PROBABILISTIC LIFE ASSESSMENT OF CHEST VALVE UNDER THERMAL STRESSES.

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Abstract

After 23 years of service several circular fatigue cracks have been discovered at the bottom of the chest valve chamber of the actual (in existence) power station high pressure piping. Finite element analyses of transient thermal stresses, caused by power station startup, are carried out in the paper. The calculation results show good agreement between the theoretical locations of the maximum stresses and the actual locations of the cracks. There is a good agreement between theoretical evaluation and actual service life, as well. A probabilistic approach to service life assessment is performed in assumption that the temperature change and the fatigue properties of the chest valve material are distributed randomly. The idea of machining out of the cracks is examined here. The machining enables us to extend the power station component's life service.

1. Introduction

The goal of this paper is to estimate the service life's model of the power station chest valve. The chest valve is located at the outlet of the main steam piping forward to the turbine. The steam, entering the turbine, is passing through the chest valve.

Two types of processes may be distinguished during the service life of the chest valve. The first type, called the operating process, is characterized by relatively slow changes in pressure and temperature. The second type, called the power station startup process, is characterized by rapid changes of loads. This transient process leads to the development of the thermal stresses in piping components. The total duration of the startup is negligible in comparison with the duration of the operating process.

The chest valve is an intricate shapes component, connecting different pipes. This component is subjected to low (negligible) level of creep stresses due to pressure and high level of fatigue thermal stresses.

After 23 years of service (about 90 cycles of power station startup) several circular fatigue cracks have been discovered at the bottom of the chest valve chamber. As ultrasonic measurements show, the cracks depth is until 30 mm. The chest valve replicas do not indicate any remains of creep, which are located far enough from the cracks' region.

The German Standard TRD[1] modified approach, based on finite elements stress analysis, has been carried out in this paper for life assessment evaluation. The stress-strain states of similar three-dimensional piping components are analyzed in Sorem and Tripton[2], Afshary et al[3] and Skopinsky and Berkov[4]. The life assessment analyses are carried out in this paper for two cases: for the actual chest valve and for the repaired one. Because of the random character of the thermal load and steel fatigue properties, a probabilistic approach to life assessment is chosen in the paper.

The possibility of machining out of the cracks is examined. The idea is to prevent cracks growing and in this way to extend the chest valve's life service.

2. Operating (steady-state) stresses

A finite elements model under static pressure loads is built, while using the ANSYS program[5]. Since there are planes of symmetry in chest valve, only one eighth of the chest valve is modeled with appropriately applied symmetry boundary conditions (fig. 1). The cracks' locations and the regions of the possible machining out of the cracks are shown in the figure, as well. In order to increase the calculation's accuracy the model is restricted to the brick elements with transitional degrees of freedom per node. The finite element Solid-5 is used in order to generate the accepted element mesh. This thermal-structure solid element enables us to model the stress-strain state by considering of the steel thermal conductivity and thermal convection process between steel and steam etc due to static and transient thermal loads.

