Strength of Materials, Vol. 38, No. 6, 2006

STRESS-STRAIN STATE OF THE HEADER–STEAM GENERATOR CONNECTOR WELDMENT INDUCED BY LOCAL THERMAL TREATMENT

G. V. Stepanov,[a] V. V. Kharchenko,[a] A. I. Babutskii,[a] V. I. Kravchenko,[a] A. A. Kotlyarenko,[a] S. V. Romanov,[b] N. B. Trunov,[c] V. V. Denisov,[c] and V. A. Piminov[c]

UDC 539.3

Results of estimation of the stress-strain state appearing in the header–steam generator connector weldment after thermal treatment used for the reduction of residual welding stresses are presented. Such treatment, including heating, holding, and cooling of a local connector area with the weld joint, is shown to give rise to rather high additional residual stresses in the weldment.

Keywords: weldment, header, steam generator, welding, thermal treatment.

Introduction. In the majority of cases undesirable residual stresses in structural components caused by prior treatment, e.g., welding, are reduced through the application of thermal treatment, including heating, holding at elevated temperature for stress relaxation, and further cooling [1]. Uniform heating of the structural component and its holding at high temperature lower the level of initial residual stresses and do not induce any additional stresses on cooling. But local heating of the structure results in plastic strains both on heating and cooling, which should be accounted for in the development of thermal treatment conditions.

The assessment of residual stresses in a thermally treated structure is one of the most complex problems in mechanics of deformable solids since one should take account of plastic deformation caused by stress relaxation in the time-variable field of temperatures and thermal stresses. This problem has not been adequately investigated and just this makes it currently central.

This study, as a case in point, examines the effect of thermal treatment (local heating, holding, and cooling) on the stress-strain state of the header – PGV-1000 steam generator connector weldment (Fig. 1) in WWER nuclear power reactors. As is known, recently at some nuclear power plants of Russia and Ukraine several weldments have been damaged before running out the design life of steam generators [2, 3]. Electric-arc welding repair works included thermal treatment of the weldment (its area near the weld joint) for reducing residual welding stresses. The calculation results were mainly employed to establish the mechanism of its effect on the formation of residual stresses and to qualitatively assess their level after the treatment. These estimates can be used to optimize the treatment conditions.

Kinetics of the Stress-Strain State Induced by Thermal Treatment. Circumferential strain and stress variations on the inner surface of the connector with the weld joint (Fig. 1) upon heating, holding at elevated temperature for stress relaxation, and further cooling are schematized in Fig. 2. Thermal expansion of a heated circular portion of the connector is restrained with its neighboring portions, which gives rise to compression stresses in the local area adjacent to the "pocket" surface (point *1*). Relaxation of compression stresses, with the total strain remaining unchanged upon holding at elevated temperature, results in the development of compressive plastic strains (stress-strain state variation along line *1–2*). On further cooling the weldment dimensions are restored and residual

[a]Pisarenko Institute of Problems of Strength, National Academy of Sciences of Ukraine, Kiev, Ukraine. [b]Machine and Structure Reliability Association, Kiev, Ukraine. [c]Gidropress Special Design Bureau, Podolsk, Russia.
Translated from Problemy Prochnosti, No. 6, pp. 43 – 50, November – December, 2006. Original article submitted March 30, 2006.

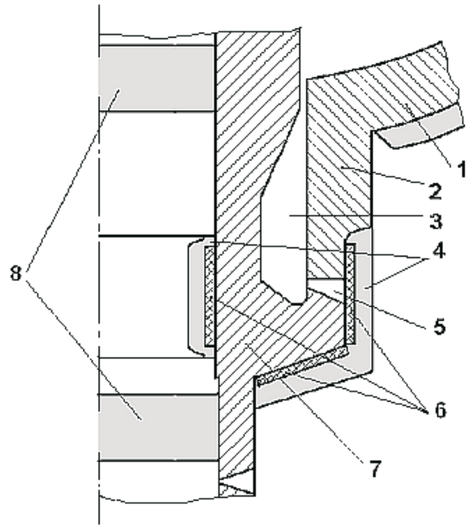


Fig. 1. Scheme of the weldment and mounting of heating elements: (*1*) steam generator vessel with thermal insulation; (*2*) connector; (*3*) pocket; (*4*) thermal insulation; (*5*) weld joint; (*6*) heating elements; (*7*) header; (*8*) thermoinsulating plugs.

