ACHIEVEMENT OF BIMETALLIC BLISKS INTEGRATED DISSIMILAR ALLOYS FOR PROMISING HIGH TEMPERATURE AVIATION GAS TURBINE ENGINES

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Abstract

The turbine wheel is a main part of the aviation engine which influences its characteristics. The turbine wheels design with disk-blades retention is limited by the possibility of design improvement in life increase, mass decrease and engine efficiently on the whole. Experience of integral mono wheels made of difference materials, manufacturing techniques, advantages of application in high temperature aviation gas turbines engines is considered as well as problems of designing.
The concept of creation and manufacturing of bimetallic disks with uncooled and cooled single crystal blades and disk parts of granulated alloy for advanced aviation turbines is discussed on the basis of the multidisciplinary analysis.

1 Introduction

Requirements to aviation engine are becoming more service. This results in the necessary to use new materials and designs.
The engine life increase and aircraft mass reduction is the major trend of development in aviation engineering.

In addition the increase of turbine efficiency is of great importance for engine development. These purposes can be achieved by increasing blade number and a decreasing disk diameter. The required number of blades is determined by gas dynamic efficiency.

The wheels with detachable joints of disk and blades do not allow to locate the required blade number based on gas dynamic efficiency due to some limitation, namely disk-blade retention strength. Besides the operation conditions of the wheel parts of the high pressure turbine are characterized by great non-uniformity of loading and heating, especially during aircraft evolutions.

Radial temperature gradients are especially high for the wheels of high pressure turbines.

That is why the requirements specified for disk and blade materials are different. Disk material must have high resistance to low-cycle fatigue and crack propagation at moderate temperatures (500-600°C), and the rim section subjected to higher temperatures (~650-750°C) must demonstrate, high stress-rupture properties. Blade materials can withstand temperatures up to 1150°C and must have high resistance to high temperature creep and low-cycle fatigue. But blade alloys are not so good at low temperature for disk-blades retention. Usually blades are formed of cast nickel base super alloys using directionally solidified (DS) or single crystal (SC) technologies. The powder alloys are often applied for disks.

The traditional approach to turbine wheel design based on application of disk-blades retention does not allow to improve design for lifetime increase, wheel mass decrease and engine efficiency improvement on the whole.

This problem can be solved by using materials of heterogeneous structure in the integrated bimetallic wheel (blisk).

1.1 Creation experience of hybrid blisks

Nowadays compressor blisks are used for reduction of wheel weight.
Turbine blades and disk cast together (blisks) were used in some engines for pilotless vehicles. The some blisks made of one alloy are already used for turbine without blades cooling

(blisk of In100 alloy for Williams F107-WR-100 engine).

The hot isostatic pressing (HIP) method based on compacting materials by means of high pressure treatment alloys to increase the resistance to low-cycle and high-cycle fatigue and creep rupture strength characteristics. This method (casting + HIP) was applied for BMW-RR T118 engine (blisk of Mar-M-247 alloy), AGT250/T63-A700B engine (blisk of Mar-M-246 alloy), for example [1].

Bimetallic and three-metallic blisks of different alloys were proposed to take into consideration the materials requirements. These blisks were developed by different companies. For examples, Williams Int. Company has constructed a blisk with blades of CMSX4 alloy, a rim of Mar-M-247 alloy and a hub of AF2-DA for pilotless vehicles. Honeywell and Hamilton Sundstrand companies have suggested to use a turbine blisk of two alloys for the auxiliary power unit (APU) 131-9 in B747NG, AirbusA320, new Comac 919 and AirbusA350 [2]. The wheel consists of a disk connected by means of diffusion welding or HIP with a ring having blades of single crystal alloy [3]. After the connection the blisk is exposed to heat treatment at lower temperature than temperature of diffusion welding. This method allows to have an optimum design that eliminates the possibility of occurrence of a great number of failures and provide a 10 … 20 % engine life increase that accordingly increases time between overhauls. One of the APU problems is the ingestion of contaminated air during ground operation that can lead to a quick deterioration of the engine. The blisk design of the wheel eliminates clearances available in the blade-disk retentions where corrosion can set by salts and other impurities in the air can begin.

