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THERMOSTRESSED STATE OF THE LOCK JOINT OF TURBINE ROTOR BLADES OF THE FIRST STAGE OF К-500-240 STEAM TURBINE MEDIUM PRESSURE CYLINDER

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This paper investigates the temperature field effect on the stress state of the turbine rotor blade lock joint elements where breakdowns were observed. The turbine rotor blade joint, when heat is supplied from the steam flow, is in conditions of uneven heating. In this case, the physico-mechanical properties of materials change, and one can observe gradients of the temperature causing unequal thermal expansion of individual parts of the structure. This leads to temperature stresses, which, in combination with mechanical stresses from external loads, can cause significant plastic deformation of the structure, cracks, or damage to structures. To clarify the distribution of structural stresses in the lock joint structure, a problem is solved taking into account the temperature field. The problem is solved in a thermal contact setting, with taking into account the heat transfer influence on the transfer of forces in the lock joint. The contact interaction problem is essentially nonlinear, and the temperature problem is connected with the mechanics problem through previously unknown boundary conditions in the contact. The stress state and the nature of the contact interaction depend on the temperature field, which is determined by interaction conditions. The solution to the thermal contact problem in the lock joint is based on the application of the contact layer model. Zones of expected contact interaction are represented by contact elements. The mechanical interaction of contact surfaces is determined by their mutual penetration. The problem is solved using the finite element method, the total number of elements being 371 498. In this model, there are several zones of contact interaction: namely, the area of contact of the pins with the disk, as well as with the locking blade and adjacent blades; the area of contact of the pressure pads of the roots of adjacent blades and the disk shaft end. In the contact zones, the mesh is thickened. The calculation results are presented in the form of the temperature distribution over the lock joint. It is shown that there is a temperature drop along the radius and width of the disk. The temperature of 533 °C from the side of the steam inlet drops to the level of 525 °C from the side of the steam outlet. Results of the calculated assessment of the stress state of the lock joint of turbine rotor blades are given for the first stage of the medium pressure cylinder of a steam turbine. These results indicate significant stresses that can cause plastic deformation.

Keywords*: turbine, lock joint, rotor blade, stress state, contact pressure, temperature field, contact stiffness.*

Introduction

Ensuring the reliability of the lock joint of turbine rotor blades requires the study of the joint stress-strain state (SSS) that meets the operating conditions. The lock joint of turbine rotor blades experiences significant loads when the temperature distribution is uneven over the radius and variable over time, which necessitates the analysis of its SSS with the combined influence of these factors.

The determination of the SSS of this lock joint has already been considered in [1, 2]. The solution was carried out in an elastic setting without taking into account the influence of temperature stresses, using a three-dimensional finite element model. As a load that determines the SSS in the joint, centrifugal forces were taken for the rotor rotating around the axis with an angular velocity of 314.16 rad/s. In connection with the symmetry of the system, not the entire disk with blades, but only its sector with the corner angle φ=20° was considered, with the symmetry conditions specified at its ends. The fixation of the model in the axial direction was carried out taking into account the displacements obtained earlier in calculating the SSS of the whole rotor. To do that, displacements of 0.128 mm and 0.16 mm were set at the ends of the disk from the steam input and output sides, respectively.

The simulation of the objects under study (Fig. 1) was carried out in the form of three-dimensional bodies, using the Autodesk Inventor geometric modeling package.

The calculated studies of the stress state of a number of finite element models of the lock joint made it possible to determine the optimal finite element (FE) size of 3 mm [3] from the condition that with a further decrease in the FE size, the calculation results change by no more than 3%.

As a result of determining the SSS of the lock joint under consideration, the following was established [3]:

– in the lock joint (Fig. 1, a), at the fillets of support pads and the holes for the pins, there are zones of increased radial stresses close to 540 MPa. Moreover, the average stress level in joint elements is low, and is about 80 MPa;

– the greatest deformations of about 0.43 mm are experienced by the disk in the radial direction under the locking blade and by the blade itself;

– the distribution of contact pressures on the support pads of lock joint elements and adjacent blades is uneven;

– the distribution of contact forces on the support pads of joint elements and adjacent blades differs from those presented in [4], where the blade root was considered in the framework of plane deformation in interaction with an axisymmetric disk. This can be explained by taking into account the influence of the locking blade, as well as by solving the problem with the use of a three-dimensional model of the joint;

– maximum stresses occur in the zone where damage was observed after the long-term operation of this type of lock joint design.