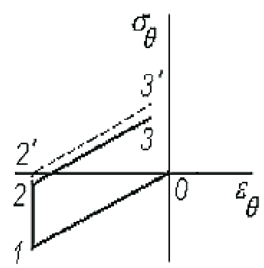


Fig. 2. Stress-strain state variation in the circular portion of the connector upon thermal treatment.

tensile stresses are formed in a plastically deformed circular portion (stress-strain state variation along line *2–3*). It is suggested that the rigidity of the connector portions adjacent to its circular portion plastically deformed with compression (along line *1–2*) is sufficient to restore the weldment dimensions on cooling. The level of residual stresses after cooling depends on the level of stresses at the moment when relaxation ceased (point *2*) at the cooling stage.

Stress-strain state kinetics in the local circular portion of the connector, with stress relaxation brought to completion, is schematized with line $1 - 2' - 3'$ (Fig. 3). Therewith the level of residual stresses after thermal treatment is at its maximum. However, in practice the relaxation of stresses upon holding does not occur in full measure [1]. Therefore, the stress-strain state kinetics may serve only for conservative assessment of residual stresses.

Calculation Scheme of the Weldment. For numerical simulation of stress-strain state kinetics upon thermal treatment, both a simplified axisymmetric calculation scheme of the weldment (Fig. 1), consisting of the header, connector, and a part of the steam generator vessel, and a there-dimensional calculation scheme (Fig. 3), including basic components of the steam generator in accordance with the design documentation, except for heat exchanger tubes, were employed.

In the axisymmetric calculation scheme of the weldment, the geometry and dimensions of the header and connector corresponded to the design ones, except for the length of a thickened connector portion assumed to be 180 mm in calculations. The steam generator vessel was simulated with a part of a spherical shell having an inner radius of 4000 mm and a wall thickness of 145 mm. The inner connector diameter with the weld joint was 1190 mm, the wall thickness in a thinned portion was 72.5 mm.

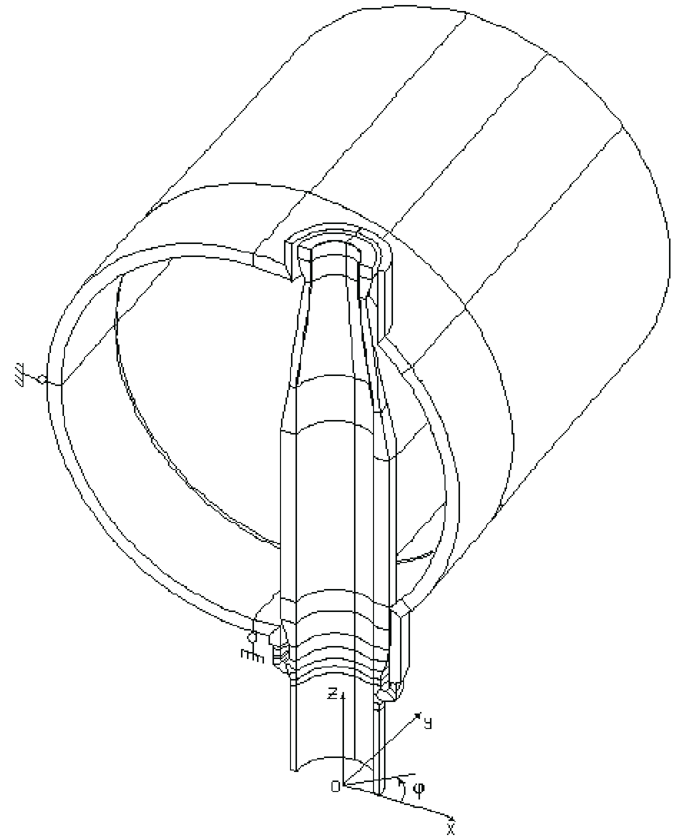


Fig. 3. Three-dimensional calculation scheme of the steam generator.