Allison Company according to HPITET program has tested a bimetallic blisk of a high pressure turbine with a hub of granulated alloy and single crystal transpiration cooling blades for the maneuverable aircraft.

Nowadays blisks are supposed to use in the high-speed low pressure turbine. DREAM consortium is engaged in development of the engine with an open rotor and MTU AeroEngines within the CleanSky program designs a blisk with shrouded blades for the advanced high-speed low pressure turbine.

1.2 Manufacturing techniques of bimetallic blisks

The basic proposed manufacturing techniques of the turbine blisk include:

- electrochemical and mechanical methods of manufacturing of blades and disks from one forging and the subsequent compacting;
- the soldering of a junction of blades with a disk;
- blades and a disk joint by pressing at high temperature;
- ·welding by friction;
- cast blades and a granulated disk joint by HIP.

The choice of technology of the joint depends on the type of the engine and its parameters.

The first of mentioned above methods is used in case of small sized rotors with uncooled blades for liquid propulsion rocket engines with short life cycles. The brazed joints of blades and disk are characterized by the lower strength of a weld and stress shear sensitivity. The disadvantage of the welding by friction is the bending of fibers of the structure of the material in the zone of plastic deformation — the fibers near the joint are arranged in directions of friction and reach the external (lateral) surface of the welded parts. The joint with such a fiber location can be the origin of a fatigue failure in parts subjected to dynamic loading and in parts to be operated in aggressive environment – the origin corrosion.

The most advanced method is the manufacture of integral blisks by means of implantation of the building in the cast blades into the disks part of granular alloy using HIP technology.

The hard phased defectless joint of powder particles each other and with the surface of monolithic materials implemented during HIP allows to join the heterogeneous materials and design method and so parts having specified gradient properties [4]. The strength reliability of the joint zone is defined by structure and density. The structure is formed as a result of process of diffusion of alloying elements during the technological cycle of HIP and the subsequent heat treatment.

2 Special aspects of design turbine blisk

HIP process allows to create bimetallic blisks integrating cast blades and powder disk section that operate in optimal thermal and loading conditions and have sufficient strength and reliability in the joint zone. This method of the joint of blades with a disk section allows to eliminate such complex structural mechanical joints, as lock and flanging joints, as well as welded and soldered joints that are stress concentrators.

These advantages can be implemented only at solving the following problems:

- design of a optimal configuration of boundary zone in relation to properties and working conditions of a part;
- required level of properties of the material in the joint zone;
- required level of properties of the basic materials as a result of "compromise" heat treatment of the whole wheel.

The implementation of blisks in high pressure turbine structures has some advantages but at the same time proposes several special tasks. The main tasks are the following:

- choice of materials;
- implementation of new technological methods for a reliable diffusion bonding of alloys of different chemical composition and structure;
- design of the joint zone based on stress-strain state and strength calculations at operated conditions taking into consideration mechanical properties of the materials;
- possibility of damping blade oscillations;
- possibility of cooling at the rim for disk and blades;
- development of overhaul technology.

2.1 Strength properties of bimetallic joints

The choice of materials for blisks also depends on the engine type and its parameters: gas temperature, rotational speed, gas dynamic and centrifugal forces, established life and others.

Durability and reliability of the joint zone is defined by structure and density. The structure is formed as a result of the diffusion process of alloying elements during compacting and the subsequent heat treatment.

The isolated cast single crystal blades are subjected to heat treatment that provides homogenization of the solid solution and segregation of a reinforcing γ' phase of optimal quantity of after the blade cooling. The subsequent HIP process and heat treatment of blades and disc section at T=1200°C may result in the undesirable variation of the blade material microstructure. These variations are minimal for poly crystal material GS6U as the temperature of hardening coincides with the HIP temperature. Small particles of γ' phase and needle-shaped refractory phases can appear in the blades of GS26DS and GS32SC alloys after HIP and heat treatment. The chemical composition of GS32SC alloy contains rhenium (Re) and tungsten (W) that are included into needle-shaped refractory phases. There are no such elements in GS26DS and GS30SC alloys. Therefore the segregation of needle-shaped refractory phases into GS26DS after HIP and heat treatment is less. Besides the compacting during HIP causes the improvement of alloy properties and compensates the unfavorable effect of microstructure deviations.