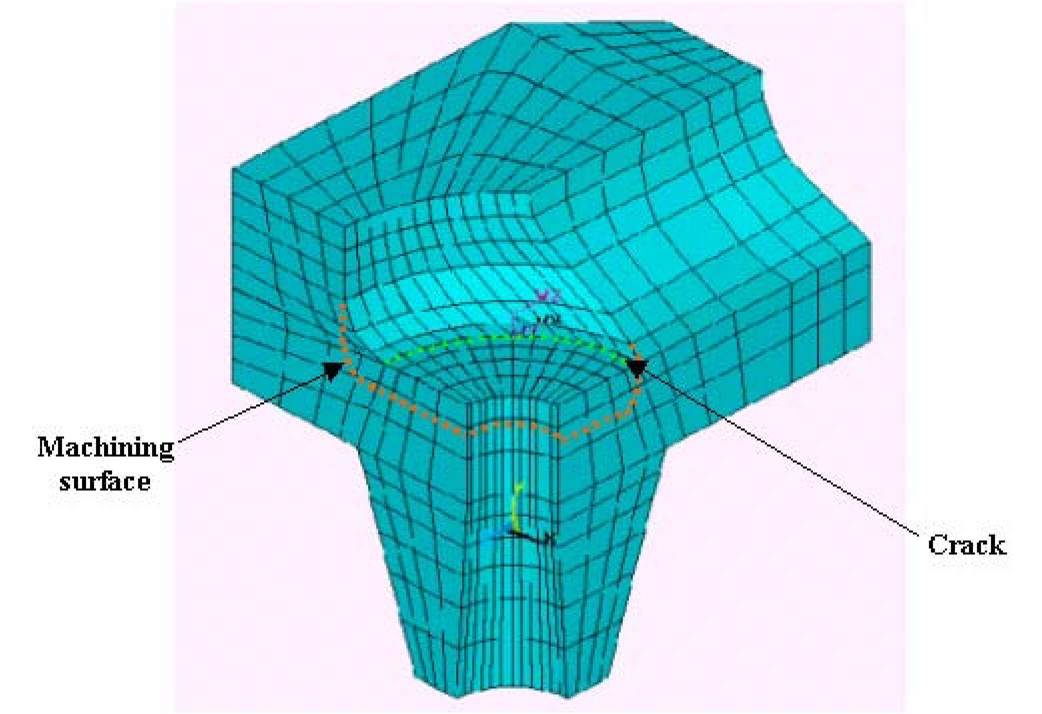

Fig. 1 The finite elements model mesh.

Mesh density is high enough in the region of the expected large stress gradients. The density in other regions is chosen roughly enough, because their stress distribution is not of interest.

In order to check the accuracy of the model the finite elements analyses are made for a number of models with different mesh densities. The model mesh density is refined till the calculation results arising from this model agree sufficiently close to the previous not refined model. In case showing discrepancy of results, a new refined model is built to compare it afresh. The final model mesh density is shown in fig. 1.

The calculations are made for the material 0.5% CrMoV. The results (Von-Mises stresses) are presented in fig. 2. As it is shown in the figure, the maximum pressure stresses occur on the internal surface of the chest valve (the maximum stress is σ_{pr} = 46.4 kN/mm^2). These stresses have a local character and they are the peak stresses according to the Standard TRD classification.

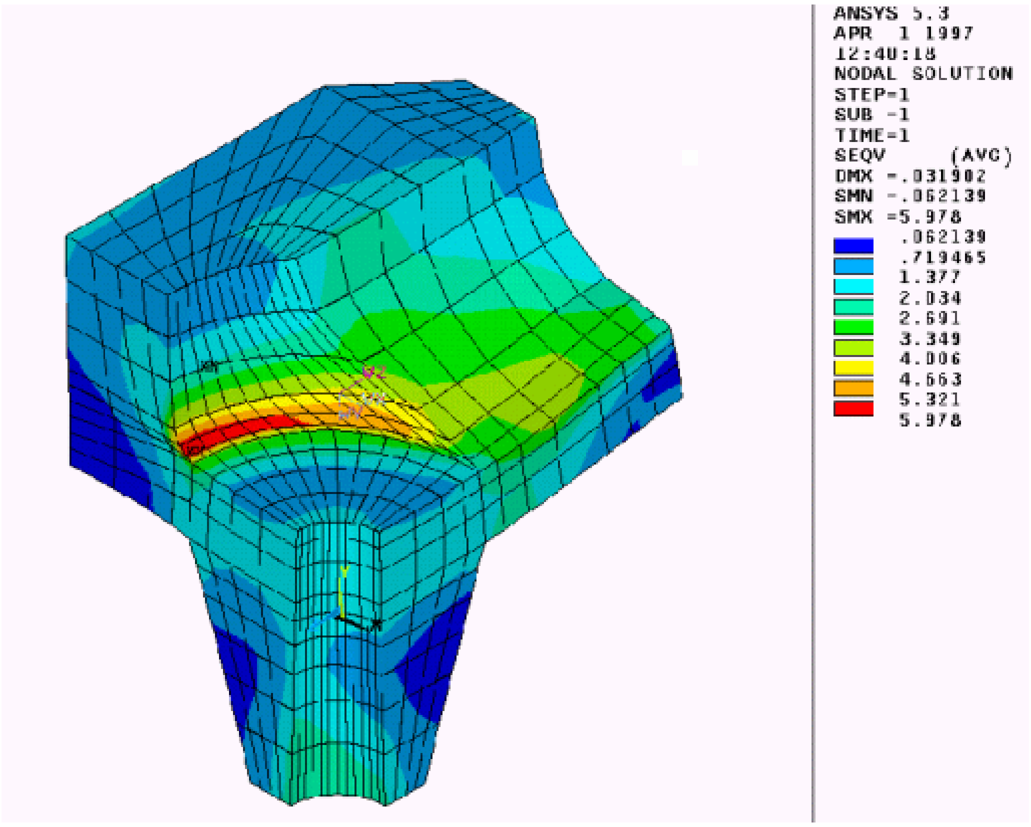

Fig. 2 The chest valve pressure stresses.