Stress-strain state kinetics of the weldment at a preset temperature variation in the local area was estimated with the finite element method [4, 5], which was used to solve the nonstationary thermoelastoplastic problem.

The stress-strain state for the axisymmetric scheme of the weldment upon its thermal treatment (Fig. 1) was calculated for zero initial stresses. The only boundary condition is zero vertical displacement over the outer contour of the shell simulating the steam generator vessel. Thermal loading: a linear temperature increase on a heated surface (under external heating elements to 630°C and under internal ones to 530°C, Fig. 1) during 30,000 s, holding at a maximum temperature during the same time and further cooling during 30,000 s down to 200°C followed by convection cooling down to the ambient temperature. These thermal treatment parameters (location of heating elements, its conditions) are consistent with those used in repair works, they will be termed the “reference” thermal treatment. A heat exchange rate through the surfaces without thermal insulation was determined by choosing the convection heat transfer coefficient $k = 20$ W/m$^2 \cdot$°C at zero ambient temperature. It was also assumed that heat exchange between the header wall and the environment in the pocket and in the space between thermoinsulating plugs (Fig. 1) was neglected.

Similar conditions of thermal loading were also used for simulation of stress-strain state kinetics in the three-dimensional scheme.

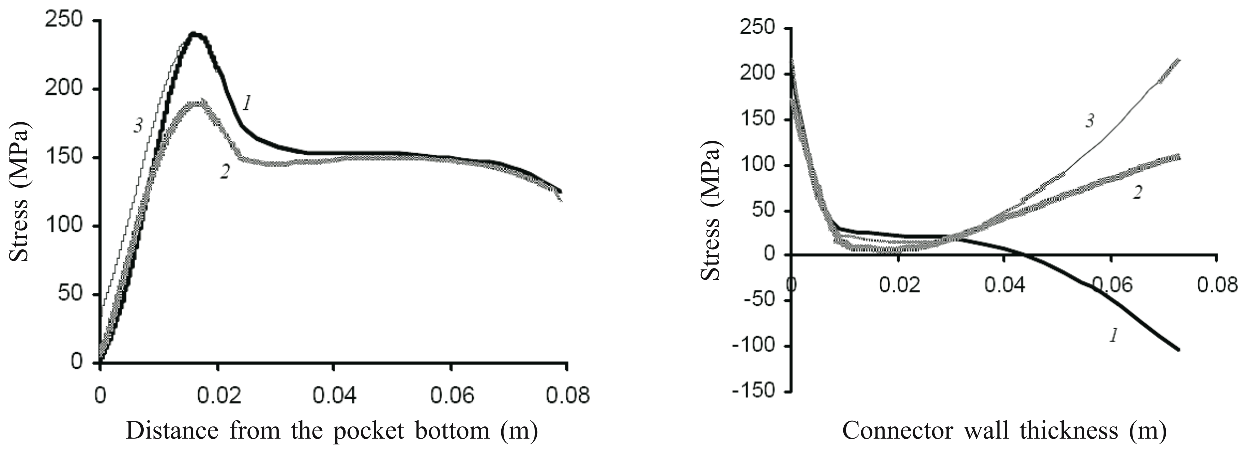
The calculations were performed for the weldment from 10GN2MFA steel. It was assumed that inelastic deformation of the material was determined by the isotropic strain hardening equation accounting for the temperature effect

$$\sigma = \sigma_Y (1+\varepsilon)(1 - T/T^*),$$

where σ_Y is the yield stress, T is the heating temperature, and T^* is the temperature parameter of the material.

TABLE 1. Physicomechanical Properties of 10GN2MFA Steel

T, °C	E, GPa	C_V, J/(m$^3\cdot$K)	η, J/(m·s·K)
0	205	487	38.0
100	202	505	37.8
200	197	530	37.2
300	190	561	36.2
400	180	600	35.0
500	169	653	33.6
600	155	720	32.0
700	142	870	30.5



a b

Fig. 4. Distribution of axial σ_z (*1*), circumferential σ_φ (*2*), and equivalent $\sigma_1 - \sigma_3$ (*3*) residual stresses on the pocket surface on the connector side (a) and through its wall thickness (b) starting from the point with a maximum stress intensity (two-dimensional calculation results).