So the choice of materials must base on the analysis of compound sample test results.

The detailed experimental study [5] of bimetallic samples has been carried out in the temperature range of 650°C…850°C at different types of loading.

The creep rupture tests (fig.1, 2), low cycle and high cycle fatigue tests demonstrate that durability and fatigue characteristics of bimetallic specimens coincides with the corresponding ones of the material, which is weaker among the two in the given conditions.

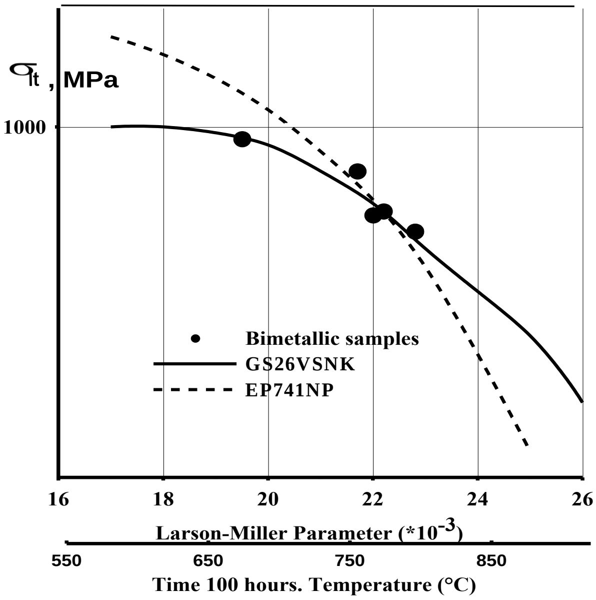

Fig. 1. Creep rupture curves for powder and DS cast alloys and test results of compound bimetallic samples

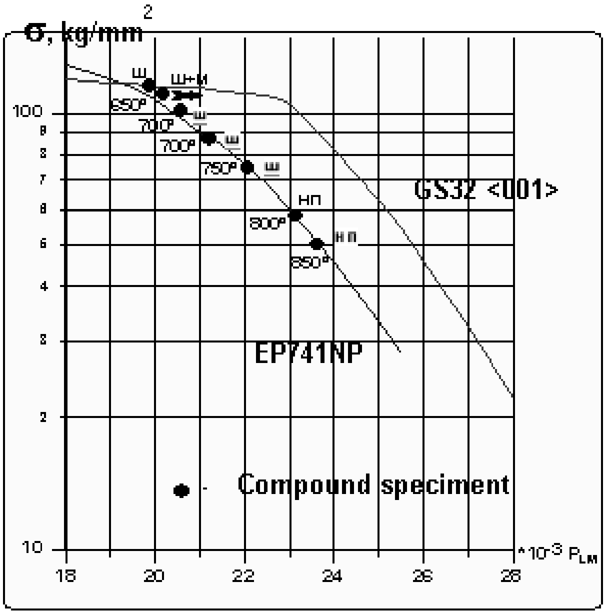

Fig.2. Creep rupture curves for powder and SC alloys and test results of compound bimetallic samples

The black points indicate the results of bimetallic sample tests. The fracture locations are shown by letters near the points.

The high cycle fatigue test results for EP741NP and GS30SC samples and bimetallic samples compound of both alloys are shown in figure 2. The levels of compound samples characteristics are no less than the properties of the alloy that has lower characteristics in the given temperature conditions.