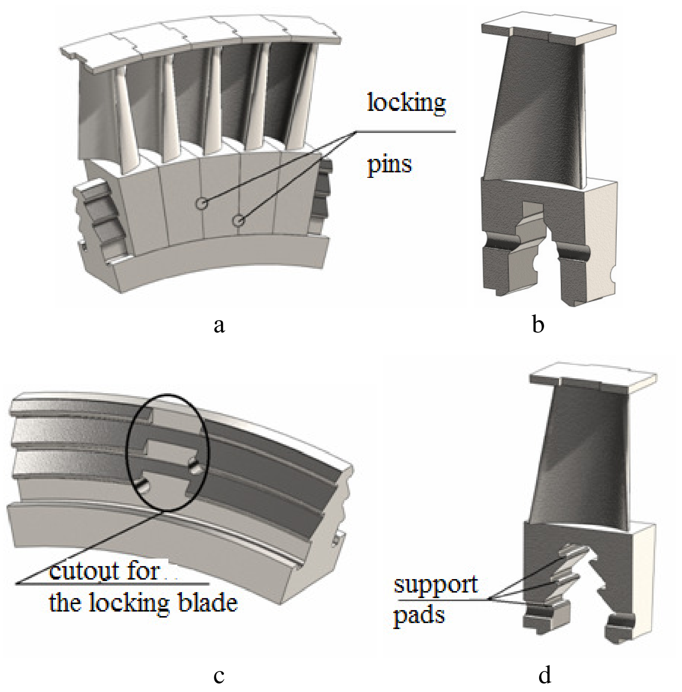

Fig. 1. Lock joint element models:
a – lock joint; b – locking blade; c – disk; d – adjacent blade

Problem Formulation

The aim of this paper is to determine the SSS of the lock joint of the rotor blades of the 1st stage of the medium pressure cylinder, taking into account the influence of heat transfer between lock joint elements.

To clarify the picture of the stress distribution over the lock joint structure, when solving the SSS problem, it is advisable to take into account the temperature field, since, as a result of heat supply from the steam flow, the lock joint of rotor blades works under conditions of uneven heating. Under such conditions, the physicomechanical properties of materials change, and there arise temperature gradients, accompanied by the unequal thermal expansion of individual parts of the structure. This causes thermal stresses, which alone or in combination with mechanical stresses from external loads can cause crack formation and structural damage. As a result of the influence of temperature stresses, there can occur a significant plastic deformation leading to a complete or progressive structural failure [5].

It is correct to take into account the influence of heat transfer on the transfer of forces in the lock joint in a thermal contact setting. In this case, the contact interaction problem is essentially nonlinear, since the mutual influence of the temperature and force components of deformations is carried out through previously unknown boundary conditions in the contact. The SSS and nature of the contact interaction depend on the distribution of temperature fields, and the temperature field, on the contact interaction of elements [6].

The thermal contact problem of the interaction of lock joint elements, being solved in this paper, is based on the application of the contact layer model [6]. In this case, the zones of the expected contact interaction are modeled using contact elements. The mechanical interaction of contact surfaces is determined by their mutual penetration. One of the main characteristics of the contact layer in this case is the contact stiffness C_n. The contact stiffness value should be sufficient enough to neglect the mutual penetration of surfaces, but such that the accuracy of the system of equations of the finite element model allows us to determine the contact stresses

$$\sigma_p = C_p \cdot \left(u_p^1 - u_p^2 - \delta_p\right)$$

where u_p^1, u_p^2 are the displacements of contact surfaces in the direction of the common normal; δ_p is the initial clearance (interference) between the contact surfaces.