It should be noted that the parameters of the equation of state ensure a reduction in the stress level from $\sigma_Y = 350$ MPa to $\sigma = 100$ MPa at a temperature increase up to $T = 700$°C, which is valid at $T^* = 980$°C. The physicomechanical properties of 10GN2MFA steel (Young's modulus E, specific heat C_V, thermal conductivity η, etc.) were taken to be variable with temperature (Table 1). The linear expansion coefficient α was assumed to change linearly from $1.1\cdot 10^{-5}$ $(°C)^{-1}$ at zero temperature to $1.42\cdot 10^{-5}$ $(°C)^{-1}$ at 700°C, and Poisson's ratio $\nu = 0.29$.

Analysis of Calculation Results. Several results of numerical simulation are shown in Figs. 4 and 5. As is seen, with chosen areas of heating, thermal treatment conditions, strain hardening and thermal softening parameters as well as the physicomechanical properties of the material, local heating of the weldment leads to local expansion of the heated area and the development of compressive plastic strains in axial and circumferential directions on the inner surface of the pocket on the connector side. Further cooling gives rise to residual tensile stresses in the areas of inelastic compression (Fig. 4). As calculation data demonstrate, the resultant stress-strain state in the weldment area subjected to heating, holding, and cooling is characterized by a significant level of tensile stresses. The distribution of axial stresses on the pocket surface on the connector side displays a typical maximum in the fillet area at a distance of about 17 mm from the pocket bottom (Fig. 4a). It should be noted that in this area the stress distribution pattern under operating loads is similar [3].

The same distribution pattern of residual stresses on the pocket surface near the fillet after thermal treatment was obtained from stress-strain state calculations by the three-dimensional scheme. Stress distribution along the circumferential coordinate was additionally established from calculation results (Fig. 5).

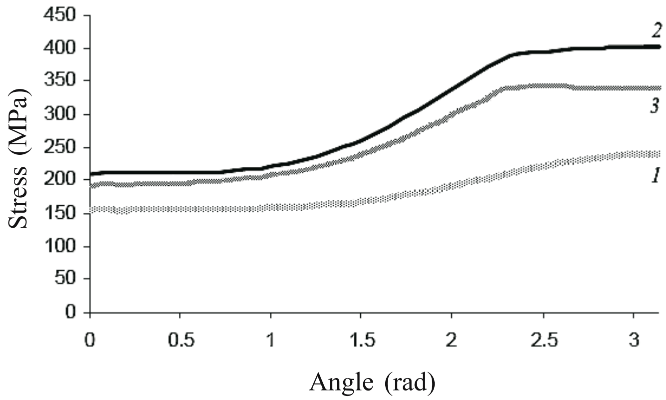


Fig. 5

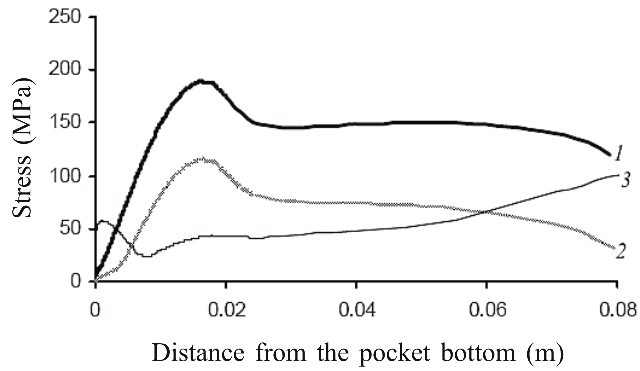


Fig. 6

Fig. 5. Distribution of circumferential σ_φ (*1*), axial σ_z (*2*), and principal σ_1 (*3*) residual stresses on the pocket surface on the connector side at a 20-mm distance from its bottom (three-dimensional calculation results).
Fig. 6. Distribution of residual circumferential (σ_φ) stresses on the pocket surface on the connector side (two-dimensional calculation results): (*1*) "reference" thermal treatment; (*2*) thermal treatment alternative with the boundary conditions being convection in the pocket; (*3*) thermal treatment alternative with additional heating of the connector.

