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IMPROVING THE EFFICIENCY OF FINISHING-HARDENING TREATMENT OF GAS TURBINE ENGINE BLADES

Dmytro Pavlenko
Doctor of Technical Sciences, Associate Professor
Department of Aviation Engine Construction Technology**
Eduard Kondratiuk
PhD, Chief Technologist***
Yuriy Torba
PhD, Head of Experimental Testing Complex
Experimental Testing Complex***
Yevhen Vyshnepolskyi
Senior Lecturer*
Dmytro Stepanov
Corresponding author
PhD, Associate Professor*
E-mail: stepanov@zntu.edu.ua
*Department of Machine Building Technology**
**Zaporizhzhia Polytechnic National University
Zhukovskoho str., 64, Zaporizhzhia, Ukraine, 69063
***Zaporizhzhia Machine-Building Design Bureau Progress
State Enterprise named after academician O. H. Ivchenko
Ivanova str., 2, Zaporizhzhia, Ukraine, 69068

This paper considers the influence of the technology to finish and strengthen compressor blade tips made of EP718-ID alloy on the characteristics of the surface quality, surface layer, and bearing capacity. Taking into consideration the special role of the finishing-strengthening treatment in the formation of the quality of the surface layer, various options for blade tip processing were investigated. The blade tips were shaped by high-speed line milling. The finishing-strengthening stage of tip machining included manual polishing and ultrasonic hardening operations with steel balls in various combinations.

The basic regularities have been established in the formation of the roughness of tip surfaces, the maximum height of micro-irregularities, the surface microhardness, and the propagation depth of the hardened layer, depending on the combination of finishing-strengthening machining techniques. The results of tests are given for multi-cycle fatigue of blade batches treated according to various variants of the technological process. The efficiency of polishing the surface of the tip after strengthening treatment has been established. To restore the quality characteristics of the surface layer after polishing, it is proposed to perform repeated strengthening treatment. It is shown that the use of double deformation hardening technology with intermediate polishing at the finishing-strengthening stage of blade manufacturing makes it possible to increase the endurance limit from 320 MPa to 400 MPa while increasing durability. Technology for the finishing-strengthening stage of machining blades made from nickel alloys, characterized by significant viscosity, has been devised. It is shown that based on the criteria of minimum labor intensity of machining and maximum endurance of blades, it is effective to use double deformation hardening with steel balls in an ultrasonic field with intermediate polishing

Keywords: compressor blades, heat-resistant alloy, surface layer, finishing-strengthening processing, double hardening, endurance limit

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1. Introduction

The primary role of the condition of the surface and the surface layer of parts operating under variable loads is to provide their bearing capacity; that predetermines the use of finishing-strengthening operations at the final stage of the technological process of manufacturing.

The surface roughness, the mechanical characteristics of the surface layer material, as well as its residual stressed state, have a significant impact on the endurance of parts. By controlling them at the finishing-strengthening stage of the technological process when manufacturing, for example, compressor blades for gas turbine engines (GTE), it is possible to achieve an increase in the endurance limit up to 50...70 %. However, despite the cumulative role of each of the factors that determining endurance, the technological support of their rational values for nickel alloys, as well as alloys that are similar in the set of their physical and mechanical properties, is associated with a number of difficulties. One feature of such materials is high strength at relatively low hardness and a high tendency to deformation hardening. The inconsistency of properties and high sensitivity to technological heredity is the reason for the ambiguity in selecting methods and modes for the finishing-strengthening treatment of parts made from nickel alloys. On the one hand, in order to reduce the value of the technological concentration of stresses on the surface due to burrs and traces of previous machining, it is necessary to apply surface polishing. However, given the high viscosity of the material, the complexity of the polishing operation to ensure an average height of the micro-irregularity of the surface at the level of 0.32...0.63 μm is significantly higher than similar values, for example, for steels and titanium alloys.

At the same time, in the process of polishing, under the influence of force and thermal factors, in the surface layer there is not only relaxation of compressive stresses but also the formation of significant (up to 500...600 MPa) tensile stresses. The implementation of plastic deformation of the surface layer by static or dynamic methods for the purpose of hardening is also problematic. Along with increasing the microhardness of the surface and the formation of favorable compressive residual stresses, a regular micro-relief is formed on the surface of the parts, contributing to a decrease in their endurance. This issue is especially relevant for parts fabricated using additive technologies. Formed as a result of 3D printing, for example, the aerodynamic surfaces of the tip of the blades made of the EP718-ID alloy have characteristic surface defects and require mandatory finishing-strengthening treatment.