In this work, the contact stiffness value was chosen in the process of solving the problem, based on the assumption that the mutual displacement of contact surfaces does not exceed the values of their roughness.

The three-support mushroom-shaped joint design used in the lock joint under consideration is subjected, during the assembly process, to additional rolling, which prevents the presence of large friction between interacting surfaces. Based on this, friction, in solving this problem, is not taken into account.

When solving the thermal contact problem, we assume that at the contact boundary of lock joint elements, there is an ideal thermal contact, and the equality of temperatures and heat fluxes is fulfilled [6]

$$T_1(x_k, y_k, z_k, t) = T_2(x_k, y_k, z_k, t), \qquad \lambda_1 (dT/dn)_k = \lambda_2 (dT/dn)_k$$

where $\lambda_1(T), \lambda_2(T)$ are the thermal conductivity coefficients of contacting bodies, depending on the temperature T.

The problem of thermal conductivity in solving the problem of thermocontact interaction of elements in the lock joint precedes the problem of thermomechanics. Values of contact stresses are specified in the iterative process. When creating the finite element mesh, we used the twenty-node *Solid226*. This element differs from the previously used *Solid186* in that it has degrees of freedom in displacements and temperature, and allows us to obtain a solution to the joint thermal contact problem (Fig. 2).

Upon refinement, a mesh of 371,498 FEs was obtained (Fig. 3). The FE model under consideration has several zones of contact interaction: the area of contact between the pins and the disk, the locking blade, and adjacent blades; the area of contact of the support pads of the roots of adjacent blades and the disk shaft end. In the contact zones, mainly those affecting the transfer of forces between interacting elements, there is a thickening of the mesh with a decrease in the FE size to 1 mm, which increases the accuracy of calculation.

The initial data are the thermophysical properties of lock joint materials from [7]. Before and behind the stage, the temperature distribution was specified in the radial direction, becoming boundary conditions of the first kind.

The stress state calculation time was 4 hours.

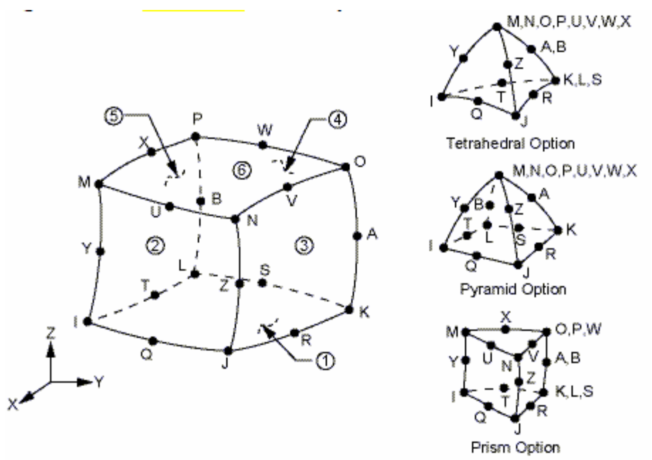

Fig. 2. Solid226 finite element

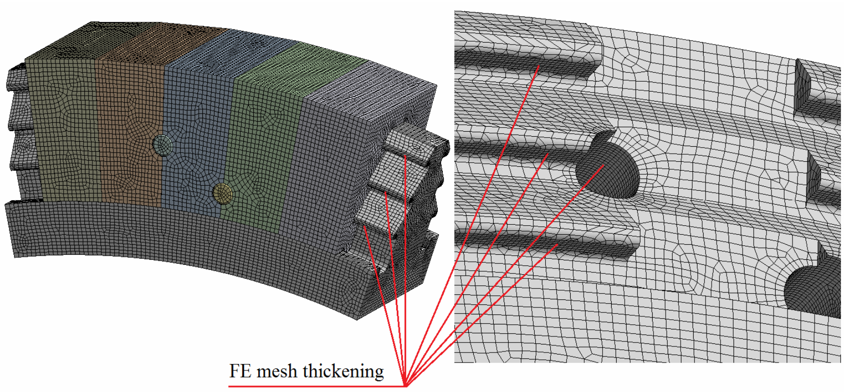

Fig. 3. Breakdown of the rotor blade lock joint model into finite elements

Numerical Analysis of the Lock Joint SSS

Fig. 4 presents the calculation results in the form of the temperature distribution in the lock joint.

