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Analysis of state of stress in turbine disks during auto- and thermofrettage

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1. Introduction

The works, in which the author of this contributions was engaged dealing with calculation and preparing programmes for a digital computer for cases where the rotor moving wheels of a steam turbine are in an elasto-plastic state or in a state of creep due to an nonuniform distribution of temperatures or high speed of rotation and centrifugal forces have recently been concluded [1-3]. At the same time with theoretical work, measurement of deformations and state of stress of disks are taken in the Skoda Works Plzeň Turbine Plant and also in some other places in Czechoslovakia with a view to designing them with more safety and design and technological methods of the state of stress are theoretically and experimentally studied.

It has been proved that the stress of turbine disks and especially the top stress can be reduced by introducting suitable internal stresses either by bringing the disk into an elasto-plastic state with the help of a high speed (this method being called autofrettage) or by means of a temperature gradient (thermofrettage). The thermofrettage was done experimentally in two ways, either by bringing the disk into the elasto-plastic state due to large temperature gradient or by utilizing relaxation, i. e. by annealing it for a long time at a temperature of about 600°C with a small temperature gradient along its radius.

To compare the theoretical calculations with results of experiment, a number of experimental disks and the last wheel of a 200 MW steam turbine were calculated.

2. Thermofrettage of the last moving wheel of a 200 MW steam turbine

The influence of five different temperature variations upon the stress distribution and distribution of residual internal stresses at the temperature gradient of 180°C was investigated. The temperature inside of the hub was 500°C, that in the rim being 680° C. Tensile tests of the mentioned material were carried out at temperatures for 400, 500, 550, 600 and 650°C. Additionally, the analytical course of the deformation curve for a temperature of 20°C was calculated. The analytical courses of the curves are as follows:

Table 1

Values of tangential stresses in the disk bore [MPa]

Degree of parabola	Elastic state $\Delta T=180°C$	Elastoplastic state $\Delta T=180°C$	Residual internal stresses $\Delta T=0°C$	Disk subjected to thermofrettage at $n=3000$ [rpm]	Plastic region
[MPa]	$\sigma_{t,a}$	$\sigma_{t,a}$	$\sigma_{t,a}$	$\sigma_{t,a}$	r_c/r_b
1	109.3	97.7	—27.2	344.6	0.48
2	151.9	104.2	—27.4	344.4	0.55
4	202.1	196.0	—15.5	356.3	0.75
5	218.5	194.2	—61.4	310.4	0.75
6	226.7	199.0	—70.5	301.3	0.75

$$T=650°C \qquad \varepsilon=0.43184\,.\,10^{-9}\,.\,\sigma^{2.47}$$
$$T=600°C \qquad \varepsilon=0.25414\,.\,10^{-9}\,.\,\sigma^{2.39}$$
$$T=550°C \qquad \varepsilon=0.59750\,.\,10^{-11}\,.\,\sigma^{2.83}$$
$$T=500°C \qquad \varepsilon=0.17963\,.\,10^{-18}\,.\,\sigma^{4.92}$$
$$T=20°C \qquad \varepsilon=0.61537\,.\,10^{-17}\,.\,\sigma^{3.88}$$

The calculations of courses of the individual curves were carried out in each case by using a method of least squares of six couples of points. For each case three calculations were carried out:

— stress distribution in elastic condition due to nonuniform temperature distribution,

— stress distribution in elasto-plastic condition due to nonuniform temperature distribution and

— distribution of internal stresses in a disk after cooling down while taking into consideration the Huber-Mises-Hencky strength hypothesis.

The main attention is related to the value of tangential stresses in the bore disk, which reach in these points their maximum values. We are giving therefore in Table 1 values of these stresses in elastic and elasto-plastic state after cooling down and in a disk, subjected to thermofrettage at the operational speed of rotation $n=3000$ rpm.

It is evident from the results that at the same temperature gradient of 180°C and different temperature variations an increase in the tensile tangential stresses occurs in the bore with the parabola degree of the temperature variation. Due to the residual internal stresses the elastic stresses become reduced, the maximum absolute drop occurring in the last case. It is obvious that the most favourable conditions occur just in that case when the tangential stresses in the disk bore are the lowest. From the results follows that within the plastic region there is a great part of the disk, i. e. of both the rim and blade and small surroundings of the bore. As the degree of the parabola gets higher the plastic region increases.

