Advanced materials and technologies for compressor blades of small turbofan engines

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Abstract. BACKGROUND: Manufacturing costs, along with operational performance, are among the major factors determining the selection of the propulsion system for unmanned aerial vehicles (UAVs), especially for aerial targets. OBJECTIVES: In this paper, the design requirements and operating parameters of small turbofan engines for single-use and reusable UAVs are analysed to introduce alternative materials and technologies for manufacturing their compressor blades, such as sintered titanium, a new generation of aluminium and an alloy based on titanium aluminides. METHODS: To assess the influence of severe plastic deformation (SPD) on the hardening efficiency of the proposed materials, the alloys in the coarse-grained and submicromonocrystalline states were studied. Changes in physical and mechanical properties of materials were taken into account. The thermodynamic analysis of the compressor was performed in a finite element analysis system (ANSYS) to determine the impact of gas pressure and temperature on the aerodynamic surfaces of compressor blades of all stages. RESULTS: Based on thermal and structural analysis, the stress and temperature maps on compressor blades and vanes were obtained, taking into account the physical and mechanical properties of advanced materials and technologies of their processing. The safety factors of the components were established based on the assessment of their stress-strength reliability. Thanks to nomograms, the possibility of using the new materials and the technologies was confirmed in view of the permissible operating temperature and safety factors of aerofoils. CONCLUSIONS: The proposed alternative materials and production technologies for the compressor blades and vanes meet the design requirements of the turbofan at lower manufacturing costs.

1 Introduction

Currently, one of the most promising areas in the aerospace and defence industry is the development of unmanned aerial systems for various purposes. They are based on unmanned aerial vehicles (UAVs) of both reusable and single use. Ukrainian and global manufacturers offer gas-turbine engines for UAVs of various types [1, 2, 3, 4]. While full-scale turboprops and turbofans, as a rule, are based on engines designed for manned aircraft, small turbofans have original structure [5, 6], which is determined by their application, as well as tactical and technical characteristics.

Small turbofan engines are designed for reconnaissance UAVs and cruise missiles such as R-360 Neptune, Kite, Kh-55, Tomahawk and Harpoon. The main features of their performance characteristics are a short life cycle (if used as weapons), small size and weight and, as a result, high thrust-to-weight ratio. Also, operation on an unmanned platform contributes to the fact that they are not subject to the aviation safety regulations. Such engines are produced by JSC Motor Sich and SE Ivchenko Progress and a number of foreign firms. Engines of this class have thrust in the range of 3.9 - 4 kN, a low bypass ratio and a small dry mass not exceeding 60 - 85 kg. At the same time, to ensure high efficiency, such turbofan engines rotate at several tens of thousands of revolutions per minute, which imposes a number of special requirements on the design of their components and selection of materials. First of all, they...
should have high specific strength under static loads and a relatively low manufacturing cost. At the same time, their durability, due to the short life cycle and lack of pilot, is secondary to them.

There are several modern technologies used for manufacturing gas turbines propelling UAVs [5]. When it comes to compressor blades, a number of candidate materials and technologies is considered, for example, sintered powder alloys; rare earth aluminium alloys; alloys based on titanium aluminides and others. To increase the strength and ductility of aircraft structural materials, the use of severe plastic deformation (SPD) technologies is promising [6, 7].

Currently, various types of titanium alloys are successfully used to manufacture compressor blades [8]. The most common are VT6 (Ti-6Al-4V), VT3-1 (Ti-6.7Al-2.5Mo-1.8Cr-0.5Fe-0.25Si) and VT8 (Ti-6.8Al-3.5Mo-0.32Si). For compressor stages with increased air temperature along the gas path heat-resistant titanium alloys of the VT25 (Ti-6.8Al-2.0Mo-2.0Zr-2.0Sn-1.0W-0.3Si) type are used [9, 10]. For the last stages of the compressor, taking into account the temperature level, heat-resistant nickel-based such as INCONEL 718 (EP718-ID) and similar are used. A common drawback of these materials, along with the high cost and energy costs of production, is their poor machinability. Having a combination of properties necessary for the compressor blades of an engine propelling manned aircraft, they are redundant when used on UAVs. This leads to increased cost of engines and UAVs in general. To meet the requirements for UAV power plants, it is necessary to introduce new materials and technologies, which reduce their manufacturing cost.

