Peculiarities of additive technologies application in the production of gas turbine engine parts

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Abstract. In test research, the technology of the blades growing on the disk part of the titanium compressor wheel by heterophase laser powder metallurgy was applied. The experiments were carried out to select the optimal modes of the process, ensuring the absence of defects in the form of pores, non-melting, cracks. The influence of granulometric composition on mechanical characteristics was also investigated.

The optimal modes of the additive technological process, providing the formation of a defect-free structure and optimal mechanical properties of the blanks are found as a result of the experiments. The samples of titanium powder alloy Ti6Al4V and hybrid samples consisting of cast and powder materials were produced with the help of technology mention above.

Tests of the grown and hybrid samples were carried out to determine the mechanical properties. Studies of micro and macrostructure of the samples were produced. Calculations of the stress-strain state and dynamic characteristics for the initial and hybrid glare using the found mechanical properties were carried out. Preparing testing hybrid titanium wheel carries out now. This technology also can be used for repairs of blisks blades.

1. Introduction.

Aircraft engines are high-technology products, the manufacture of which involves innovative techniques. Technological viability and manufacturing costs are the key factors in the successful development of new engines.

Blisks compressors of gas-turbine engine are usually produced by machining from a single forging. The significant time and cost are required for this method of production.

The process of large compressor and fan wheels manufacturing can be simplified, for example, as follows. The blades may be created on the disk part of the wheel, manufactured by traditional technology, by a direct laser deposition technique from a powder alloy of the same chemical composition, as a disk part. With this blisks production method, the material utilization rate increases dramatically, and time costs decrease from several months to several days.

However to use this technique, it is necessary, as in all other technologies, to study of mechanical and strength characteristics of design especially the zone of connection of materials with different structures.
2. Designing of light disks.

To increase the strength of high-speed rotors drives turbines, it is often necessary to increase the thickness in the area of turbine disk hub. This leads to an increase in the mass of disks of gas turbine plants and engines.

Improving strength and weight characteristics of the disk is possible and based on the use of new design solutions. It is necessary to evaluate their effectiveness and feasibility from a technological point of view at the developing similar solutions. In works [1-9], various kinds of optimization were used for disk design: topological and parametric. For example, the result of work [1] was the design of the turbine disk from powder alloy FHG96, consisting of a rim, a hub and two disk bodies, i.e. hollow disk (figure 1a). Using parametric optimization [7-9], it was possible to obtain hollow structures of disks with a minimum mass satisfying the requirements of strength reliability (figure 1b, c).

![Figure 1. Hollow Disk Designs: a) the result of topological optimization [5], b) with a closed cavity, c) with a cut [7-9].](image)

As a result of computational studies it was established that the decrease in mass and the increase in cyclic life of hollow disks in comparison with disks of the same dimensions with one blade for the same operating conditions depends on the dimension of the disks. The largest gain in mass was obtained for small-sized high-speed disks and blisks - 30 and 45%, respectively, with an increase in cyclic life of 2.8 and 1.6 times.

3. Additive manufacturing methods of disks.

The most common approaches to the manufacture of turbine disks are the machining of stamped blanks and powder metallurgy. Hollow disks consisting of two parts can be produced by joining them by various welding methods, including rotational friction welding, hot isostatic pressing (HIP). However, the mechanical properties of the joining zone of disk parts by such methods are below the properties of basic material.

For the manufacture of hollow disks of turbines, direct laser welding methods can be used, in which the powder is fed directly into the action zone together with the laser beam. Using direct additive technologies, there are usually no restrictions on the object size. Configuration of the blank part is controlled by five-coordinate equipment (the possibilities of turning the equipment table and the manipulator) and the flowability of the powder. The powder used to realize direct additive methods has a dimension of the order of 50-100 μm.

One of such methods is the method of heterophase powder laser metallurgy (HPLM – LMD analogue) [10, 11]. Key point of the technology lies in the controlled melting of the powder particles in the laser radiation field, which is ensured by combining the gas-powder jet with the laser beam. The powder particles remain in a two-phase state (partially liquid and solid). Such material will have a fine grain structure after crystallization. The production of a hollow disk with a diameter of 260 mm with a closed cavity was made from a heat-resistant nickel powder alloy EI698P of a granulometric...
composition -100 + 63 (TU-1-809-56-2015) (Table 1) produced by OAO VILS, Russia. The distribution of powder particles by size and their physical form are shown in figure 2.

| Powder   | Content of elements, mass.% |
|----------|-----------------------------|
| EI698P   | Ni  | C  | Si  | Mn  | Fe  | Cr  | Al  | Ti  | Nb  | Mo  | W  |
| base     | ≤0.08 | ≤0.6 | ≤0.4 | ≤0.1 | 13- | 2.3- | 2.35- | 4.5- | 0.6- | 7.7- |
|          | 16  | 3.0 | 2.75 | 6.5  | 1.2  | 9.5  |

Table 1. Chemical composition of powder for HPLM technology.