3. Autofrettage of the last moving of 200 MW steam turbine wheel

The difference between the stress disiribution in a disk having been subjected to autofrettage and that not subjected to it was followed. The moving wheel was tested at overspeed $n=5230$ rpm without taking into account the temperature gradient. The values of the elasticity modulus and the temperature expansion coefficient, as well as the creep limit at a temperature

Table 2

Values of tangential stress $\sigma_{t,a}$ in a disk that has been subjected to autofrettage

Speed n [rpm]	State	$\sigma_{t,a}$ [MPa]
3000	elastic	371.8
5230	elastic	872.0
5230	elasto-plastic	651.6
3000	elasto-plastic	150.7
0	internal stresses	—94.7
3000	disk having been subjected to autofrettage	277.1

of 20°C were taken being constant: $E=2.15\,.\,10^5$ MPa; $\alpha=12\,.\,10^{-6}$ cm/cm°C; $\sigma_y=6000$ MPa. The calculations were carried out in several stages:

— the stress was calculated at 3000 rpm while starting to run at the overspeed; it has been shown that the wheel is in elastic state;

— in the second stage the stress was calculated at $n=5230$ rpm in elastic state; as the region of the bore was in plastic state, a repeated calculation was carried out;

— in the third state was determined the stress during tripping out at $n=$ $=3000$ rpm;

— finally, the internal stresses existing in the disk after tripping out were ascertained.

In Table 2 values of tangential stresses in two disks are listed, one subjected to autofrettage and the other to thermofrettage.

While the drop of stress in the bore of the disk subjected to thermofrettage due to plastic deformations was not more than 10 per cent, the drop in the disk subjected to autofrettage reached about 25 per cent. The plastic region in the autofrettaged disk extends in the region of the bore and about 15 per cent of the whole disk.

4. Autofrettage and thermofrettage of test disks A-1,2

To check whether or not the method of calculation is correct, two examples of test disks made of carbon steel were by high speed brought into elasto-plastic state, calculated and afterwards measured.

A-1: $r_a=10.25$ cm, $r_b=35$ cm; $h=3.5$ cm. The overspeed testing was done at 8000 rpm.

A-2: has the same dimensions as A-1, and the overspeed testing was done at 8100 rpm.

The calculation was realised in both cases separately in several stages. There were calculated variations of stress state at $n=4000$ rpm in elastic state (no plastic state occurred there), at $n=8000$ (or 8100) rpm in elastic and elasto-plastic states respectively, at $n=4000$ rpm at tripping out and closely after completely stopping down. As the differences in the results at the both disks were small, we shall mention in the following only the values for the A-2 disk.

The curve of deformation given by the following relationship was used: $\varepsilon=0.26078.10^{-12}\,.\,\sigma^{2.75}$. The drop in the stress due to the plastic deformations at a speed of 8100 rpm is about 22 per cent. It follows from the comparison with measurements that the calculated values of the internal stress in the

Table 3

Values $\sigma_{t,a}$ in the test disk A-2 that has been subjected to autofrettage

Speed n [rpm]	State	$\sigma_{t,a}$ [MPa]
4000	elastic	146.3
8100	elastic	600.1
8100	elasto-plastic	465.1
4000	elasto-plastic	11.4
0	internal-stresses	—134.9
4000	disk having been subjected to autofrettage	11.4

Table 4

Values $\sigma_{t,a}$ in A-2 test disk that has been subjected to thermofrettage

Temperature and state	ΔT=200°C elastic	ΔT=200°C elasto-plastic	ΔT=0°C internal stresses	Disk subjected to thermofrettage at n=4000 [rpm]
$\sigma_{t,a}$ [MPa]	330.9	289.2	—44.5	101.8

disk having been subjected to autofrettage are within the region of the disk bore higher ($\sigma_{t,a}= -175.0$ MPa — measured by means of strain gauge), whereas in the middle portion of the disk they are lower.