In this regard, it should be noted that despite existing body of research, the task to control the quality characteristics of the surface layer is relevant and is exacerbated in connection with the development of new materials and manufacturing technologies.

2. Literature review and problem statement

The sensitivity of the mechanical, physical, and structural characteristics of the surface layer material to deformation hardening makes it possible to control them in order to increase the bearing capacity of the parts [1]. The effectiveness of the use of surface hardening (SH) for parts from different classes of materials operating in the range of moderate temperatures is currently quite well theoretically substantiated and experimentally confirmed. The authors of [2] note the high efficiency of the use of ultrasonic processing to increase the endurance limit of samples from the Inconel 718 alloy. The increase in endurance is associated primarily with the riveting of the surface, the formation of compressive residual stresses, and the reduction of surface roughness. However, the cited paper does not address the issue of the complexity of achieving a favorable combination of characteristics of both the surface and the surface layer. The authors of [3], while noting the favorable role of SPD SH for parts from the nickel alloy EC79-ID point to the need to prevent excessive riveting of the surface layer under irrational hardening regimes. At the same time, the cited study considers the hardening of parts obtained only by the technology of hot deformation processing. The effectiveness of the application of finishing-strengthening machining for parts obtained by selective laser sintering is not investigated. The purpose of studies on the influence of SPD SH and various methods of finishing the surface of blanks sintered from powders is mainly a differentiated assessment of their effect on the quality of the treated surface. Their integrated application is not examined. Thus, work [4] experimentally studies the effect of various post-processes, including mechanical, abrasive, and impact machining on surface quality. In [5], the influence of a wide range of finishing-strengthening processing methods is further analyzed from the point of view of residual porosity and the stressed state of the surface layer. In both works, the surface layer of samples from the Alloy Inconel 718 obtained by selective laser sintering was investigated. It is noted that it has low quality characteristics but the final vibration hardening can significantly improve them. As a criterion for machining efficiency, the cited works do not consider the durability of hardened parts.

Among the methods of post-processing without material removal aimed at increasing the durability of parts, the most common is pneumatic blasting and ultrasonic processing. Pneumatic blasting of Inconel 718 samples results in a significant increase in fatigue resistance characteristics compared to non-hardened samples [6]. In work [7], the influence of the mode parameters of pneumatic-threaded blast hardening on the properties of the surface layer of parts from Inconel 718 is investigated; their rational combination is established. However, the authors of the cited work and of most available studies in the field of finishing and hardening of GTE parts consider the main effects of their application in terms of exclusively increasing the special properties of parts. At the same time, the issue of increasing the efficiency of processing, from the point of view of laboriousness, is not given attention.

It is known that the main effects of the use of surface plastic deformation methods are provided both by directly increasing the strength of the surface layer [8] and by inducing compressive residual stresses [9]. However, the cited studies do not pay attention to technological stress concentrators, which can have an equally significant effect on the endurance limit. The authors of [10] noted the possibility of obtaining SPD SH of gradient materials, which makes it possible to alter their strength and plasticity. Great attention in science and technology to materials with a heterogeneous structure due to their high structural efficiency is also noted by the authors of work [11]. However, the hardening coefficient, defined as the ratio of the endurance limit of a hardened part to an untreated part, can vary significantly depending on the material, hardening modes, as well as the operating temperature [12].

The influence of SH methods on surface roughness is also ambiguous and is determined by both the material of the part and the hardening technique. The use of static methods of hardening, for example, diamond ironing [13], leads to a decrease in micro-irregularities on the surface of the part. At the same time, the application of dynamic methods, for example, hardening with a free shot, can lead to both a decrease and an increase in surface roughness [14]. Polishing surfaces by hand or vibration helps reduce roughness and strengthen the surface layer [15]. At the same time, the effectiveness and, consequently, the laboriousness of the polishing operation is typically determined by the hardness of the treated surface [16]. Mechanization of the polishing operation through the use of polymer-abrasive tools contributes to a significant reduction in its labor intensity [17]. However, in this case, it is necessary to provide a combination of processing modes in which there is no melting of the polymer fiber and overheating of the surface.