We can see that there is a temperature drop both in disk radius and in disk width. So, the temperature of 533°C from the side of the steam inlet drops to the level of 525°C from the side of the steam outlet.

As a result of computational studies, the distribution of radial stresses over the lock joint was obtained (Fig. 5).

As follows from the results obtained, the distribution of radial stresses in the disk section under consideration has a complex spatial character. The compression zones of engagement elements in the lock joint are alternated with the tension zones throughout the remaining region. Moreover, the maximum level of compressive stresses is relatively small and reaches no more than 50 MPa. The maximum level of tensile stresses can be observed at the holes in the disk for the installation of pins that fix the locking blade, reaching 1,787 MPa. The Mises equivalent stresses in this zone were about 2,800 MPa, which indicates the possibility of plastic deformations (Fig. 6).

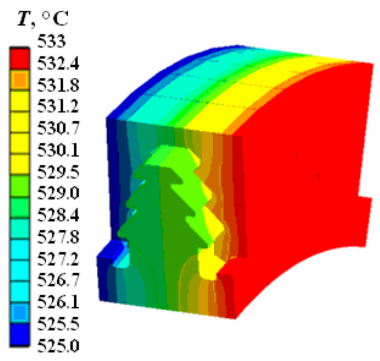

Fig. 4. Temperature field in the lock joint of rotor blades

It follows from the figure that the yield strength level $\sigma_{0.2}$ for the disk material, EI-415 steel, at operating temperatures is about 450 MPa.

Maximum values of the stresses arising in the places of transmission of stresses from the locking blade to the disk gradually decrease with increasing distance from the holes. At the same time, excessive tensile and yield strengths of the material at the temperatures under consideration can be observed along the entire base of the rotor blade lock joint model under consideration. In the upper sections of the disk section under consideration, the stress level is somewhat lower, however, it is still significant and reaches a value of 550 MPa.

The distribution of radial stresses over rotor blade roots is not constant either. The maximum values occur in the region of fillets of the lower support pads of blade roots, as well as at the holes for the adjacent blades to be locked with pins. Moreover, the stress level is much lower than their level in the disk, and reaches 350–400 MPa.

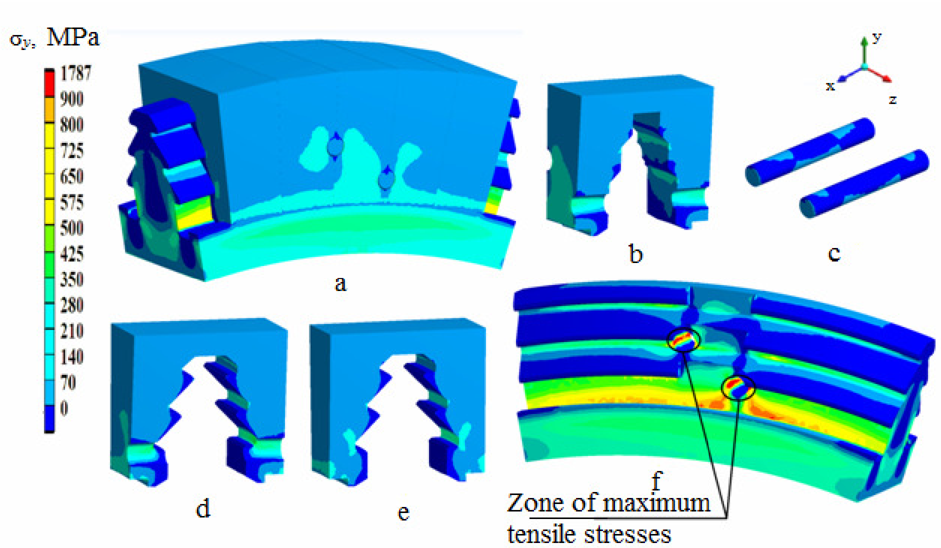

Fig. 5. Distribution of radial stresses:
a – lock joint; b – locking blade; c – pins; d – disk; e – rotor blade; f – adjacent blade

A significant increase in stresses can be observed in comparison with the results obtained earlier [2], which is probably caused by the influence of the temperature field. So, in the place where the rotor disk has a cutout for the locking blade, there are zones of maximum tensile stresses, the value of which significantly exceeds the yield strength, which is likely to lead to plastic deformations.