It is known that the use of sintered titanium alloys is an effective measure to reduce the manufacturing cost [11, 12]. However, the residual porosity and low ductility of sintered alloys are the reasons that up to now they are used in aircraft engine manufacturing for a narrow circle of lightly loaded, non-essential components [13]. At the same time, a number of studies [14] show that the characteristics of sintered titanium alloys subjected to additional strain hardening, and in some indicators exceed, similar values for alloys in cast and deformed states. In a number of works, based on the analysis of the stress-strain state of the aerofoils, it was shown that the safety margin of blades made of sintered titanium alloy with subsequent SPD, meets operating conditions [15]. However, an important factor limiting the use of alloys in the compressor design is the elevated temperature caused by air compression in the gas path. Information on the operating temperature of the compressor blades of small turbofan engines is very limited [16, 17]. Also, given the high rotational speed of the engine, close to 40-50 thousand revolutions per minute, stress calculation results are very sensitive to the uncertainty of the assumed pressure field.

The effectiveness of applying the alloys based on titanium aluminides in the last stages of compressor blades is controversial. On one hand, due to the combination of specific strength and heat resistance, they can be an effective replacement for traditional nickel-based alloys [18, 19]. On the other hand, the technology of their production and processing is quite energy-intensive, which makes them cost-ineffective in the case of small turbofan engines. While heat explosion is a significantly cheaper technology to synthesize such materials [20], their mechanical properties are not satisfactory for aircraft components, in particular for aero-engines.

In this case, a promising, cost-saving technology for the preparation of semi-finished intermetallic γ-TiAl alloys for aircraft, in particular compressor blades, is a technology based on the methods of self-propagating high-temperature synthesis and subsequent SPD of the initial blanks. Taking into account that this technology not only reduces the cost of manufacturing compressor blades, but also increases the level of their mechanical characteristics, assessing the possibility of their use in the design of engines for UAVs is an urgent task.

Given the high specific strength of aluminium alloys with lithium and scandium, which exceeds those of titanium alloys [21, 22, 23], their use in the design of the turbofan engine is no less relevant. However, it is necessary to take into account the temperature of the working medium since their heat resistance is significantly lower than that of titanium and nickel aviation alloys.

The aim of this work was to assess the strength margin of the blades of all stages of the compressor of a small turbofan engine and the possibilities of using candidate materials and processing technologies for their manufacturing. The main tasks, the solution of which is necessary to achieve the goal of work, were airflow simulation and obtaining pressure fields on aerofoil surfaces of all stages, determining the gas temperature, blade stress and assessing their static safety factor.

2 Materials and methods

The effectiveness of the use of candidate materials for manufacturing blades and vanes was evaluated for an axial compressor having the geometry and compressor maps representative for small turbofan engines.
The stress-strain state of blades was estimated by a coupled Finite Element Analysis, which included a flow calculation to determine the pressure field and a direct strength calculation to determine the field of acting forces [24, 25, 26]. The analysis was performed for a 6-stage axial compressor (Figure 1). The profile of the blades corresponded to the standard aerodynamic profile of NACA 7404 - 7405 AIRFOIL.

![Figure 1: Axial compressor](image)

Using the Unigraphics NX system, models of blades and vanes (one pair per each stage) and inlet guide vanes (IGV) were built. To develop the aerofoil profile, the surface modelling method was used, while for roots, the method based on Boolean operations with geometric primitives (Figure 2). To create finite element models, an ICEM CFD grid generator was used. The mesh models of the blades consisted of 15,000 - 18,000 hexagonal SOLID 186 elements. ANSYS Workbench version 2019 R3 was used for the calculations. Blades were fixed at the root plane.

![Figure 2: Structural model](image)

Temperature along the compressor gas path and pressure on the aerodynamic surfaces of the blades was determined by flow calculation in Ansys CFX with the finite element method. CFD model of the compressor inter-blade channel was obtained by arranging the domains of each compressor stage in the axial and radial directions.

To build a mesh of the compressor flow, the TurboGrid grid generator was used. Volumetric finite elements intended for CFD calculations were used. To reduce the required computing power, one blade was modelled for each compressor stage with the cyclic symmetry along the boundaries of the domain (Figure 3). The boundary conditions were set in the form of total inlet pressure, airflow at the compressor outlet, and rotational speed.

