Structure, properties and heat treatment of aluminum alloy BAC1 synthesized by 3D printing

R S Fachyrtdinov, P E Kuznetsova and I D Savichev
FSUE All Russian scientific-research institute of aviation materials, 105005 Russia, Moscow, Radio str. 17
E-mail: ravel@bmstu.ru, kuznetsovapolinae@yandex.ru, ilix77@yandex.ru

Abstract. Article is devoted to studying of influence of the process of selective laser melting and subsequent various heat treatment on the structure of aluminum alloy. On the basis of scientific and technical literature describes the need for and relevance of the application of modern technologies of 3D printing, the possibility of its application. The authors investigate the microstructure and determine the porosity of the synthesized samples of aluminum alloy of the Al-Si-Mg (Cu) system. The dependence of the porosity of the samples on the energy density is established. Also, the author investigated the influence of annealing and hardening modes with aging on the hardness of the samples of aluminum alloy. On the basis of the conducted researches characteristic properties and features of the synthesized material and preferable heat treatment were determined.

Keywords: selective laser melting, aluminum alloys, additive technologies, metal-powder composition, heat treatment.

1. Introduction
Currently, a wide range of different technologies is used for the manufacture of body parts of aircraft units. Mainly for metals used casting followed by machining. Silumins-aluminum alloys of Al-Si system are used for casting of cases. They have high technology in casting. However, the yield of suitable in the manufacture of products is reduced due to a variety of casting defects associated with the characteristics of crystallization of alloys. For a number of complex profile elements of the design of units in the casting process reduced yield due to casting defects associated with the characteristics of crystallization of alloys, while the design and manufacture of equipment, as well as the development of technology require significant time and resources. This approach imposes restrictions on the choice of technological solutions of a node, due to the possibility of its manufacture. As a result, the weight of the unit increases, reliability decreases, the coefficient of use of the material falls. An alternative way to obtain complex shape parts are actively developing in the last few decades additive 3D technologies [1]. With the use of additive technologies, it is possible to implement step-by-step topological optimization of nodes by means of rapid changes in the structural appearance according to the results of tests and, accordingly, to increase the weight efficiency of the structure. It can be achieved by increasing the CMM by obtaining blanks of parts with the most approximate dimensions and reducing the cost of subsequent processing, and by reducing the marriage and increasing the yield of suitable in comparison with casting technologies. The advantages of additive manufacturing technologies can be applied in the aerospace industry, automotive manufacturing and other areas of mechanical engineering.

Interest in additive technologies arose in aviation, space industry and power engineering. It is in these industries that production is measured by tens or hundreds of products of complex shapes made of
special materials. Often, the use of such methods in these industries is economically feasible. In many cases, additive technologies are even less expensive than traditional technologies. Direct cultivation of finished metal products is an alternative to traditional technological methods for the production of marketable products.

The essence of additive technologies is the layer-by-layer synthesis or layer-by-layer "growing" of a model or a finished product from a digital model, without the use of technological equipment. Thus, the construction of the part occurs by adding material in contrast to traditional technologies, where the creation of the part occurs by removing the "excess" material [2].

Layer-by-layer synthesis to obtain details of complex configuration was used in the late 19th century. Thin wax plates, paper sheets, wooden veneer were used as materials for cutting out elements, created structures, three-dimensional maps of the Earth's surface, landscape, technological equipment (forms for printing, castings). At the moment, the technology allows you to create structures and parts not manually, but on automated equipment and by 3D printing [3].

Cultivation methods involve the use of materials of different nature. Polymer materials, ceramics, metals and alloys, as well as titanium and aluminum alloys are used [4]. Machines in which, for example, metals are used as a material are divided according to the principle of feeding the material into: jet release, mixing the powder into a paste, surfacing with a jet feed and the most studied selective fusion of a metal powder with a powerful electron beam or selective laser fusion.

Selective laser fusion (SLS) technology is the process of manufacturing a product by layer-by-layer fusion of a powder, the particles of which are joined by melting them with the help of a laser beam that moves along a set trajectory. Today it is one of the most promising areas in the production of parts for the aviation and aerospace industries. Compared with traditional methods of creating products, SLS has a number of advantages [1; 5].

All SLS installations work on the same principle. First, a 3D model of the part is generated using CAD or scanning. The program divides the model into layers. A special device distributes a layer of powder on the surface of the substrate. The laser beam then melts the powder according to a specific algorithm, scanning the cross-section generated by the 3D model. After scanning each layer, the substrate on which the product is synthesized is lowered by a certain amount. The process is repeated, all layers of the product are made [6]. At the end of the printing process, the platform with the product is removed and the product is cleaned of the remaining powder. The thickness of the melted layer is usually about 30 microns, this is due to the quality of the resulting material and the possibility of complete further penetration without the formation of pores and discontinuities.

Aluminum alloys are widely used in the aircraft industry, and the modern technology of selective laser fusion will save time for manufacturing parts, but at the same time preserve the strength properties [7;8]. All mechanical characteristics and structure of the obtained parts will directly depend on the parameters of the SLS and at the same time differ from the properties of the part, which will be made by traditional casting methods with subsequent machining. In works [9-10] composite materials (CM) on the basis of aluminum matrix obtained by SLS technology are considered. These materials have a composite structure, that is, the dispersed phase is evenly distributed in the matrix, they are separated by a boundary and are not dissolved in each other. To create modern technology requires materials with a complex of properties that do not have standard metal alloys.

A rather narrow range of materials is used for SLS. The main requirement for the material for SLS-good casting properties to ensure alloying and continuity. For this reason, silumins are widely used, they are the most technologically advanced in casting. Al-Si alloys are used abroad: AlSi10Mg (ak9ch analogue), AlSi12 (AK12), AlSi7Mg. The most studied of them is the alloy AlSi10Mg [11-28].