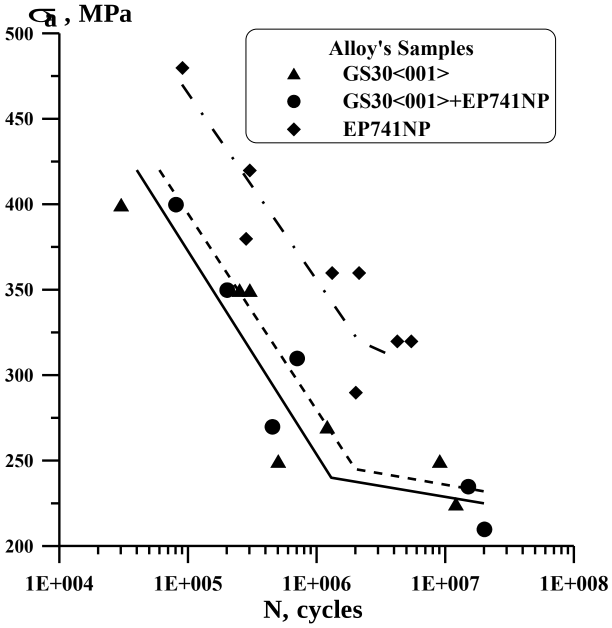

Fig. 3. High cycle fatigue curves of samples at the test temperature 650°C

2.2 Configuration and location of the zone of the disk and blade joint

The design of the configuration of the zone is based on the stress-strain state (SSS) at operation conditions. The blade root dimensions and geometry can be various.

The SSS analysis of the blade and disk joint has been carried out for the ‘classic’(with fir-tree root) wheel (I) and blisks with different configuration of the blade root (II, IV, V, VI) and without the blade root (III) using a 2D finite element method (FEM). Disk section of all structures is made of EP741NP powder alloy and blades GS32SC alloy. This zone of the joint is subjected to centrifugal forces caused by blade and thermal loading. The contact of teeth without friction has been taken into consideration (I). There is no such contact in the blisks (II-VI).

The calculation has shown that the butt joint is more apt in relation to strength [6]. The comparison analysis of the thermal state and SSS for several modifications of the turbine wheels has been carried out by FEM using 3D simulation.

A wheel sector has been taken as a model. The following structures have been analyzed: A-assembled wheel (blades of SC alloy and a disk of PM joined with the fir-tree root); B -

cast wheel (blisk of one cast alloy); D – bimetallic blisk (a root free structure manufactured by joining blades of SC alloy and a disk of PM by HIP); E–optimized bimetallic blisk D.

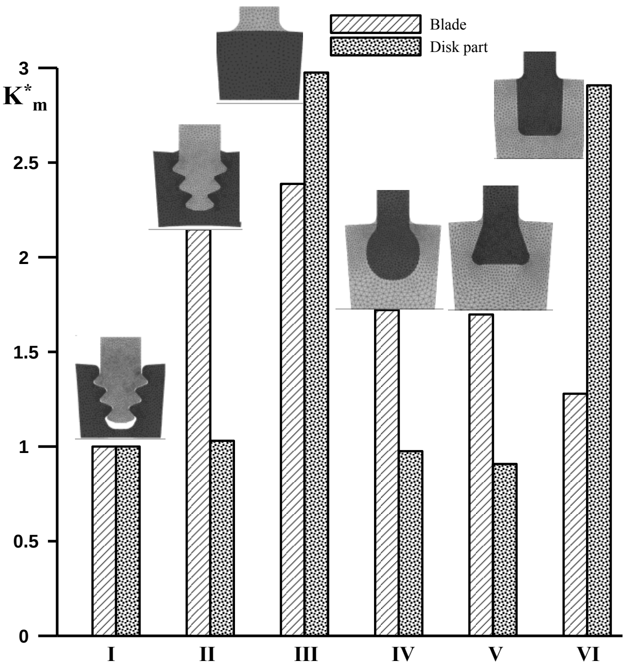

Fig. 4.Comparison diagram of minimal relative local safety margins (K^*_m) for different designs of disc and blades joint (light colour blades, dark disk section)