To increase the efficiency of the polishing process, the scientific literature also provides information on the use of methods for locally reducing the viscosity of the surface layer material, for example, by cold treatment. In [18], it is shown that the microhardness of the surface layer of titanium alloy samples after ultrasonic shock treatment in argon increases by 3...3.5 times. Despite the positive effect of cooling parts before SH, this technology, taking into consideration the large-scale type of production, is not used in the fabrication of GTE blades.

Existing technologies are based on the removal of stitches on the surface of the blade tip from previous high-speed milling by manual or vibration polishing [19]. For complex surfaces, such as the surfaces of the grooves of the compressor discs of the «dovetail» and «pigeon tail», treatment in the medium of pseudo-liquefied abrasive is used. For surface hardening, the use of dynamic methods based on the collision of steel balls with treated surfaces is common, including for parts obtained on the basis of additive technologies [20]. Analysis of the features of the application of finishing-strengthening methods reveals that today they are used consistently. At the first stage, the quality of the surface is ensured, and at the next stage, the surface layer is ensured. At the same time, given, in some cases, their multidirectional effect on the surface and surface layer, such a processing technology may not lead to a significant increase in endurance [3]. In some cases, when machining tips of the blades for a high-pressure compressor made of EP718-ID alloy, an increase in the complexity of polishing was noted in comparison with a similar operation performed for steel blades. Significant differences in the topography of the surface of the transition zone of the studied blades indicated the instability of the manual polishing process [21].

Thus, despite the large amount of information on the application of finishing-strengthening processing methods in the production of GTE parts, our review of the literature indicates a number of contradictions and problems related to their practical application. For parts made of nickel-based alloys, characterized by high relative strength and low hardness, the main task is to ensure high surface quality when polishing. Surface quality must be ensured while maintaining a favorable residual stressed state of the surface layer and the rational labor intensity of the operation.

3. The aim and objectives of the study

The purpose of this study was to devise a technology for improving the efficiency of the final stage of processing parts from nickel-based alloys through the integrated application of finishing-strengthening processing methods on the example of GTE blades. This will reduce the complexity of the final stage of the technological process while ensuring high performance of the endurance of the parts.

To accomplish the aim, the following tasks have been set:

– to investigate the effect of manual polishing on the roughness of the surface of the blade tip, the quality of the surface layer, and the labor-intensity of the operation after high-speed milling and deformation hardening in various combinations;

– to establish the most rational technology for the finishing-strengthening stage of the manufacture of blades according to the criteria of labor-intensity of processing and endurance.

4. The study materials and methods

The object of this study was the technology of finishing-strengthening treatment of the tip of blades for the 6th stage of the high-pressure compressor in the gas turbine engine D-18T, made from the alloy EP718-ID (KHN45MVTBYUBR). The subject of our study was the parameters of the quality of the surface and surface layer, as well as the limit of endurance of the blades. The main hypothesis of the study assumed that the labor-intensity of polishing the tip of blades decreases as the hardness increases. The experience of manufacturing compressor blades at GP «Ivchenko-Progress» demonstrated that polishing of viscous alloys is associated with the formation of «influxes» on the treated surfaces. Achieving the required surface quality is accompanied by a significant increase in the operation labor-intensity. Preliminary increase in hardness due to deformation hardening increases its manufacturability. At the same time, the current study assumes that the quality of the surface layer is determined by the degree of riveting and the thickness of the hardened layer.

The aerodynamic surfaces of the blades were shaped according to the procedure described in work [22] at the high-speed machining center Starrag-051B/C. Annealing was performed after milling to relax inner stresses.

We studied the surface roughness parameters at the profilograph-profilometer of model 171621, produced in Ukraine. For metallographic studies and evaluation of the parameters of the surface layer riveting, we used samples cut by the electro-erosion method from the blade tip and transition zone (Fig. 1, *a*, *b*). The core and surface layer of the tip were examined (Fig. 1, *c*).

The deformation parameters of the surface layer were investigated by measuring microhardness at different distances from the surface on «oblique micro sections». The measurement was carried out at the Vickers microhardness tester MICROTECH® HVA-1, made in Ukraine, with an indenter load of 50 g and a loading time of 30 s [23]. Oblique micro sections were made by pouring at an angle of 5...9° transverse section of the blade (Fig. 1, *c*). The angle of an oblique micro section was provided by installing the sample when poured into a paper clip. The installation angle of each sample was measured from a 50-fold magnified and digitized X-ray image of the samples (Fig. 1, *d*) with an accuracy of 0.01°.