The appearance of additional temperature stresses in the lock joint structure is apparently associated with the presence of structural elements with different coefficients of linear thermal expansion [7]. So, XN70BMJuT alloy (pins) has the largest coefficient of thermal expansion, and EI-415 steel (disk), the smallest one. The thermal expansion occurring during the heating of some joint elements exceeds the thermal expansion value of others, which ultimately causes the appearance of additional temperature stresses.

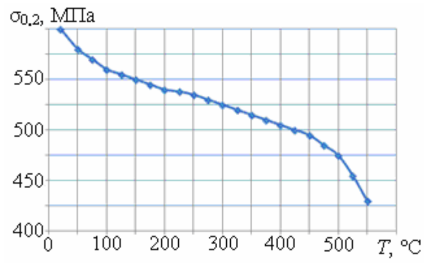

Fig. 6. Dependence of the level of EI-415 steel material yield strength from temperature

The blade root bending deformations noted earlier in [2] practically do not appear in this case.

Fig. 7 shows the distribution of contact pressures on the rotor blade support pads in the lock joint. When considering the results obtained, the contact support pads are numbered as follows. The upper pair of support pads is the first pair, the middle pair is the second pair, the lower pair is the third pair, and the lateral support surfaces of the root are shoulders.

The distribution of contact stresses on support pads is also of a complex spatial nature and depends on the position of a blade in the lock joint with respect to the locking blade.

The presented results of the distribution of contact pressures on the support pads of the roots of the locking and adjacent blades (Fig. 6, a, b, c) allow us to assess the change in the nature of the contact interaction of these blades with the disk in the joint. The highest level of contact pressure can be observed on the 3rd pair of the support pads of adjacent blades. In this case, the maximum pressure is achieved from the side of the hole for additional pinning, and mainly depends on the position of the pin in height. The change in contact pressures