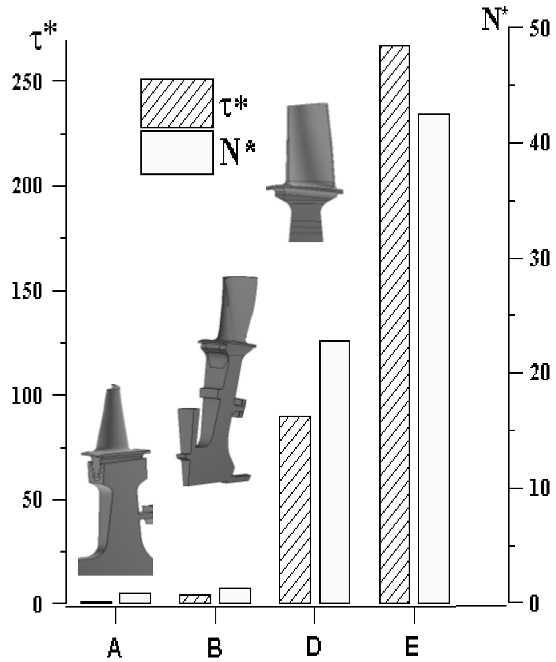

Fig.5.t Relative static durability and relative low cycle durability of different structures of a turbine wheels

The results of analysis of these structures are shown in figure 5, where are $\tau^* = \tau/\tau_{\min}$ - relative static durability, $N^* = N/N_{\min}$ - relative cycle durability. The estimation of the structures has shown the advantages of the bimetallic blisks compared with the structures using a fir-tree root joint. The cyclic durability of bimetallic blisk can be ~30 times more than ones of the wheel with a fir-tree blade attachment [7].

The location of the zone of the blades and disk joint can be chosen according to equality of creep rapture for both alloys in the range of temperatures at operation. The location of this zone can be established according with the operating time and the radial temperature distribution of the wheel.

For example, the test results (fig. 1) allow to make a following conclusion. The disk and blade alloys have equal creep rupture at temperature 620°C and durability of 100 hours. These properties of the blade alloy are better than the disk alloy t higher temperature and properties of the disk alloy are better at lower temperature. The “temperature - time” functional relation for the same value of creep rupture of both alloys is shown in figure 6.

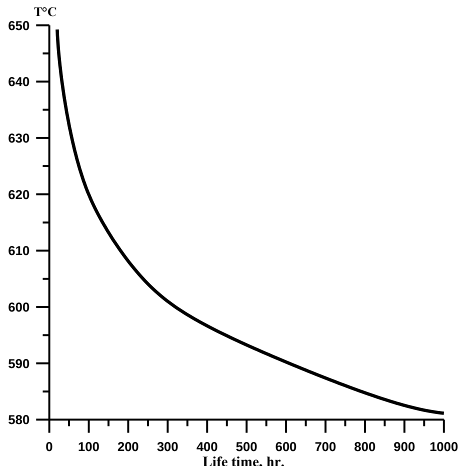

Fig. 6. Curve of equality creep rapture of disk and blade alloys at different temperature and operating time

3. Problems of blade oscillation damping

The absent of construction damping in the blades and disk joint results in the vibration stress increase. This problem can impose some restrictions on blisk usage. The main task of blisk design is to provide high resistance to oscillations. One of the major trends of solving this problem is designing of dry-friction damping units below blade platforms. It is possible if the blade has a long shank of a necessary size and the damper parameters by mass and rigidity are properly chosen. If there are no shanks the damping can be fulfilled by installing a clamping disk to ensure the contact interaction with a blade platform.