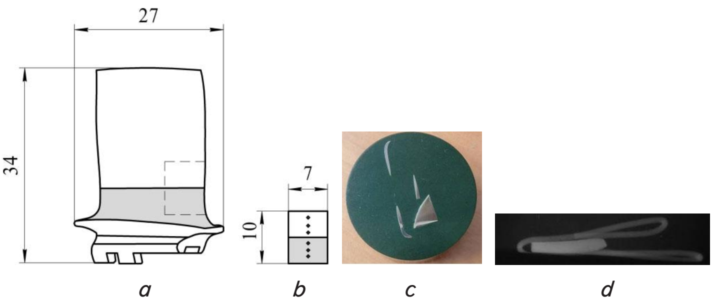


Fig. 1. Sample cutting from blades (transition zone shown in grey): *a* — sample cutting scheme; *b* — a sample for studying the quality of the surface layer with the location of points for measuring microhardness on the surface; *c* — metallographic «oblique micro section»; *d* — X-ray image to determine the angle of the «oblique micro section»

Fatigue tests were carried out on full-scale compressor blades according to the methodology reported in [24] at the equipment of SE «Ivchenko-Progress» (Ukraine). The tests were performed at room temperature on an electrodynamic vibration bench equipped with a device for automatically maintaining the amplitude of oscillations of the cantilever end of the blade. The test base was 10^7 cycles.

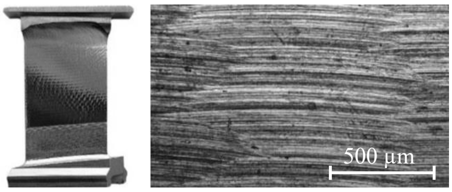
Plastic deformation of the aerodynamic surfaces of the blade tip was induced by the kinetic energy of steel balls in the ultrasonic field. Standard ultrasonic equipment, made in Ukraine, was used: the ultrasonic generator UZG 2-4M with feedback; the magnetostrictive converter IMS-15A-18; strengthening bodies – steel balls according to GOST 3722-81. The oscillation frequency of the wave concentrator was 17.5 kHz, which corresponds to the resonant frequency of the system «wave concentrator – hardening bodies». The resonant frequency was determined by the maximum value of the kinetic energy of the balls using a hardening intensity sensor and the amount of sound pressure that is generated by the walls of the concentrator. Hardening was carried out according to the following mode: the diameter of the balls is 1.6 mm; hardening time is 10...15 min; processing intensity is 4.1...4.2 mV; the total mass of balls is 400 g.

5. Results of studying the effectiveness of finishing-strengthening processing technologies

5. 1. Results of investigating the quality of the surface and surface layer of the blade tip and the labor-intensity of manual polishing

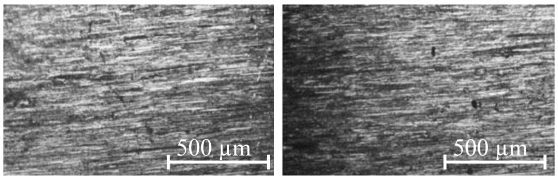
The structure of the technological process of manufacturing compressor blades in pilot production includes the stages of fabricating individual blanks from round rolled products. The main operations of tip and shank shaping are high-speed milling (HSM), manual polishing, and ultrasonic shot peening (USP). The micro profile of the surface of the blade tip after HSM is characteristic of parts machined by line milling (Fig. 2). We observed the formation of a regular microrelief directed in a transverse direction relative to the axis of the blade. The width of the milling lines was 0.7 mm.

Manual polishing of the blade tip made it possible to partially eliminate the unfavorable, from the point of view of bearing capacity, micro-relief after high-speed milling (Fig. 3). As a result of the study of the topography of the surface of the blade after polishing, it was found that transverse burrs were still observed on several blades. Differences in the topography of the surface areas of the transition zone of the studied blades indicate the instability of the manual polishing process, which, in turn, can lead to a decrease in the performance characteristics of the blade.



a *b*

Fig. 2. Compressor blade surface quality after high-speed milling: *a* — blade tip; *b* — milling lines



a *b*

Fig. 3. Aerodynamic surfaces of the blade tip after high-speed milling and manual polishing: *a* — backrest; *b* — trough

To reduce the influence of unfavorable technological heredity from previous processing methods, it was proposed to additionally perform SH with steel balls in an ultrasonic field. In order to determine the optimal variant of finishing-strengthening treatment, four batches of blades were manufactured, machined according to various technological schemes (Table 1).