Figure 2. a) Particle size distribution of EI698P powder, b) SEM photo of EI698P powder.

To obtain the hollow disk blank, the sequence of deposition was worked out by the method of HPLM. Formation disk is due to the superposition of beads, formed during deposition of the powder to the desired path. Powder is fed into the zone of action of laser beam, wherein the melt pool formed by melting of the substrate and powder. During subsequent crystallization, beads are formed. Due to the complete or partial re-melting of the filler material, a single lead is formed which is metallurgically bonded to the product.

A hollow disk with a closed cavity (figure 1b) is a rotation body. 3D model of the product is decomposed into individual ring areas with a given step along the radius and by displacement in the development of the trajectory of moving the manipulator. When carrying out the annular path, a separate closed bead is applied, their combination forms the final product (figure 3).
Some difficulty is represented by the zone where the cavity should be closed. Depending on the size of the gap between the disk bodies, this zone may be formed a slight gradual narrowing gap or the manipulation position of the object and the head construction. The photo of the disk blank after fabrication using the HPLM is shown in figure 4a. Product appearance after machining is presented on figure 4b.

There are additional requirements to the design of the product, which must be taken into account in the optimization of the design when using additive technologies. After fabricating of products by AT methods, a number of problems arise that need to be addressed, in particular, by post-processing. Depending on the chosen additive production method, such problems can include: porosity, surface quality, appearance of residual tensile stresses, anisotropy of properties, low mechanical properties and their instability, necessity of subsequent machining. These problems do not detract the benefits of using AT and must be solved for each specific case of manufacturing objects.

To reduce the porosity, the hot isostatic pressing procedure can be used. However, this procedure can only be applied to parts with open cavities. Correctly selected heat treatment helps to remove residual stresses.
Parameters such as surface roughness and anisotropy of structure and properties also affect the mechanical properties and functional characteristics of the parts produced by additive methods. In the manufacture of components with inaccessible cavities there is a problem to remove residual powder from these cavities. For example, in the manufacture of one of the disks with a closed cavity (figure 5), a fragment was formed from the remnants of a metal powder that had not been removed during the construction of the disk by the HPLM, the presence of which would negatively affect the operability of the disk.

4. Mechanical properties

To determine the mechanical properties of parts obtained from the powder alloy EI698P by the HPLM method, samples were prepared for tests for short-term strength and cyclic durability. During the tests, the influence of the deposition direction and heat treatment (HT) on the level of characteristics was investigated. To study the effect of anisotropy on mechanical characteristics, samples were cut from deposited rectangular plates in two directions. For some of the samples, the load axis of the load coincided with the direction of deposition, while in the other part, these directions are perpendicular to each other. The heat treatment applied to a part of the samples corresponded to the standard regime for parts produced by the HIP method from the EI698P powder alloy.

Strength characteristics are higher for specimens in which the axis of the specimen is perpendicular to the direction of deposition. The adhesion of particles between layers is worse than inside one layer. These conclusions coincide with the studies of other authors for different metallic powder compositions [12]. Figure 6 shows a tensile stress-strain diagram of heat-treated specimen, in which the axis of application of the load is perpendicular to the direction of deposition.
As the temperature of the test increases, the effect of anisotropy decreases. Analysis of the test results showed that cylindrical samples, which were subjected to heat treatment, have low and unstable tensile strength both at room temperature and at $T = 650 \, ^\circ C$. The values of yield strength and tensile strength are much lower than those of the wrought alloy. On the other hand the ductility characteristics are higher. Initial samples without heat treatment have low levels of hardness. After heat treatment, the hardness of the material increases noticeably and exceeds the reference data. The characteristics of the heat-treated sample have values of structural strength characteristics close to the reference data for the deformable alloy of EI698-VD, but the modulus of elasticity and the short-time strength limit are 5% below reference data of the EI698-VD alloy.

The effect of HT is observed in the low cycle fatigue tests for the asymmetric cycle ($R_\varepsilon = 0$) at 650 $\, ^\circ C$ and the strain range $\Delta \varepsilon = 0.6\%$. The heat-treated samples stood for 50,000 cycles without failure. The results of the tensile tests at room temperature of the heat-treated samples cut from the disk coincide with the reference for the alloy EI698-VD. Based on the results of testing the samples obtained with AT, a preliminary set of design strength characteristics of the EI698P was generated, which was used to correct the evaluation of the static strength and cyclic durability of the designed hollow disk.