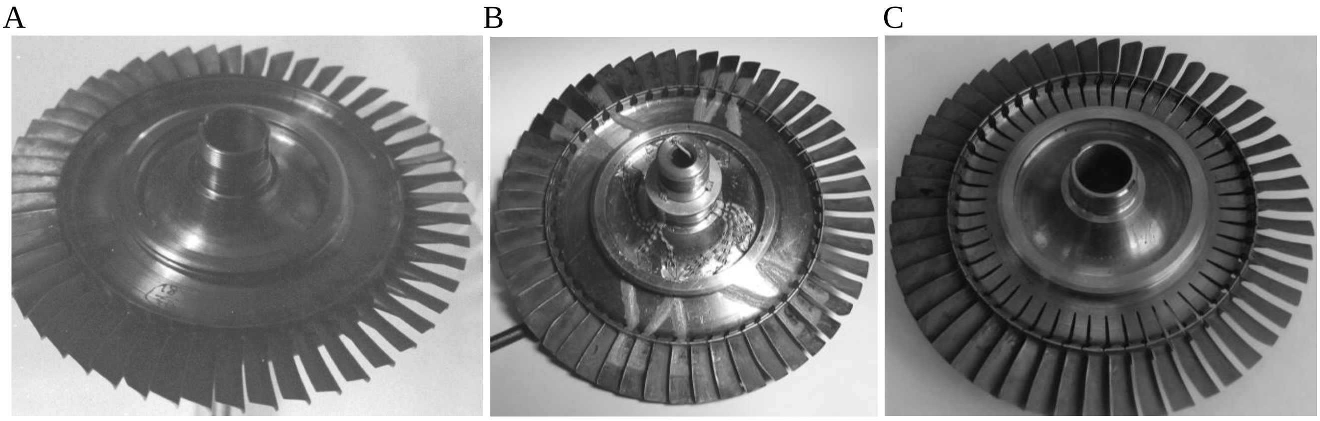

Fig.7. Bimetallic blisks. The blades: A) without shanks, B) with short shanks, C) with long shanks.

The experimental investigations of the bimetallic blisks of powder and cast Ni-base super alloys manufactured by a HIP process have been carried out at the resonance vibration excitation [8, 9].

The blades had different configurations (types “A”, “B” and “C”).

Type “A”. The blade root represents a billet for a root. The material joining surface runs along the blade root and platform (fig. 7A). There are no shanks, as well as clearances between the platforms.

Type “B”. The bimetallic blisk has blades with small shanks (fig. 7B). The shanks are made by burning through by an electric spark method. There are clearances between the platforms.

Type “C”. A new design of the blisk has been manufactured from the previous structure by burning through radial gaps in the disk section between the shanks by an electric spark method (fig. 7C). This process provides an elongation of the shank.

The Investigations of blisks “B” and “C” without and with units of different mass: 0.66g, 0.80g, 0.98g, 1.22g, and 2.5g have been carried out. The damping units of a tube-shape are installed between the blade shanks. Damping of blades of blisk “A” is performed by a pressure-exerting disk. The disk was pressed to blade platforms by different loads.

The level of resonance stresses has been determined during tests. The comparisons investigations of dynamic characteristics of blisk “A” without shanks and modified wheels with small and long shanks have been fulfilled.

The installed damping units increase a damping decrement of blade vibrations by ~ 4…7 times. The optimal damper mass for blisk “B” is 1.22g. The optimal damper mass for blisk “C” is 0.8-1.22g.

In addition the level of vibration stress is decreased by 4…7 times depending on the damper mass as compared to the case without damping units.

It is necessary are to take into account these dynamic characteristics during the design process of blisks.

These investigations will help to solve a problem of blisk oscillations.

4. Problems of blades cooling in blisk structures

The cooling of the rim part of disks with root joins and cooled and uncooled blades is achieved by scavenging through the clearances in the root joins. The blisks has no root joins therefore the cooling of the rim is a problem to be solved too. The cooling of the rim part of the disk is possible if the blades of the blisk have shanks. The air flowing under the platforms between the shanks and the rim provides cooling of the rim. Besides the shanks allows locate dampers.

Air supply systems for blade cooling in blisks require new design and technological proposals. The air can be supplied to the blades through channels in the disk formed during powder pressing at HIP (fig. 8a). The cooling air can be supplied to blades through holes in the shanks (fig. 8b). The other variant - the air can be directed into special air manifolds and channels (fig. 8c).