Analysis of profilograms and parameters of the roughness of the blade tip (Fig. 4) indicates that the use of ultrasonic hardening after HSM (batch 2) significantly improves the roughness R_a, from 5 to 2.5 µm. However, transverse burrs remain on the surface. The presence of large peaks, up to $R_{\max}$ of 4.1 µm, can lead to the subsequent formation of fatigue cracks.

Table 1

Variants for blade tip finishing technologies

Batch No.	Treatment technology
1	HSM (initial, after annealing)
2	HSM+USP
3	HSM+USP+manual polishing
4	HSM+USP+manual polishing+USP

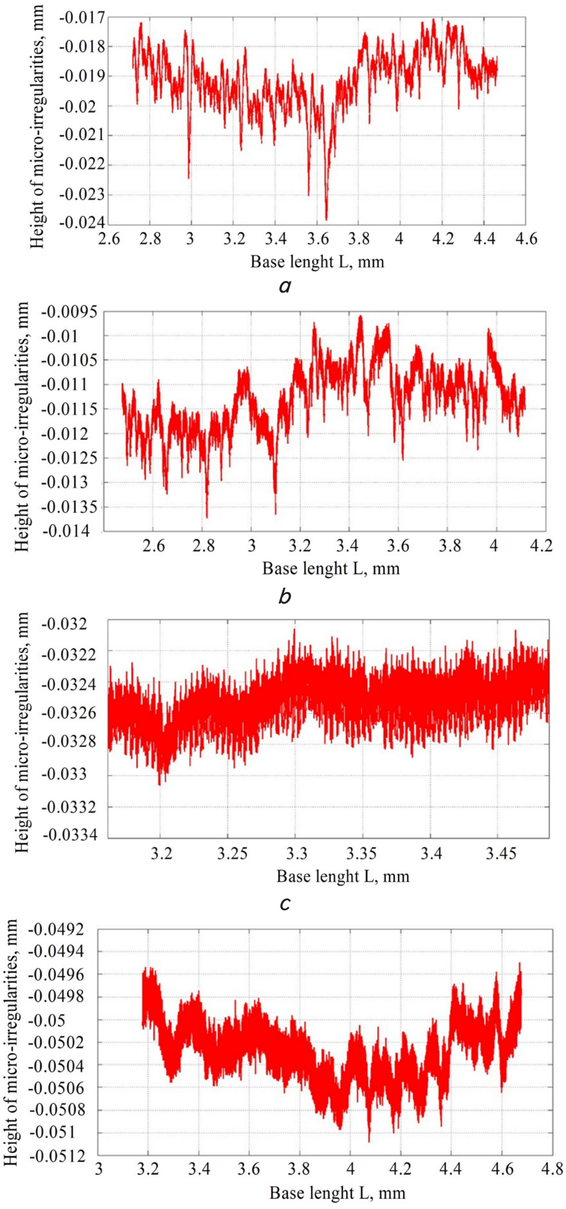


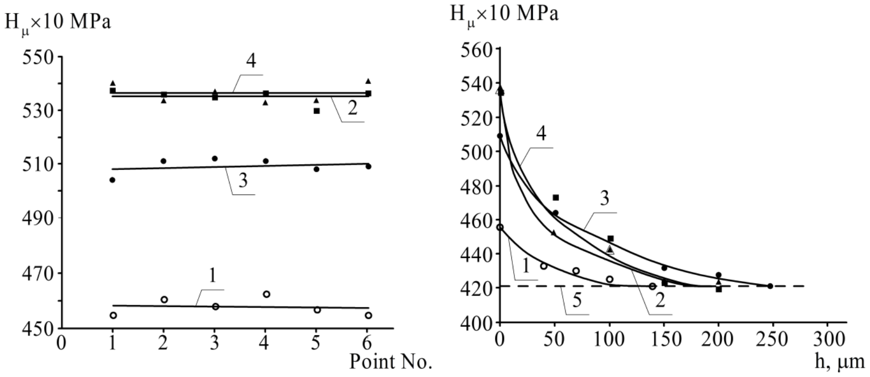
Fig. 4. Profilograms of blades made of EP718-ID alloy, manufactured according to different variants of the technological process of the finishing-strengthening stage: *a* — batch No. 1 (R_a 5.0 µm; $R_{\max}$ 6.7 µm); *b* — batch No. 2 (R_a 2.5 µm; $R_{\max}$ 4.1 µm); *c* — batch No. 3 (R_a 0.6 µm; $R_{\max}$ 1.0 µm); *d* — batch No. 4 (R_a 0.8 µm; $R_{\max}$ 1.0 µm)