An interface between stationary and rotating regions (Stage Mizing-Plane) was defined on the mating boundaries of regions belonging to different steps, which allows for the interpolation between mating grids. A satisfactory criterion for the convergence of the calculation was the value of the mean square residual at the level of $10^{-6}$. This convergence was achieved at 1200 - 1400 iterations. We used the SST $k-\omega$ model of turbulence [27], as the most accurate and reliable for flows with a positive pressure gradient when flowing around profiles. At the inlet and outlet of the compressor, the mass flow rate and temperature were set corresponding to the emergency operation of the compressor. The adequacy of the simulation was evaluated according to the method described in [28].
The physical and mechanical properties of considered blade materials (Table 1) were determined via in-house tensile testing. The last column shows that materials after SPD become less heat-resistant because intensive grain grow begins at a lower temperature in their case. Tensile testing was carried out on the INSTRON 8802 servohydraulic machine under programmed loading at room temperature. The extensometer span was 25 mm. The specimen test portion strain was controlled with an accuracy of 1 μm. The accuracy of stress measurements in the test sample cross-section was ±3 MPa. Extensometer and spring dynamometer readings were ADC-processed and sampled with a rate of \( \Delta t=0.01 \text{s} \) [29].

To assess the stress-strain state of the blade and temperature distribution, a structural analysis was performed fed with the results of the flow calculation. The aerodynamic surfaces of the blades (pressure and suction sides) were loaded with the pressure and temperature fields obtained as a result of preliminary flow calculation.

### Table 1: Mechanical and physical properties of the alloys considered for compressor aerofoils

| Alloy and process | \( E \) (MPa) | \( \rho \) (kg/m³) | \( \text{UTS} \) (MPa) | \( \sigma_{0.2} \) (MPa) | \( \mu \) | \( E/\rho \) \( \times 10^6 \text{Nm/kg} \) | \( \text{UTS}/\rho \) \( \times 10^6 \text{Nm/kg} \) | \( T_{\text{max}} \) (°C) |
|------------------|----------------|------------------|----------------|---------------- |---|----------------|----------------|----------------|
| VT8              | 1.20 E5        | 4520             | 980            | 850            | 0.30 | 26.5           | 0.22           | 500            |
| VT8_spd          | 1.08 E5        | 4400             | 1250           | 1150           | 0.38 | 24.5           | 0.28           | 460            |
| VT8_spk          | 0.95 E5        | 4000             | 700            | 450            | 0.10 | 23.8           | 0.18           | 500            |
| VT8_spk_spd      | 1.10 E5        | 4400             | 1040           | 960            | 0.32 | 25.0           | 0.21           | 460            |
| Ti-46Al-5Nb-2W-spdk | 9.50 E4        | 4200             | 720            | 650            | 0.30 | 22.6           | 0.17           | 750            |
| Ti-46Al-5Nb-2W_spd | 8.50 E4        | 4100             | 920            | 880            | 0.34 | 20.7           | 0.22           | 680            |
| Al 88% Si 9.5%   | 6.90 E3        | 2700             | 75             | 60             | 0.33 | 2.6            | 0.03           | 120            |
| Al 88% Si 9.5%_spd | 6.20 E3        | 2680             | 203            | 180            | 0.35 | 2.3            | 0.08           | 100            |

UTS - ultimate tensile strength, SPD - alloy of a submicrocrystalline structure formed by SPD SPK (sintered metal powder) - alloy obtained by powder metallurgy methods

Typically, evaluation of new components is performed by the margin of static and fatigue life [30, 31]. Considering that fatigue proprieties of materials were not available, only the static safety factor (\( SF \)) was calculated with the following formula:

\[
SF = \frac{\sigma_{0.2}}{\sigma_{Mises}}
\]

where \( \sigma_{0.2} \) - conditional yield strength of the blade material, \( \sigma_{Mises} \) - maximum value of the von Mises stress in the compressor blades

### Results and discussion

The calculated values of the pressure fields on the aerodynamic surfaces of the blades, as well as the temperature of the flow around them are shown in Figure 4. The flow temperature (boundary conditions of the third kind) was used as the initial data to calculate the surface temperature of aerofoils. Given relatively small thickness of their profiles, temperature distribution over the cross-section was considered uniform.

