the machining process or by carrying out multiple passages with the tool along the machining line, it is possible to eliminate such defects with the formation of a more
homogeneous structure in the machining zone. Such materials with homogeneous or heterogeneous structure have rather high mechanical properties, significantly exceeding the properties of the samples obtained by the method of additive electron-beam production and being at the level of properties of rolled sheets, which makes it expedient to combine these methods. Also relevant is the use of friction treatment to improve the properties of additive materials, which makes the absence of pores and other defects, typical for additive production.

![Image](image_url)

**Figure 6.** Inhomogeneity of the structure of a polymetallic sample of the Cu-Al system obtained by friction-stir treatment.

Formation of materials by combined additive-thermomechanical method was tested on AA5056 alloy. The obtained additive structures with defects and low mechanical strength from 190 to 240 MPa were treated with friction-stir treatment. After the treatment mechanical properties of the samples increased up to 300-330 MPa. Mechanical properties were determined on the samples cut along the processing line in such a way that only the treated area was located in the stretching zone. In the structure of samples (Fig. 7) in the region without defects the structure of the material is presented by the standard distribution of the mixing zone, the thermomechanical affected zone and the thermal affected zone. A recrystallized ultrafine disperse structure is formed in the area of the mixing zone, which is favorable for mechanical properties.

![Image](image_url)

**Figure 7.** Structure of defect-free sample of AA5056 alloy obtained by electron beam additive technology and subsequent friction stir processing.

In a sample with a large number of defects in the structure in the form of pores, the structure in the mixing zone has traces of defects through which the processing is carried out (Fig. 8). Pores in the area
of treatment at friction mixing influence almost completely collapse and are removed at the expense of material mixing. The pores in the thermomechanical affected zone are squeezed due to material heating and tool pressure, but the structure remains defective in the form of irregularities. Mechanical properties of such samples decrease by a small value and are about 280-300 MPa. Thus, frictional stirring treatment of additively obtained material allows not only to obtain ultrafine disperse structure of surface or internal volume of the material, but also to eliminate defects that occur during printing.

4. Conclusion
The research shows that the process of additive reception of materials by a method of electron-beam manufacture with wire filament possesses a number of the lacks leading to formation in structure of defects connected with inhomogeneity of process or discrepancy of parameters to demanded values. The obtained materials have rather low mechanical properties, which is unacceptable in many cases. Friction mixing treatment with individual structure defects allows to obtain materials with higher mechanical properties and more homogeneous and favorable metal structure. Defects resulting from the manufacture of materials by additive manufacturing are successfully eliminated by friction treatment, and their impact on the mechanical properties is leveled. However, it is impossible to obtain complex shaped parts by frictional mixing treatment, and without additive technology it is extremely ineffective for these purposes. Thus, it is shown that the hybrid additive-thermomechanical process of obtaining parts is actual and feasible and combines the positive aspects of additive obtaining and friction treatment.

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