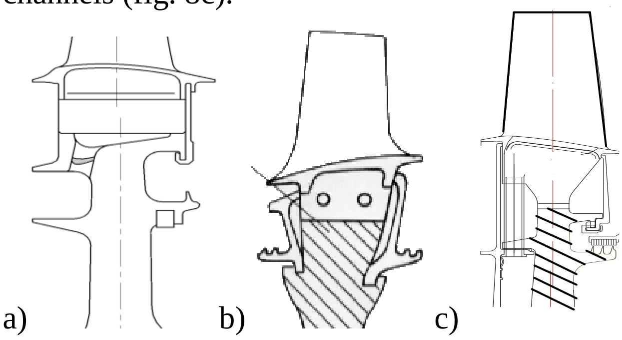

Fig.8. Air systems for cooling of blisk blades

The shortcoming of first scheme is the presence of holes in the disk rim that are stress concentrators in the high temperature zone. This result is the reduction of margins in cyclic durability. Besides, surfaces of the zone of the blades and disk part joint become smaller.

The design with air channels in the shanks can be more preferable. In this case there are no holes and channels in the disk part for supply the cooling air to the zone of the disk and blades joints. The air can be supplied by a special device directly to the blade shanks outside of the joint zones. It is necessary to provide special devices for cooling rim for example covering disks. The air channels (fig. 8b) are strongly bent at the transition from holes in the shanks to a profile part of the blades. This causes an essential increase of stresses in the zone of the channel bending.

The blisk has been designed according to the cooling scheme (fig. 8c) on the base of a wheel with the fir-three disk-blades joint. The thermal and strength analysis has shown the advantage of this scheme in comparison with the previous ones. The minimal local safety margins of the designed blisk are considerably higher than the admissible ones. It allows to improve the wheel durability by several times. Besides the reduction of mass of the optimized bimetallic blisk in comparison with the initial wheel is more than 33% [9].

Overhaul

The problem of failed mono wheels repair exists not only for bimetallic blisks of turbines, but also for widely used blisks of compressors. However it doesn't prevent from the application of such designs due to essential advantages compared to traditional designs.

The M88-9 engine has a HP rotor consisting of three mono-block titanium stages blisks [11]. The GE’s tech-X engine for business Bombardier aircraft Global 7000 and 8000 will have single - piece metal fan blisk in diameter of 1320 mm [12]. According to experts of the company such fan of a blisk type will eliminate typical problems of balancing, reduce vibrations and improve resistance to failure. There are no air leakage paths in the one-piece design. It can result in increasing the overall flight efficiency of the engine. GE conducts investigations on the choice of a blisk alloy and studies a possibility of quick replacement of such big wheel in case of its damage. F414 EPE has a new two-stage fan of a blisk technology. It provides a 10 % increase of air blow and allows to have a gas generator with higher temperatures. These improvements allow to ensure the hot section life increase by three times and improving the engine specific fuel consumption [2]. The application of bimetallic turbine blisks considerably improves life in comparison with the locking structure designs. It gives a possibility to increase considerably the time before overhauls.

The repair of a separate blade of the blisk is connected with the removal and disassembly of the turbine. The replacement of a defected blade of the bimetallic blisk can be carried out by the removal of this blade and attachment of a new blade by means of a diffusion welding. This process is carried out without melting - down of the basic metal at the expense of heating and squeezing of jointing parts. However repair methods for blisks aren't yet developed.

Advantages of blisk application in gas turbines

The advantages of the application of bimetallic blisks have been established on the basis of experimental and numerical investigations of turbine wheels [13].

The basic advantage of blisks is a possibility of 15-30 % of mass decrease of the wheel that results in the reduction of a rotor inertial effect, followed by the acceleration time reduction and simplification of the engine start.

The absence of blade - disk lock joints allows to prevent leakages, to solve a problem of the blade location on the disk, i.e. to provide the turbine lattice density required for high gas dynamic parameters that can result in the engine efficiency increasing.

The static strength and cyclic durability of blisks are several times more than ones of wheels with blade and disk lock joints due to the exclusion of stress concentrators in lock joints. It results in the life, speed rotation and gas temperature increase. The last leads to power increase and specific fuel consumption reduction.

Thus the multiple investigations show that the bimetallic blisks made by means of the joint super alloy blades and granulated disk sector by HIP can be success used for turbines of advanced gas turbine engines

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