2. Materials and methods.

The object of the study was a metal-powder composition of silumin system Al-Si-Mg-si, produced by gas atomization in FSUE "VIAM" with a given chemical composition, which is presented in table 1. The chemical composition of the powder was determined on the optical emission spectrometer MagellanQ8 according to GOST 24231.
### Table 1. Chemical composition of metal-powder composition of silumin [11]

| Alloy grade | Mass fraction of elements, % |
|-------------|-------------------------------|
|             | Core components               |
|             | Al   | Si    | Mg   | Cu   | Zr   | Ce   | Fe   |
| BAC1        | Base | 10.5  | 0.63 | 0.7  | 0.25 | 0.23 | 0.15 |

Samples were made from powder of 10-63 microns fraction according to the selected modes on 1 cube with a side of 20 mm for each mode, also samples were subdivided in the directions of printing. Printing took place along the z and x axes.

Production of metallographic samples of the alloy was carried out according to the traditional method. Etching was carried out in 0.5% HF. The hardness of the samples was measured using the EMCO-TESTDuraJet instrument on the HRB scale.

3. Results and discussion.

The microstructure of the alloy after synthesis has a characteristic "track" structure, this is shown in figure 2 (a, b). It consists of a supersaturated solid solution of aluminum and dispersed inclusions of silicon and intermetallics. On the surface in the longitudinal section traces of laser passage in the form of "scales" are visible, and in the transverse melt baths are ellipses of irregular shape.
Figure 1. The microstructure of the synthesized material: a) cross-section in the XY plane; b) longitudinal section in the xz plane; c) in general form.

When comparing the cast structure of the aluminum alloy Ak9ch and the synthesized sample from the powder composition (figure 2, b), it is seen that the structure of the synthesized sample is uniformly distributed particles of secondary fine phases in a solid solution of aluminum, while the cast structure shown in figure 3 has a pronounced dendritic structure.

Figure 2. The cast structure of the alloy AK9

The microstructure of the synthesized alloy depends on the parameters of the SLS. These parameters are intertrack distance, laser power, laser scanning speed. All parameters in the aggregate reflects the formula, which was given in [6].

\[ E = \frac{P}{v \times s \times t} \]

where \( E \) is the laser energy density (J/mm\(^3\)), \( P \) is the laser power (W), \( v \) is the scanning speed (mm/s), \( s \) is the distance between tracks (mm), \( t \) is the layer thickness (mm).

With different combinations of SLS parameters, samples with different porosity are obtained. As the energy density increases, the porosity of the synthesized material decreases.
To study the effect of heat treatment on the structure and properties of the material, a batch of samples from the metal-powder composition of the alloy under study was synthesized. The hardness of the synthesized sample without heat treatment is 76 HRB. The hardness of cast silumin is in the range of 52.6-57.1 HRB. In the process of synthesis, a high concentration of silicon in a solid solution of aluminum is achieved - up to 6-8%. The formation of a supersaturated solid solution, the presence of dispersed inclusions of silicon and intermetallics explains the high hardness values. Annealing of AlSi10Mg alloy was carried out at temperatures from 300°C to 450°C with a duration of exposure from 1 to 9 hours. Annealing at a temperature of 300 degrees, is taken for the lower threshold because at lower temperatures the relaxation of internal stresses does not occur completely [12-13]. The microstructures of annealed alloy samples are shown in figure 5.
The study of the microstructure showed that the annealing process is accompanied by a change in the structure. The hardness of the alloy also changes (figure 6). In the annealing process, eutectic silicon particles fall out of the solid solution of aluminum and coagulate, the material tends to an equilibrium state. The track structure is eliminated, the anisotropy of the structure is reduced, and therefore the anisotropy of the properties is reduced. This state is quite stable and devoid of flaws synthesized state and is quite applicable to aircraft parts.

The hardness of the alloy depends on the temperature-time parameters of the annealing mode (see figure 6). The graphs reflect the expected sharp drop in hardness as the temperature and annealing time increase. At 300 °C annealing and 3 hour exposure, a high level of hardening is maintained, but the anisotropy of the structure is not completely eliminated. Increasing the annealing temperature reduces the hardness and reduces the anisotropy of the structure and properties.

Figure 4. Microstructures of synthesized alloy samples after annealing:
a), b) - at an exposure time of 1 hour and T=300S and magnification ×500 and ×1000
c), d) - at an exposure time of 3 hours and T=300S and an increase of ×500 and ×1000
e), f) - with a holding time of 9 hours and T=450S and an increase of ×500 and ×1000
4. Conclusion

Methods of metallographic analysis was carried out to estimate the porosity of the samples grown on various regimes of selective laser melting. The dependence of the porosity and hardness of the samples on the laser energy density is established. With an increase in energy density of more than 50 j/mm³, the number of pores becomes less than 0.3%. As the energy density increases, the hardness of the synthesized material decreases. These data can be used in the further development of technologies for manufacturing products from alloys of the Al-Si-Mg system by the SLS method.

The structure of the synthesized samples has a track structure different from that of the cast sample having a C dendritic structure.

The effect of annealing on the structure and properties of Al-Si-Mg-silumin synthesized by 3D printing was studied.

It was found that during the annealing process, the material is softened, which is associated with the release and coagulation of silicon particles. The higher the temperature and duration of exposure, the higher the degree of softening. It was found that during the annealing process at 300 °C for 3 hours a relatively high level of hardness (57.5 HRB) is provided while maintaining the anisotropy of the structure. An additional increase in strength can be achieved by subsequent hardening treatment.

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