Manual polishing after ultrasonic hardening (batch 3) significantly reduces the average value of micro-irregularities, to Ra 0.6 μm, but, at the same time, the surface layer is decomposed and removed within the removable allowance. Repeated ultrasonic hardening after polishing (batch 4) slightly worsens the roughness parameter Ra, from 0.6 to 0.8 μm, but leads to the restoration of the hardened layer.

Our study of roughness has made it possible to establish that from the point of view of the quality of the aerodynamic surfaces of the blade tip, the most rational treatment technology is double hardening with intermediate polishing (batch 4).

The microhardness on the surface of the back of the tip of the blades, strengthened in all the studied variants of the technology, exceeds the values for the blades of the original batch (Fig. 5, *a*). However, polishing a pre-hardened tip leads to a decrease in the microhardness value, from 535 MPa to 510 MPa, which is probably a consequence of the thermal factor and partial removal of the riveted layer. The subsequent repeated SH operation leads to the restoration of microhardness, the value of which is about 530...540 MPa. At the same time, there is a decrease in the depth of the riveted layer by 25...30 %, which is also probably associated with the wear of the surface layer and its plastic deformation (Fig. 5, *b*).

Thus, our analysis of the magnitude and nature of the distribution of microhardness on the surface and in the surface layer of the blade tip has made it possible to establish the most rational processing technology. The most favorable state of the surface layer, in terms of the magnitude and depth of deformation propagation, is achieved with double hardening with intermediate polishing (batch 4). Repeated use of USP after polishing completely restores the microhardness of the surface obtained after the primary hardening.



a *b*

Fig. 5. Distribution of microhardness after different variants of finishing-strengthening treatment: *a* — on the surface of the blade tip; *b* — in depth; 1...4 — blade batch numbers, 5 — core

5. 2. Assessment of the endurance of blades and the choice of a rational technology for finishing-strengthening treatment

Despite the significant role of the quality of the surface and surface layer in ensuring the bearing capacity of the blades, they are its indirect assessment. Taking into consideration the peculiarities of the operation of compressor blades, in which they are exposed to periodic loads from the gas flow, the most important characteristic that determines their bearing capacity is the limit of endurance during multicycle loading. Thus, the choice of a rational technology for finishing-strengthening the tip of blades is based on the criteria of minimum labor intensity of processing and maximum endurance.

Our analysis of the endurance curves of the tested batches of blades has shown an increase in both the endurance limit and the limited durability of the blades in the case of double-hardening technology (Fig. 6).

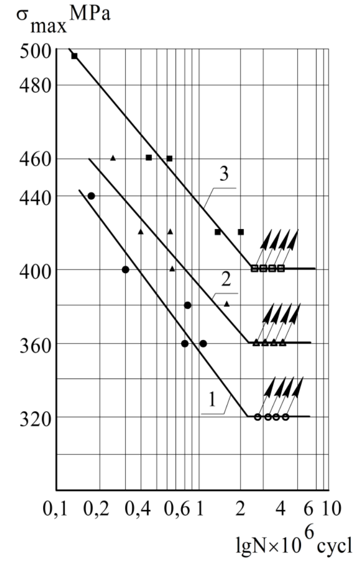


Fig. 6. Endurance curves of blades made of EP718-ID alloy, manufactured according to various variants of the technological process of the finishing-strengthening stage (1, 2, 3 — batch numbers of blades)

The endurance limit of the batch of blades after polishing and USP (batch 2) was 360 MPa, which was 40 MPa higher than the endurance limit of the blades after HSM. The use of double hardening technology made it possible to ensure the endurance limit at the level of 400 MPa, which is 40 MPa higher than the values for blades with a single hardening, and 80 MPa of blades after milling. It should be noted that along with the increase in the endurance limit, there was also an increase in strength in the area of limited durability. Thus, at a stress of 440 MPa, the durability of the original blades was $0.18 \cdot 10^6$ cycles, and for once and twice hardened – $0.38 \cdot 10^6$ and $0.8 \cdot 10^6$ cycles, respectively.