5. Surface roughness

The surface quality of parts obtained by direct additive production methods is lower than the required values for use in aircraft engine building. In particular roughness can serve as a stress concentrator, contribute to a decrease in strength characteristics. To reduce the surface roughness, mechanical, electroerosive, hydroabrasive treatment, electrochemical polishing, chemical etching, sandblasting, shot blasting, ultrasonic liquid cleaning of internal channels, etc. are used.

The internal surfaces of the hollow disks are difficult to access or are not generally accessible for processing by conventional mechanical methods. To provide access to the disk cavity in the structure, holes located in one or another region of the disk or slots, for example in the hub part of the disk, must be provided. However, the presence of holes significantly reduces the cyclic durability of the structure, which can negate the advantages of a hollow configuration. In the disk made by the HPLM method, a narrow slot was made in the hub part, which allowed electrochemical polishing of the cavity using a special electrode.

Surfaces of closed cavities of disks can be processed in the manufacturing process. The method comprises manufacturing separately two parts of the disk, then joining them and forming a single blank part. Before joining the parts of the disk, it is possible to mechanically process of surfaces, which form the cavity.

To implement this method of manufacturing a hollow disk, the technology of growing the "Direct Metal Tooling" (DMT) of the Korean company “InssTek” was used, which is based on complete melting of the powder and rapid cooling of the melt, which leads, according to the “InssTek” [15], to almost 100%.

Based on this technology, models were designed, methods [13, 14] were developed, and disks with a closed cavity in size and configuration similar to those described above (Figure 1b) were made. The
disk model will be divided into 3 or 4 parts, two of which are internal (main and insert), and external closing ones. The manufacturing process was carried out in several stages.

![Manufacturing of hollow disk by “InssTek” [15].](image)

Figure 7. Manufacturing of hollow disk by “InssTek” [15].

Two main parts and a liner were made separately (figure 7), their internal surfaces after mechanical polishing and assembling form a disk cavity. Then, external closing parts were added to the assembly. The disks obtained by the described method have closed "clean" cavities from foreign elements with the required specified surface cleanliness.

Currently, a new direction is developing, so-called hybrid technologies - a combination of additive and subtractive (subtractive) technologies. The equipment of Japanese companies DMG MORI and MATSUURA combines printing laser heads and tools for machining (cutters, drills). The software controls the sequence of operations. As the AT used in the equipment of the named firms, there can be SLM or DLD. For example, the 3D printer LUMEX Avance-25 is able to laser-weld a metal powder with a laser by layer-by-layer laser cutting and process the construction part with a milling cutter, alternating these operations as needed.

6. Non-destructive testing

To non-destructive testing of the main GTE parts, which include turbine disks, higher requirements are imposed. The control of the disks is carried out at all stages of manufacture, starting from the stage of obtaining the blank. For disks produced by AT methods, non-destructive testing should take a special place and begin with the control of the process of growing the blanks. Hollow disks obtained by HPLM were investigated using various methods of non-destructive testing (luminescent penetrant testing, eddy current, electropotential and X-ray computed tomography) by which defects are revealed.

In one of the disks, the longest surface crack was recorded with a LYM1-OV control of 10 mm long (figure 8a). The maximum values of crack depths were recorded of 1.13 mm and 0.92 mm, respectively, eddy current and electro-potential methods (figure 8b). The length of cracks on the first disk according to the results of X-ray tomography was from 1.7 to 3.8 mm. The maximum recorded crack depth on the second disk was 2.7 mm and was determined from the results of X-ray tomography (figure 8c).
X-ray 3D inspection, applied to disks manufactured by the DMT method, showed no defects (figure 9a). The geometric dimensions of the resulting cavities when superposed on three-dimensional models coincided with the design ones (figure 9b).

The detected defects of the disk produced by the GPLM method did not significantly impair its load capacity. In tests on the RS-2C "CIAM" booster bench, the load-bearing capacity of the disk at a frequency of 30,200 rpm (90% of the rated breaking frequency) was confirmed. Disk can not be destroyed.

7. Conclusion
- Design-technological solutions for the production of hollow disks of turbines with the use of additive technologies (AT) have been developed.
- The problems arising in the manufacture of hollow disks by direct additive methods are formulated, the ways of their solution are outlined.
- Mechanical tests of EI698P alloy samples manufactured by AT methods were carried out. They showed the need to develop heat treatment regime for each manufacturing process.
- Several variants of hollow disks are produced by different methods. Their research was conducted by non-destructive methods of control.
- Preliminary tests of the disks on the booster stand showed satisfactory results.

Acknowledgement
The authors thank engineers of SMTU K.D. Babkin and A. Vildanov and engineers of CIAM N.V. Tsykunov, D.V. Shadrin, A.V. Semenov for participating in the work on optimization, refinement, control and testing of disks. The authors thank to the specialists of SovTest Service Ltd for tomographic inspection of disks and INSSTEK, which manufactured two disks using hybrid technology.
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