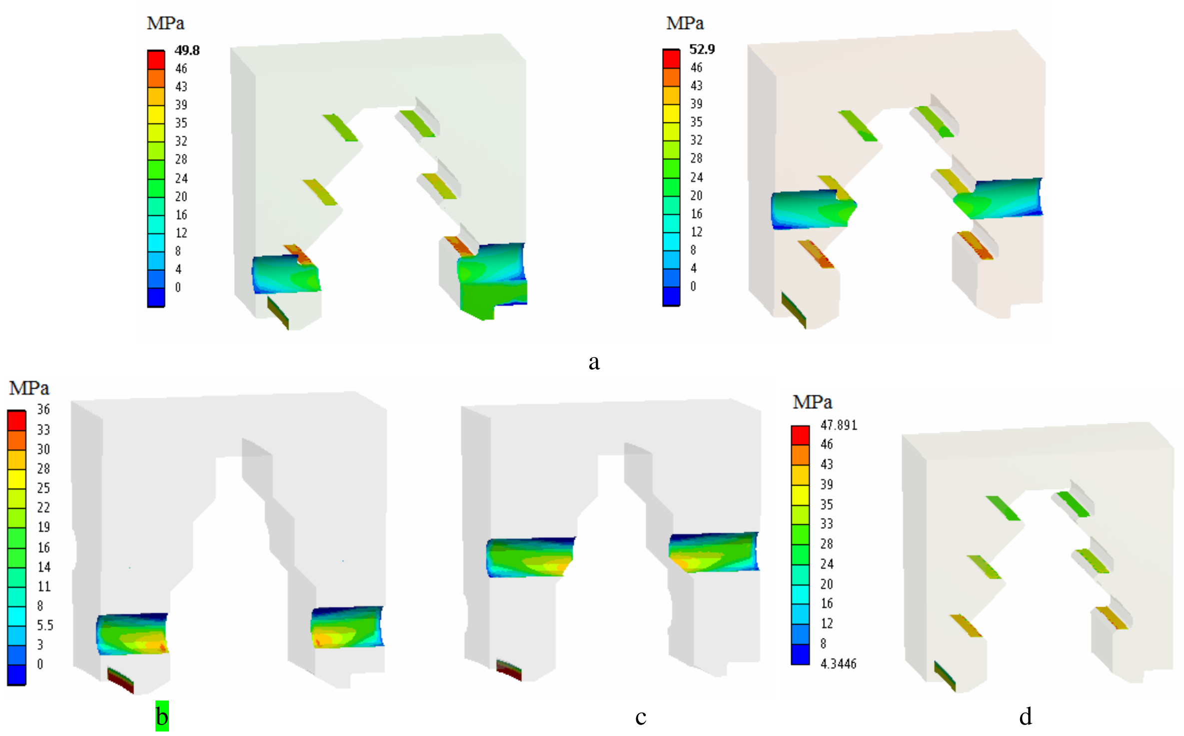

Fig. 7. Distribution of contact pressures on blade support pads in the lock joint:
a – adjacent blade (with the lower pin); b – adjacent blade (with the upper pin); c – locking blade); d – rotor blade

on the adjacent blade with the lower pin location is characterized by relative constancy for the 3rd pair of support pads and a pronounced gradient for the second pair. At the same time, a slightly different picture can be observed in the distribution of contact pressures on the adjacent blade root with the upper pin location. In this case, the second support pad is located at the same level with the pin, and the distribution of contact pressures on it can be described as constant. At the same time, there is a pronounced gradient in the level of contact pressures on the third lower support pad, of from 39 to 52 MPa.

From the picture of the distribution of contact pressures on the support pads of the root of extreme rotor blades in the lock joint (Fig. 6, d), it follows that the maximum pressure level can be observed at lower support pads, and is almost constant along the length of the support pad, reaching 42.45 MPa. On other support pads of the blade root under consideration, the stress level is lower, reaching 25.59 MPa for the first pair, and 33.14 MPa for the second pair. The nature of the distribution of contact forces both on the support points indicated and the third pair is constant. At the same time, a change in the contact forces on shoulders indicates the presence of a gradient in height from 28 MPa in the upper part of the support pad, to 39 MPa in its lower one.

The table below shows the pressure values averaged over the contact area at the support points of the rotor blades in the lock joint, both taking into account and without taking into account the influence of temperature effect.

The results of the distribution of contact pressures on the support pads of the rotor blades in the lock joint (Fig. 6, table) indicate that, as in the case of solving the problem in the elastic formulation without taking into account the influence of temperature stresses [3], there is an uneven distribution of loads on support pads. However, there are significant differences. A redistribution of stresses took place on support points, which is probably associated with a different coefficient of linear expansion of the materials of the disk shaft end and blades and, as a result, with various deformations of the lock joint elements in the radial direction. So, when solving the problem, taking into account the influence of temperature deformations, the third pair of support points turned out to be the most loaded. The general picture of the distribution of forces on the support pads of the adjacent blade (with the upper pin) is as follows: 23% for the first pair, 34% for the second pair, 43% for the third pair, which has obvious differences from the calculation results for the case without taking into account the influence temperature deformations, where the most loaded pair of support points was the second one, and the efforts were distributed as follows: 34% for the first pair, 34% for the second pair, 32% for the third pair.

As in the case of solving the problem without taking into account the influence of temperature stresses, there is a difference in the values of contact pressures on the support pads of adjacent blades with different pin location along the radius.