Analogous character of the thermal stress field is obtained for the repaired chest valve, while the regions containing the cracks are machined out (the maximum pressure stress here is $\sigma_{pr} = 59.8\ kN/mm^2$).

3. Transient (fatigue) thermal stresses

It is assumed that the chest valve works only under fatigue conditions (the influence of the creep is negligible) and as a result the life assessment calculations are based on the usage of damage coefficient. When the coefficient reaches the value of 100%, the service life is completed. The thermal transient (fatigue) stresses in the chest valve arise from rapid temperature change of steam during power station startup. Finite elements analyses of thermal stresses are carried out for similar problems in Miroshnik et al[5] and Aquino and Manesky[6].

A typical process of steam temperature θ change with time t is schematically shown in fig. 3. There are three process steps in the graph: the first and the third ones are characterized by constant, slightly increasing rates of temperature change. These two steps do not result in any value of thermal stresses. During the second step the temperature changes with high rate from its minimum value $T_{\min}$ to the maximum one $T_{\max}$. The duration of the second step is negligible when compared with the first and the third ones.

The maximum Von-Mises thermal transient stresses are shown in fig. 4. The maximum stress is $\sigma_{th} = 974\ kN/mm^2$, it has a local character and it is the peak stress, as well.

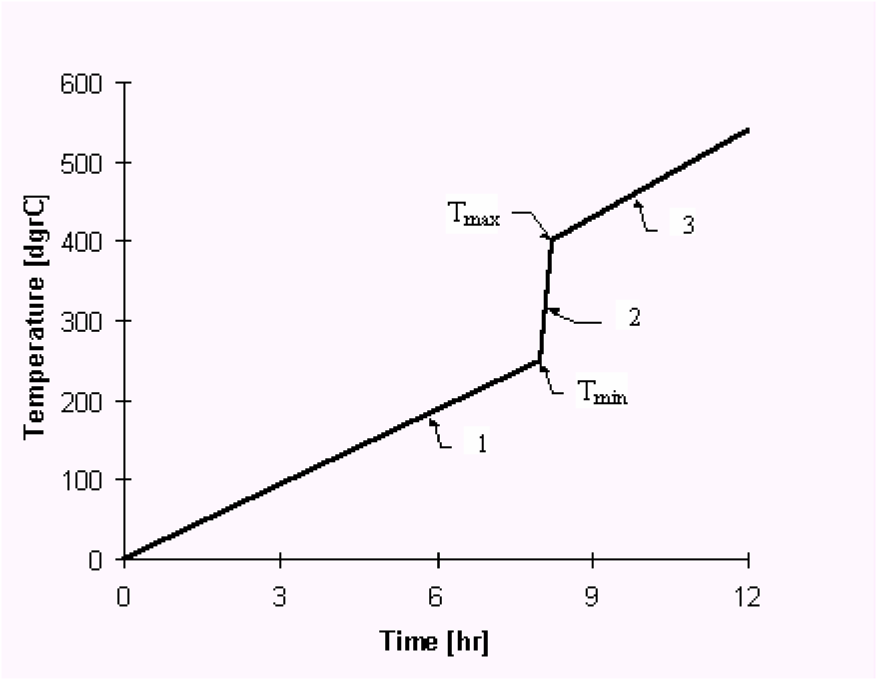

Fig. 3 The typical process of the steam temperature change.

