Research of mechanical properties and chemical composition of samples made of aluminium alloy AMg6 and obtained by electron beam additive manufacturing with wire feeding

A V Gudenko1,3, G V Grigoriev2, A P Sliva1, R Yu Agafonov2, A N Kasitsyn2

1National Research University “Moscow Power Engineering Institute”, 14, Krasnokazarmennaya st., Moscow, 111250, Russia
2Corp. “Russian Space Systems”, 53, Aviamotornaya st., Moscow, 111250, Russia
3E-mail: alexguddy@gmail.com

Abstract. This paper is devoted to the definition of mechanical properties, porosity and chemical composition of the samples made of wrought aluminium alloy AMg6 and obtained by electron beam additive manufacturing with wire feeding. It has been established that ultimate strength of the deposited metal is 90 % of the rolled metal. Chemical composition of the samples has not differed significantly from wire. According to rough estimations porosity has not exceeded 0.055%.

1. Introduction
One of the most perspective technologies in the field of additive manufacturing is electron beam additive manufacturing with wire feeding. In addition to advantages of the wire feed additive technologies [1] the process is carried out in a vacuum chamber that has a positive effect on quality of deposited material. In addition, the use of electron beam as a power source and vacuum chamber makes it possible to produce parts form wide range of materials such as titanium alloys [2] actively interacting with atmospheric gases, nickel alloys [3], stainless steels [4] and fusible aluminium alloys [5]. However, there is a lack of attention to investigation of additive manufacturing with the use of an electron beam and aluminium wire.

Electron beam additive manufacturing with aluminium wire could be used to produce large-sized details with complicated shape of walls because additive technologies lead to increase in the rate of the use of materials. Moreover, this technology could be applied to restoration a shape of parts in a repair operation.

An example of such parts is an aluminium case for electronic hardware (figure 1) that is used in aerospace industry where the main task is to decrease mass and dimensional characteristics without reducing mechanical properties.

The purpose of this paper is to study the possibility to use electron beam additive manufacturing with wire feeding for producing parts of aluminium alloy AMg6 and restoring their shape and dimensions in a repair operation.

2. Research methods
Two specimens made of aluminum alloy AMg6 in the form of walls were deposited to examine chemical composition, porosity and mechanical properties.
An AMg6 wire with the diameter of 1.6 mm was used. Two AMg6 blocks with dimensions of 120x28x20 were used as a substrate.

Chemical composition of AMg6 alloy is shown in Table 1.

| Fe   | Si    | Mn     | Ti     | Al    | Cu    | Be      | Mg     | Zn     | Other |
|------|-------|--------|--------|-------|-------|---------|--------|--------|-------|
| < 0.4| < 0.4 | 0.5-0.8| 0.02-0.1| 91.1-93.68| < 0.1| 0.0002-0.005| 5.8-6.8| < 0.2| < 0.1 |

The deposition was carried out using an electron beam machine with an accelerating voltage of 60 kV that was equipped with an automatic wire feeder. The wire feed rate was 2 m/min and the deposition rate was 60 m/h. Before the deposition of the first layer the trajectory was cleaned by an electron beam. The beam power was 360 W during cleaning pass.

![Electron Beam](image1.png)

**Figure 1.** The reconstruction scheme of the reconstruction of the original size of radioelectronic equipment case walls.

The deposition modes were chosen in accordance with the calculation method [6] and were adjusted experimentally (Table 2). Power decrease from layer-to-layer is necessary for obtaining a wall with constant thickness since an increase of layers number leads to deteriorating of heat transfer conditions as a result of temperature growth of the substrate and upper layer during deposition process. The change of the deposition conditions, in its turn, leads to the growth of melt pool temperature and the reduction of surface tension leading to width increase and height decrease of the deposited layer. However, heat transfer stabilizes at the certain layer and further decrease of electron beam power can lead to interruption of the deposition process.

| Beam power, W |
|---------------|
| **Layer number** | **Sample 1** | **Sample 2** |
| 1              | 1140         | 1200         |
| 2              | 1020         | 960          |
| 3              | 780          | 840          |
| 4 - 12         | 720          | 780          |
An oscillation of type “3 concentric circles” was applied. The diameters of the circles were 3, 2 and 1 mm. The oscillation frequency was 1000 Hz. It has previously been established that the use of this type of oscillation leads to the more stable formation compared to the “circle” type. This type of oscillation results in the more equal distribution of power density in the treatment area. It is necessary to redistribute power density more equally because of intense evaporation of aluminum alloy at the high densities which results in instability. The deposited specimen is shown in Figure 2.

The specimens were mechanically processed and further radiography, chemical and mechanical tests were carried out. Machined specimens are shown in Figure 3. Radiography tests were done to detect pores and other defects and to assess their dimensions. Rough estimation of porosity was carried out by calculating pores volume that were visible in the X-ray picture and dividing this volume by the volume of metal depicted.

![Figure 2. Deposited specimen](image)

The specimens for the tensile tests had dimensions of 55x8x1.5 mm (flat specimens were made in accordance with GOST 1497-84). The deforming velocity was 5 mm/min. Ultimate strength values of deposited metal have been established.

Chemical composition tests (GOST 7727-81) were performed with the use of emission spectrometer Foundry Master to assess chemical composition changes during deposition process.