Evaluation of stress distribution (Figure 5) made it possible to determine the possibility of using candidate materials and processing technologies in view of their structural integrity.
Figure 4: Pressure and temperature field on blade surfaces

(a) pressure field  (b) temperature field

Figure 5: von Misses stress in blades and vanes made from VT8_spk_spd alloy in engine emergency mode

Values of maximum equivalent stress and static safety factor of blades and vanes made from candidate materials are given in Table 2 and 3.

Table 2: Equivalent stress and static safety factor of blades made from candidate materials

| Rotor stage | R1 | R2 | R3 | R4 | R5 | R6 |
|-------------|----|----|----|----|----|----|
| Alloy/process | σ_{max} MPa | SF | σ_{max} MPa | SF | σ_{max} MPa | SF | σ_{max} MPa | SF |
| VT8         | 480.2 | 1.77 | 481.1 | 1.77 | 805.5 | 1.05 | 893.3 | 0.95 | 717.6 | 1.19 | 864.5 | 0.98 |
| VT8_spd     | 481.9 | 2.39 | 515.1 | 2.25 | 802.4 | 1.43 | 859.4 | 1.34 | 718.4 | 1.60 | 880.4 | 1.29 |
| VT8_spk     | 477.2 | 0.94 | 517.3 | 0.87 | 801.2 | 0.56 | 938.6 | 0.48 | 719.9 | 0.63 | 882.2 | 0.51 |
| VT8_spk_spd | 481.7 | 1.99 | 474.2 | 2.02 | 804.3 | 1.91 | 860.0 | 1.08 | 717.4 | 1.33 | 872.2 | 1.10 |
| TiAl        | 483.6 | 1.34 | 473.6 | 1.37 | 803.1 | 0.81 | 892.3 | 0.73 | 717.2 | 0.91 | 873.5 | 0.74 |
| TiAl_spd    | 483.6 | 1.82 | 462.9 | 1.90 | 801.3 | 1.10 | 877.3 | 1.00 | 717.5 | 1.23 | 885.5 | 0.99 |
| Al 88 Si 9.5 | 460.0 | 0.13 | 451.1 | 0.13 | 789.8 | 0.08 | 877.0 | 0.07 | 717.0 | 0.08 | 922.4 | 0.07 |
| Al 88 Si 9.5_spd | 460.0 | 0.39 | 450.9 | 0.40 | 789.0 | 0.23 | 868.7 | 0.21 | 717.3 | 0.25 | 928.3 | 0.19 |

Analysing the obtained data, we can conclude that the candidate materials and processing technologies can be used for manufacturing compressor blades. Considering that the analysis of the application area of titanium alloys by the criterion of temperature and strength is complicated due to the variety of technologies used for their preparation and processing, nomograms were developed for this purpose (Figure 6). Thus, for blades, VT8 alloy is limited to rotor stages 1-2 in terms of their strength reliability. The use of SPD methods expands the scope of its application up to the 7th stage; however, in terms of the level of the thermal state, VT8 usage is limited to blades of the first five stages.
Table 3: Equivalent stress and static safety factor of vanes made from candidate materials

| Stator stage | S1  | S2  | S3  | S4  | S5  | S6  |
|--------------|-----|-----|-----|-----|-----|-----|
| Alloy/process | $\sigma_{max}$ | SF | $\sigma_{max}$ | SF | $\sigma_{max}$ | SF | $\sigma_{max}$ | SF | $\sigma_{max}$ | SF |
| VT8 | 8.8 | 96.2 | 45.5 | 18.7 | 54.0 | 15.8 | 133.5 | 6.4 | 140.6 | 6.5 |
| VT8_sspd | 8.9 | 129.7 | 43.6 | 26.4 | 53.8 | 21.4 | 128.4 | 9.0 | 140.8 | 8.2 |
| VT8_spk | 8.8 | 51.3 | 48.9 | 9.2 | 53.7 | 8.4 | 140.2 | 3.2 | 141.1 | 3.2 |
| VT8_spk_spd | 8.8 | 84.6 | 44.8 | 16.7 | 53.9 | 13.9 | 132.4 | 5.7 | 140.6 | 5.3 |
| TiAl | 8.9 | 73.9 | 44.8 | 14.5 | 53.8 | 12.1 | 133.3 | 4.9 | 140.5 | 4.6 |
| TiAl_spd | 8.9 | 98.9 | 43.7 | 20.1 | 53.7 | 16.4 | 131.1 | 6.7 | 140.6 | 6.3 |
| Al 88 Si 9.5 | 8.5 | 7.1 | 42.6 | 1.4 | 52.9 | 1.1 | 131.6 | 0.5 | 140.5 | 0.4 |
| Al 88 Si 9.5_spd | 8.5 | 21.3 | 42.6 | 4.2 | 52.9 | 3.4 | 129.8 | 1.4 | 140.4 | 1.3 |