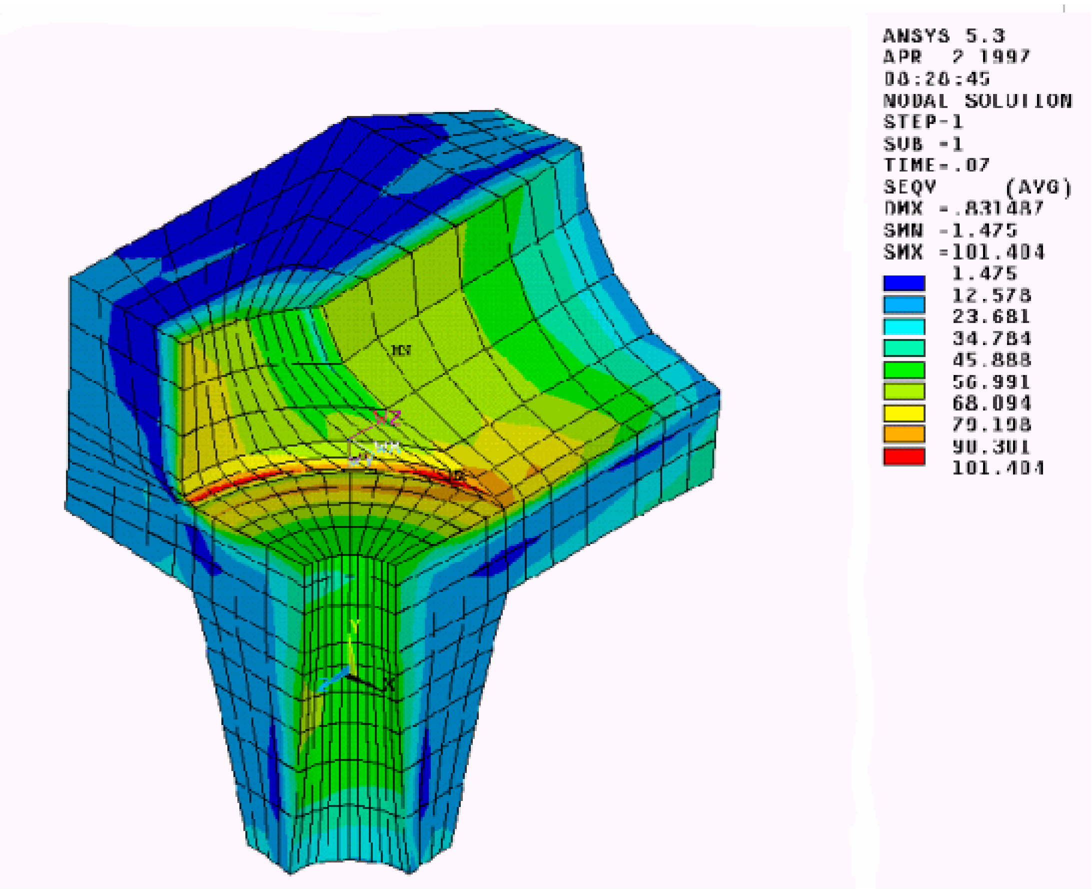

Fig. 4 The chest valve transient thermal stresses.

These calculations are carried out for the mean values of the temperature difference $\Delta T = (T_{\max} - T_{\min}) = 200$ °C and of the temperature rate 200 °C/hr. The maximum thermal stress is developed on the internal surface of the chest valve exactly at the same region where the cracks are observed in the actual component. The maximum overall stress is $\sigma_{\Sigma} = 975 \ \ kN/mm^2$ for the actual chest valve due to pressure and thermal transient. Notice, that the thermal stresses occurring at the depth of 30 mm in the future internal surface (after machining out) are lesser than $100 \ \ kN/mm^2$ and their influence on the service life of the repaired chest valve is negligible.

The thermal stress field is obtained under the same conditions for the repaired chest valve, while the regions containing the cracks are machined out (the maximum stress occurs on the analogous area and here is $\sigma_{th} = 1015 \ \ kN/mm^2$). For the repaired chest valve the maximum overall stress is $\sigma_{\Sigma} = 1017 \ \ kN/mm^2$ due to pressure and thermal transient.

The results of the calculations are presented in table 1 for the actual chest valve and for the repaired one.

Table 1. Results of deterministic calculations for chest valve.

Calculation result	Actual chest valve	Repaired chest valve	% of variation
Pressure stress [kN/mm^2]	46.4	59.8	29
Thermal stress [kN/mm^2]	974	1015	4.2
Overall stress [kN/mm^2]	975	1017	4.1
Life service [cycles]	84	79	-6.3

The dependence of the maximum thermal stresses on the temperature change rate is examined as well. As these results (fig. 5) show the rate's influence practically disappears after the value of about 5000 °C/hr.