To enable comparison another calculation was made with the same disk which was subjected to thermofrettage at a temperature gradient of 200°C at linear temperature variation from 200 to 400°C and at the creep limit dependent on the temperature; analytical expressions of the individual deformation curves were obtained again from tensile tests for the carbon steel:

$$T = 20°C \quad \varepsilon = 0.19968 \cdot 10^{-13} \cdot \sigma^{2.91}$$
$$T = 400°C \quad \varepsilon = 0.63026 \cdot 10^{-15} \cdot \sigma^{3.86}$$
$$T = 300°C \quad \varepsilon = 0.18709 \cdot 10^{-13} \cdot \sigma^{3.17}$$
$$T = 200°C \quad \varepsilon = 0.37035 \cdot 10^{-19} \cdot \sigma^{4.69}$$

The creep limit for the given material σ_y (at 20°C) = 382.0 MPa. In the first stage the calculation was made of the elastic and elasto-plastic states of stress due to a temperature gradient of 200°C and finally the calculation of internal stresses after cooling down. It is shown that at the operational speed $n = 4000$ rpm autofrettage which substantially reduces the stresses in the bore is more suitable.

5. Thermofrettage by relaxation of B-1, 2, 3 trial disks

Except thermofrettage at a large temperature gradient and autofrettage due to high speed there exists one still more suitable method of prestressing of disks utilizing the phenomenon of relaxation. By a small temperature difference (at temperatures of 500 to 650°C) a region of internal stresses will occur in the disk and by annealing at this temperature during the time of 6 to 12 h these stresses let to relax. The arisen plastic deformations form again after the temperature compensation a similar region of internal stresses as in the autofrettage.

Due to the comparison of measurements there were carried out calculations of the trial disks and determined internal stresses occurring during thermo-

Table 5

Values $\sigma_{t,a}$ and $\sigma_{t,b}$ in *B* 1-3 disks subjected to thermofrettage

$\sigma_{t,a}$ / $\sigma_{t,b}$	Elastic stresses	Elasto-plastic stresses	Residual internal stresses
B — 1	92.2	90.9	— 3.0
	— 58.7	— 51.0	19.4
B — 2	141.4	120.7	— 47.1
	— 71.3	— 34.3	82.7
B — 3	553.4	394.1	—158.8
	—163.2	—162.4	1.0

frettage due to relaxation and large temperature gradient. Three alternatives were examined:

— thermofrettage due to relaxation with a temperature gradient of 100°C within a temperature range of 500 to 600°C;

— thepmofrettage due to relaxation with a temperature gradient of 130°C within a temperature range of 500 to 630°C;

— thermofrettage due to a total temperature gradient of 300°C within a temperature range of 120 to 420°C.

The geometrical and physical parameters were as follows: $r_a=2.5$ cm; $r_b=15.0$ cm; $h=2.5$ cm. Deformation curves mentioned above for temperatures 650°C to 20°C were used.

The comparison of the calculation with the results of measurements showed a very good agreement along the whole disk profile. The resultant values of tangential stresses $\sigma_{t,a}$ and $\sigma_{t,b}$ in the bore and at the edge of the disk are presented in Table 5.

Comparing the values of internal stresses obtained by thermorelaxation and thermofrettage at a large temperature gradient it follows that the stress gradient of the last disk is considerably larger and the steep stress top is made to vanish. The comparison indicates that the thermofrettage at a large temperature gradient is considerably quicker than that due to relaxation and any accuracy of prestress can be obtained. A disadvantage, on the contrary, is the rather steep distribution of pressure prestress in the disk. The stress distribution of a disk subjected to thermofrettage under relaxation approaches to the stress distribution of a disk under constant utilization of material in the whole disk web.

The distribution of internal stresses can be influenced in the case of thermofrettage by the variation of temperature of the disk; to attain a suitable prestressing it is necessary to choose this distribution as convex. In this case the residual stresses have the same character as in the case of autofrettage. The variation of temperature must show a gradient increasing toward the internal diameter of the disk.

Of importance is also the konwledge of the correct distribution of deformation curves of the material even at higher temperatures.

From the above calculations it cannot in general be decided which of the above methods is more suitable in practice. This will be the aim of further theoretical and experimental research.

Literature

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