From these nomograms it can be inferred that the strength of the blades of all compressor stages, made of titanium alloy in the sintered state, is below the acceptable value (1.1 - 1.15). Therefore they cannot be used, despite the significantly lower manufacturing cost in comparison with an alloy in a deformed state. However, the use of SPD methods, due to the elimination of porosity, the formation of a submicrocrystalline structure in the entire cross-section and the homogenization of alloying elements, contributes to a significant increase in strength and, as a consequence, the expansion of their application at all stages [32, 33, 34, 35, 36].

At the same time, the operating temperature of the alloy in the submicrocrystalline state is lower than one in its standard form which does not allow for their use in 6th stage blades (Figure 6a). Considering that the compressor stator vanes experience a load only from the flow, the field of application of the VT8 alloy is limited only by its operating temperature, regardless of the technology of production and processing (Figure 6b). Despite the great strength, the sintered VT8 alloy synthesized from a mixture of powder components and subjected to severe plastic deformation, in comparison with the sintered alloy, has a smaller range of application due to the lower operating temperature. Taking into account the lower cost of obtaining sintered titanium alloys, it can be argued that for the 5th stage blades, their use is the most rational.

Alloys based on aluminium with a coarse-grained and submicrocrystalline structure according to the thermal criterion can be applied only to blades of the first and second stages. However, a safety factor assessment indicates that their applications are limited by stator vanes. At the same time, the use of modern aluminium alloys as the material for the blades is possible without the use of additional pressure processing technologies, which reduces the cost of their production. Given the low weight and cost of blades made of aluminium alloy compared to titanium blades, their use can be considered justified. Moreover, the well-known problems of such alloys as, for example, low hardness and resistance to sand erosion, are an uncritical factor for UAV engines.

Alloys based on titanium aluminides are the most heat resistant of the considered ones, which predetermines their use for manufacturing blades of the last compressor stages. From the point of view of the permissible operating temperature, this alloy can be applied to blades of all stages regardless of their structural state (Tables 1, 2, 3). At the same time, from the point of view of strength reliability for blades, their use is allowed up to stage 3 without additional strain hardening and up to 4th stage with processing by SPD methods (Table 2).

For all stator stages, the safety factor of vanes made from titanium aluminides is higher than the threshold regardless of the use of SPD (Table 3). Thus, this alloy is used for manufacturing vanes of stages 5 and 6, for which, due to temperature limitations, lighter titanium alloys may not be applicable. Nevertheless, the replacement of more heat-resistant INCONEL 718 alloys with titanium aluminides will reduce the weight of gas turbine engines.

It should be noted that the considered limitations associated with the temperature state of alloys in the submicrocrystalline state are determined based on the conditions of the onset of recrystallization processes. Considering that recrystallization processes take a relatively long time, exceeding the flight cycle of single-use UAVs (cruise missiles, disposable reconnaissance vehicles, aerial targets, etc.), this restriction can be removed for such turbofan engines. In this case, their use in terms of the maximum allowable temperature will be similar to alloys in a coarse-crystalline state. The calculated values of the safety factors for compressor components made from considered alloys and technologies let us propose their field of application (Figure 7).
4 Conclusions
The analysis of the thermal and stress-strain state of the blades and vanes of the compressor made it possible to develop recommendations for using alternative materials in a small turbofan:

(i) Vanes of the first fifth stator stages can be made of sintered VT8 titanium alloy without strain hardening. Respectively, the blades of the first fifth rotor stages can be made of sintered VT8 titanium alloy, subjected to SPD processing.

(ii) Al88-Si9.5 alloy regardless of the use of SPD, can be used to make vanes of S1-S2.

(iii) Titanium aluminides after SPD can be used to make 5th-stage blades but their application in the engine is irrational as VT8 works for this stage.
Future work should assess the effect of material properties on blade vibration and fatigue life. For the studied compressor, Campbell diagrams will be produced and the surge margin predicted.

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