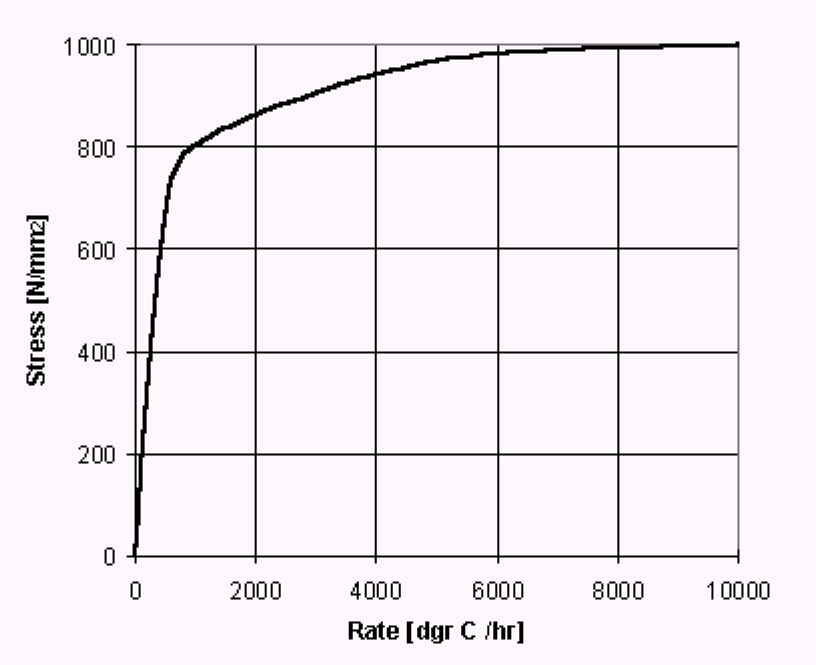

Fig. 5 The dependence of the thermal stresses on the temperature rate.

4. Probabilistic life assessment

A probabilistic approach to service life assessment is performed in assumption that the temperature change and the fatigue properties of the chest valve material are distributed randomly.

The flow diagram of the probabilistic calculations, which are carried out by using a FORTRAN program, is shown in fig. 6. There are two cycles of Monte-Carlo simulations in this program. The external cycle is the simulation of the material's fatigue properties and the internal one is the simulation of the temperature difference. The minimum number of simulations that does not influence on calculation results is above 5,000 for each cycle.

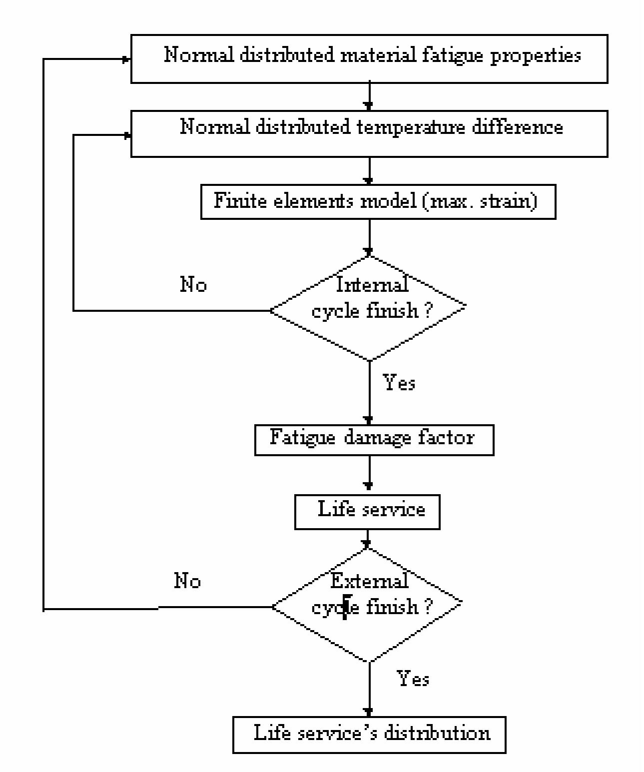

Fig. 6 The flow diagram of the probabilistic calculations.

During the first step of the external cycle the fatigue curve describing the material fatigue properties is chosen as result of Monte-Carlo simulation. It is assumed that this curve (the expected number of fatigue cycles until the failure $N_{\max}$ versus the maximum thermal strain ε) is situated between the maximum and minimum fatigue curves (fig. 7) according to the normal distribution.