Visual inspection of the fillet area in the pocket reveals a large number of defects: corrosion pits being the result of heat-transfer medium effects and corrosive deposits (copper, etc.) [6]. Higher stresses and their concentration in defective areas may be responsible for crack initiation caused by the distribution of stress tensor components over the connector wall (Fig. 4b). After that cracks propagate in radial (outwards) and axial (along the connector generatrix) directions.

As analysis of calculation results demonstrated, the influence of the connector areas adjacent to the weld joint and limiting radial expansion of the heated area is the decisive factor in the formation of the field of residual tensile stresses on the pocket surface. The stress-strain state of the weldment was calculated after thermal treatment, including additional heating of the thickened portion of the connector up to 480°C (Fig. 1). As follows from the calculations, this additional heating reduces its influence on the stress-strain state of the weld area. The calculated distribution of residual circumferential stresses on the pocket surface after such treatment is presented by way of illustration in Fig. 6 (curve *3*). Calculation results point to the possibility of a significant decrease in the level of residual stresses after optimal thermal treatment.

Correct stress-strain state calculations for thermally treated structural components require adequate account of their heat exchange with the environment. To evaluate the sensitivity of the calculation scheme to the choice of heat exchange conditions, the calculations were performed with changed boundary conditions in the pocket area: thermal insulation was replaced with convective heat exchange [$k = 20\ \mathrm{W/(m^2 \cdot {}^\circ C)}$]. Results shown in Fig. 5 (curve *2*) demonstrate that the boundary conditions exert significant influence on the estimates, which should be taken into consideration in their analysis and application.

Conclusions. Repair works of the header–steam generator connector weldment that included thermal treatment give rise to a residual stress-strain state characterized by tensile stresses of considerable amplitudes in axial and circumferential directions in repair areas.

Maximum tensile stresses formed in the fillet area of the pocket are the result of plastic strains upon high-temperature holding.

In case of crack initiation in a maximum-stressed area of the weldment, the distribution of residual stresses through the wall thickness contributes to further crack propagation in the plane going through the connector axis.

Analysis of calculation results demonstrated that a considerable reduction in the level of residual stresses induced by thermal treatment could be achieved by additional heating of the steam generator connector.

Further investigations should be aimed at the search for optimum thermal treatment parameters providing a decrease in a maximum stress intensity of the weldment under repair.

REFERENCES

1. B. S. Kasatkin, V. M. Prokhorenko, and I. M. Chertov, *Welding Stresses and Strains* [in Russian], Vyshcha Shkola, Kiev (1989).
2. A. S. Zubchenko, N. P. Razygraev, I. L. Kharina, et al., "Results of studies on operating damages of the metal in the weldment areas of headers with Du 1200 connectors of PGV-1000 steam generators," in: Proc. VII Int. Conf. *Materials Science Problems in Design, Manufacture, and Operation of Nuclear Power Plant Equipment*, Saint Petersburg (2002).
3. G. V. Stepanov, V. V. Kharchenko, A. I. Babutskii, et al., "Stress-strain state evaluation of a welded joint of hot collector to nozzle of NPP steam generator PGV-1000," *Strength Mater.*, **35**, No. 5, 536–544 (2003).
4. O. C. Zienkiewicz, *The Finite Element Method in Engineering Science*, McGraw-Hill, London (1971).
5. A. S. Sakharov and I. Al'tenbakh, *Finite Element Method in Mechanics of Solids* [in Russian], Vyshcha Shkola, Kiev (1982).
6. I. L. Kharina, "Results of studies on the effect of external factors of the medium on the stability to slowed-down deformation corrosion cracking of low-alloy steels in water of high parameters," in: Proc. VI Int. Conf. *Materials Science Problems in Design, Manufacture, and Operation of Nuclear Power Plant Equipment*, Saint Petersburg (2000), Vol. 2, pp. 243–257.