Distribution of Contact Pressures on Support Pads

Computational model		1st pair		2nd pair		3d pair	
		MPa	%	MPa	%	MPa	%
Adjacent blade (with the upper pin)	with temperature not taken into account	42,67	34	43,15	34	40,88	32
	with temperature taken into account	24,34	23	34,9	34	44,92	43
Adjacent blade (with the lower pin)	with temperature not taken into account	41,94	34	42,78	34	40,17	32
	with temperature taken into account	25,11	24	33,11	32	45,08	44
3D rotor blade	with temperature not taken into account	40,5	33,5	41,31	34	39,23	32
	with temperature taken into account	25,59	25	33,14	33	42,45	42
2D rotor blade [4]		–	37	–	30	–	33

Conclusions

When solving the problem of the SSS of the lock joint of rotor blades, taking into account the influence of the temperature field, we observe the results that differ from those obtained previously [3].

There is a significant stress increase caused by the presence of temperature fields. The appearance of significant temperature stresses was mainly facilitated, apparently, by not so much the presence of a slight temperature difference in the joint, as by the difference in the coefficients of the linear thermal expansion of its elements. The areas with the highest tensile stresses, as in solving the problem without taking into account the influence of temperature deformations, are the areas of the disk shaft end at the holes for the pins, as well as the fillets at the support pads of blade roots. So, the values of tensile stresses in the holes significantly exceeded the yield strength at a given temperature.

The solution to the problem in the thermal contact formulation made it possible to assess the degree of influence of temperature deformations in the lock joint on the distribution of contact pressures on the support pads of its elements. It is shown that there is a redistribution of stresses between pairs of the support pads of adjacent blades in comparison with the results of solving the problem without taking into account the influence of temperature deformations.

The results of solving the SSS problem in the formulation under consideration indicate the need to take into account the influence of the temperature field, since the contribution of temperature deformations to the general SSS is very significant. In the future, it seems appropriate to solve the problem in an elastic-plastic formulation, as well as with taking into account creep strains.

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Термонапружений стан замкового з’єднання робочих лопаток першого ступеня турбіни К-500-240

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Досліджується вплив температурного поля на напружений стан елементів замкового з'єднання лопаток турбіни, де спостерігалися поломки. З'єднання робочих лопаток турбін при підводі тепла від парового потоку знаходиться в умовах нерівномірного нагрівання. За таких умов змінюються фізико-механічні властивості матеріалів *і спостерігаються градієнти температури, що викликає неоднакове теплове розширення окремих частин конструкції. Це призводить до температурних напружень, які в поєднанні з механічними напруженнями від зовнішніх навантажень можуть викликати істотну пластичну деформація конструкції, породжувати тріщини або пошкодження конструкцій. Для уточнення розподілу напружень по конструкції замкового з'єднання розв'язується задача з урахуванням температурного поля. Розв'язання задачі здійснюється в термоконтактній постановці з урахуванням впливу теплообміну на передачу зусиль в замковому з'єднанні. Задача контактної взаємодії є істотно нелінійною, і зв'язок температурної задачі із задачею механіки здійснюється через заздалегідь невідомі граничні умови в контакті. Напружений стан і характер контактної взаємодії залежать від розподілу температури, що визначається умовами взаємодії. Розв'язок термоконтактної задачі в замковому з'єднанні базується на застосуванні моделі контактного шару. Зони передбачуваної контактної взаємодії визначаються контактними елементами. Механічна взаємодія поверхонь контакту визначається величиною їхнього взаємного проникнення. Задача розв'язується з використанням методу скінченних елементів, загальне число елементів - 371498. У розглянутій моделі є кілька зон контактної взаємодії: а саме, область дотику штифтів з диском, а також із замковою лопаткою і призамковими лопатками; область дотику опорних площадок хвоста призамкової лопатки і хвостовика диска. У зонах контакту здійснюється згущення сітки. Наведені результати розрахунку у вигляді розподілу температури по замковому з'єднанню. Показано, що має місце перепад температури по радіусу і ширині диска. Температура 533 °С з боку входу пари падає до рівня 525 °С з боку виходу пари. Наводяться результати попередньої оцінки напруженого стану замкового з'єднання робочих лопаток першого ступеня циліндра середнього тиску парової турбіни, які свідчать про значні напруження, здатні викликати пластичну деформацію.*

Ключові слова: *турбіна, замкове з'єднання, робоча лопатка, напружений стан, контактний тиск, температурне поле, жорсткість контакту.*

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