During the first step of the internal cycle the expected temperature difference ΔT with the normal probability density $p_1(\Delta T)$ is obtained as result of Monte-Carlo simulation, as well.

The deterministic finite element model of the chest valve enables us to build the function of the maximum thermal strain ε versus the temperature difference ΔT $\{\varepsilon = f_1(\Delta T)\}$. During the second step of the internal cycle the thermal strain ε is computed according to this function.

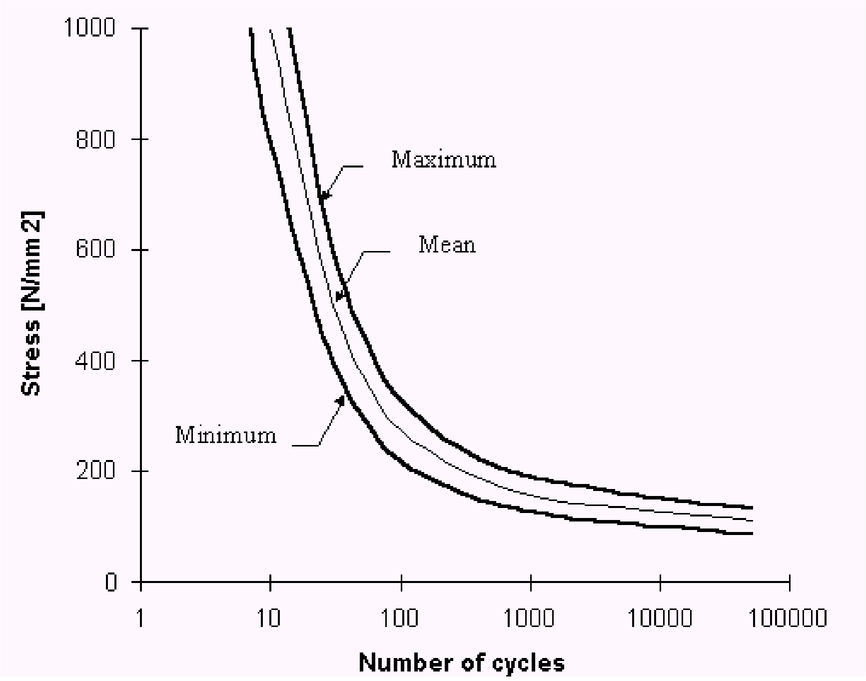

Fig. 7 The probabilistic fatigue curves of the material.

During the last step of the internal cycle the expected number of the material's fatigue cycles until the failure $N_{\max}$ is calculated according to the fatigue curve which is chosen earlier $N_{\max} = f_2(\varepsilon)$. At the end of the step the probability density $p_2(N_{\max})$ of the number of thermal cycles until the failure $N_{\max}$ is obtained.

The internal cycle is repeated each time for the different fatigue curves. After this the life assessment evaluation, based on the calculation of the usage damage coefficient e, is carried out. The value of the fatigue usage damage coefficient e_1 is calculated due to one randomly cycle of thermal stresses as:

$$e_1 = \int \frac{p_2(N_{\max})}{N_{\max}} dN_{\max} \tag{1}$$

The expected service life (number of the chest valve's cycles of the thermal stresses until the failure) N_f is calculated as

$$N_f = \frac{1}{e_1} \tag{2}$$

At the end of the external cycle the probability density of the service life is obtained.

Table 2 The life service (cycles) of the actual chest valve.

		Standard deviation of the temperature difference, %								
		5			10			15		
		min	mean	max	min	mean	max	min	mean	max
Standard deviation of the fatigue properties, %	5	65	85	101	56	92	120	50	98	140
	10	63	83	98	54	90	117	47	95	136
	15	61	81	94	52	88	114	43	92	131

The probabilistic calculations are carried out for the intervals of the temperature change from 180 °C to 220 °C (the confidence level is 0.997) for different standard deviations. The standard deviation of fatigue material properties is changed as well . The results of these calculations for the actual chest valve are presented in table 2.

5. Conclusions

The probabilistic model of the service life of the power station chest valve is built. This model enables us to obtain a good agreement between the actual location of the cracks and theoretical location of the maximum thermal stresses, as well as between the actual service life and its theoretical evaluation. It is proved, that machining out the cracks will prevent their growing and will extend the chest valve's life service.

6. Acknowledgment

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