6. Discussion of results of studying the effectiveness of finishing-strengthening treatment technologies

The results of our study into the quality of the surface and surface layer of the blade tip both after separate technological operations and their complex use allow us to form a strategy for building a finishing-strengthening stage of treatment. Given the poor workability of viscous materials with abrasive tools and the tendency to deformation hardening, it is rational to carry out the SH operation twice.

In the first case, it is performed immediately after HSM. Despite the presence of significant stitches from the previous treatment, the use of USP at this stage of the technological process helps increase the hardness of the tip surface (Fig. 5). At the same time, the amount of surface roughness remains almost unchanged and does not meet the requirements of design documentation (Fig. 4). An increase in the hardness of the material contributes to a significant reduction in the labor intensity of the subsequent polishing operation, which helps reduce roughness with partial de-strengthening. The subsequent USP operation restores the hardened layer, practically without changing the quality of the surface due to the characteristic ultrasonic treatment of the «soft» interaction of the strengthening bodies with the surface. At the same time, despite the increase in the total number of operations in the technological process, the total labor intensity is reduced by 4...6 % by reducing the complexity of the manual polishing operation.

Simultaneously with reducing the labor intensity of the technological process, improving the quality of the surface and surface layer, the use of double SH provides for an increase in the endurance limit of the blades by 25 % (Fig. 6). The main reasons for increasing endurance when using double-hardening technology are to reduce the size of technological stress concentrators on the surface while effectively hardening the surface layer. At the same time, the hardening of the surface layer can be considered both from the point of view of a direct increase in the hardness and strength of the material, and from the point of view of the formation of favorable compressive residual stresses.

In the process of both HSM and polishing and USP, it is possible to control the magnitude and depth of residual stresses within certain limits [3]. Given the well-known role of technological residual stresses in increasing the endurance of compressor blades, at the next stage of the study it is rational to establish the patterns of their formation, taking into consideration technological heredity. In this regard, a comprehensive study of the heredity of the stressed-strained state of the surface layer and the optimization of the modes of individual technological operations will make it possible to achieve a further increase in the endurance limit of the blades.

The proposed technology of finishing-strengthening treatment can be extended to a number of other parts and materials prone to deformation hardening, for example, titanium alloys. The ultrasonic hardening modes in the first and second stages, in this case, should be selected so as to prevent excessive riveting of the surface layer. In addition, the technology of double hardening can be used in the manufacture of other parts, both gas turbine engines and parts of rocket and space technology. The main criterion for the rationality of its use is the need to ensure high quality of the surface and surface layer. However, taking into consideration the need to increase the total number of technological operations, the rationality of its application should be assessed by the results of the study of technological heredity.

7. Conclusions

1. Based on the analysis of the effect of manual polishing on the roughness of the surface of the blade tip, the quality of the surface layer, and the labor-intensity of the operation in various combinations, it was found that it reduces the average height of micro-irregularities from 5 μm after high-speed milling and 2.5 μm after ultrasonic hardening to 0.6...0.8 μm. At the same time, the maximum height of micro-irregularities decreases, respectively, from 6.7...4.1 μm to 1.0 μm. The labor-intensity of polishing the tip after hardening treatment is 25...40 % less than polishing an unpolished surface. Based on the study of the microhardness of the surface and its distribution in the surface layer, it was established that manual polishing leads to a decrease in the level of microhardness of the pre-hardened surface by 4...6 %. The subsequent operation of ultrasonic hardening helps restore the microhardness of the surface with a slight decrease in the depth of propagation of the hardened layer.

2. Based on the criteria of minimum labor intensity and maximum endurance, the most rational technology of the finishing-strengthening stage for the manufacture of blades has been established. It was found that the use of double deformation hardening technology with intermediate polishing at the finishing-strengthening stage of blade manufacturing makes it possible to increase the endurance limit from 320 MPa to 400 MPa while increasing durability. Taking into consideration the established reduction in the labor intensity of polishing the blade tip, a rational technology of the finishing-strengthening stage of manufacturing is a double hardening operation with steel balls in an ultrasonic field with intermediate polishing.

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