![Figure 3. Specimens after milling](image)

3. Results and discussions

Based on radiography (figure 4) it has been established that pores have been distributed evenly by volume. The size of pores has not exceeded 100 µm for each specimen. Some pores with size of about 200-250 mm could be observed. According to rough estimation porosity has not exceeded 0.055%. Also, it could be noted that fine pores are concentrated in the bottom area of the specimens.
Porosity in the specimens has been connected to preparation quality of the wire surface. The surface layer of the wire adsorbs water steam that evaporates and makes cavities after crystallization. It could be possible to reduce the number of pores by increasing the time during which metal stays melted, that is, by decreasing deposition rate. On the other hand, increasing the time during which metal stays melted may lead to the evaporation of some elements which have high vapor pressure that could cause negative impact on mechanical properties of a part. Thus, it is safe to say that it is necessary to adjust modes in such a way that it does not lead to porosity and significant evaporation of elements e.g. magnesium. It is also necessary to prepare wire surface carefully.

The ultimate strength of the specimens has been established based on tensile tests. The results of the test and the ultimate strength of cast, wrought, and rolled materials are shown in Table 3. The ultimate strength of deposited material has exceeded by 40 % this parameter of cast material. Such exceedance is related to the high speed of crystallization that leads to refinement of grains and to the increase of mechanical properties.

![Radiography pictures of the specimens 1 (left) and 2 (right).](image)

The ultimate strength value of deposited metal has been about 90% of rolled metal. The lower value could be explained by the fact that the deposited metal is not strain hardened. Moreover, there are pores in the deposited metal that decreases its mechanical properties.

It should be considered that mechanical properties were investigated in the same direction as the direction of deposition. In other directions properties could differ significantly [7].

| Additive manufacturing  | Specimen 1 | Specimen 2 |
|------------------------|------------|------------|
| AMg6, cast [8]         | 210        |            |
| AMg6, wrought [9]      | 330        |            |
| Amg6, rolled [10]      | 340        |            |

Table 3. Mechanical properties of deposited metals and their comparison with cast, wrought, and rolled metal.

Studies of chemical compositions have been carried out in several areas of both specimens (figure 5).
The chemical composition of deposited specimens has not differed significantly from the chemical composition of the wire (table 4). High feed rate and not significant overheating of melt pool do not lead to much evaporation of magnesium. It could be said that there is no significant evaporation of magnesium during deposition of AMg6 alloy that could lead to loss of strength of material.

Table 4. Chemical composition of deposited metal and wire, %

| Element | Wire AMg6, % | Deposited specimens (average), % |
|---------|--------------|----------------------------------|
| Al      | balanced     | balanced                         |
| Si      | 0.124        | 0.116                            |
| Fe      | 0.312        | 0.224                            |
| Cu      | 0.081        | 0.057                            |
| Mn      | 0.690        | 0.650                            |
| Mg      | **6.214**    | **5.980**                        |
| Zn      | 0.034        | 0.029                            |
| Ni      | 0.004        | 0.003                            |
| Ti      | 0.145        | 0.103                            |
| Be      | 0.002        | 0.001                            |
| Pb      | 0.018        | 0.010                            |

4. Conclusions
Based on the research on deposited specimens of aluminum wrought alloy AMg6 it has been established that the size of pores has not exceeded 100 µm in the majority cases. However, some pores with the diameter of 200-250 µm have been observed. The size of pores largely depends on the quality of wire surface preparation and on time during which metal stays at high temperatures.

Chemical composition has not changed significantly as a result of deposition. There is not much evaporation of elements with high vapor pressure such as magnesium that leads to loss of strength.

The ultimate strength of specimens studied in the direction of deposition has been 40% more than ultimate strength of cast metal and has been about 90% of rolled metal. High mechanical properties are related to high deposition rate that leads to grain refinement.

Thus, electron Beam additive manufacturing with wire feeding with the use of alloys such as AMg6 could be used to manufacture parts with complicated shape and with the mechanical properties that are higher than the properties of cast metal as long as it is cost-effective.

Acknowledgements
The research was carried out in National Research University “Moscow Power Engineering Institute” with the financial support of the Russian Science Foundation (project No. 17-79-20015).

5. References
[1] Ding D, Pan Z, Cuiuri D, Li H 2015. Int J Adv Manuf Technol 81(1–4):465–81
[2] Gurianov D A et al. 2019 IOP Conf. Series: Material Science and Engineering 597 012042
[3] Xu X, Ding J, Ganguly S, Williams S 2019 J of Materials Processing Tech. 265 201–209
[4] Tarasov S Yu et al 2018 J. of Alloys and Compounds 803 364-70
[5] Brice C et al 2015 Materials Science and Engineering A 648 9-14
[6] Gudenko A V et al 2018 Svarochnoe proizvodstvo 8 12-19 (In Russian)
[7] Bird R K, Atherton T 2010 NASA Tech Memorandum (TM-2010-216719)
[8] Chuvil’deev V N et al 2008, Mechanical properties of microcrystalline AMg6 aluminum alloy Vestnik NNGU 4 35-42 (In Russian)
[9] Fridlander I N 2001 Non-ferrous metals and alloys. Composite metal materials. (Moscow: Mashinostroenie) (In Russian)
[10] Miklyaev P G 1994 Mechanical properties of lightweight alloys in conditions of temperatures and forming processes velocities (Moscow: Metallurgy) (In Russian)