DOI 10.1007/s11223-015-9659-6
Strength of Materials, Vol. 47, No. 2, March, 2015

DETERMINATION OF STRESS INTENSITY FACTORS IN THE WELDED JOINT BETWEEN THE HEADER AND SHELL OF PGV-1000M STEAM GENERATOR WITH A DEFECT IN THE FORM OF A CAVITY WITH A CRACK

S. V. Kobel'skyi, S. M. Ban'ko,
and V. V. Kharchenko

UDC 539.4

The stress intensity factors in the welded joint between the header and shell of steam generator with a defect in the form of a cavity with a crack has been investigated. The influence on the history of thermomechanical loading on the stress intensity factor at the crack tip has been analyzed. A comparative analysis of the stress intensity factors for the crack and cavity with a crack has been performed.

Keywords: elasto-plastic state, stress intensity factor, steam generator, cavity, crack.

Introduction. At the Ukrainian nuclear power plants (NPP) with WWER-1000M type reactors in operation one can observe damages in the form of cavities and cracks at the internal surface of the welded joint between the "hot" header and the shell of PGV-1000M steam generator (further referred to as "welded joint"), which are caused by the cumulative action of stresses at the yield point and by the influence of the corrosive medium. Such damages are mainly within the fillet region and welded joint No. 111. Many aspects of the problem of crack initiation near the stress concentrator in corrosive media and evaluation of the stress intensity factor (SIF) in power equipment elements are considered in paper [1, 2]. However, since at present the problem of removal of damages at the internal surface of the welded joint is not solved, in the assessment of its integrity special attention is paid to the methodological aspects of the computational analysis involving the development of adequate computational models, consideration of history of elastoplastic deformation, residual heredity and presence of defects. The papers [3–5] are devoted to the investigation of the problem of the stress-strain state of the welded joint, where the results of calculations are presented in the elastic statement without considering residual manufacturing heredity, history of thermomechanical loading and presence of defects in the welded joint No. 111.

Over the last years at the Pisarenko Institute of Problems of Strength of the National Academy of Sciences of Ukraine there have been carried out the activities aimed at improving the procedures of calculation of the stress-strain state of equipment component of the NPP primary circuit, in particular welded joint, based on the three-dimensional models considering the elastoplastic behavior of the materials, residual manufacturing stresses and history of thermomechanical loading [6].

The paper presents new results of the calculated assessment along with the use of the SPACE-RELAX [7] software for SIF of the welded joint considering the defect in the form of a cavity with a crack within the fillet region. The results of SIF calculations have been obtained using the method of equivalent volumetric integration [8].

The results of testing of the calculated procedure in the solution of model problems on tension of a hollow cylinder with a defect in the form of a crack starting from the cavity tip are presented in papers [9, 10]. Moreover,

Pisarenko Institute of Problems of Strength, National Academy of Sciences of Ukraine, Kyiv, Ukraine.
Translated from Problemy Prochnosti, No. 2, pp. 95 – 100, March – April, 2015. Original article submitted March 23, 2015.

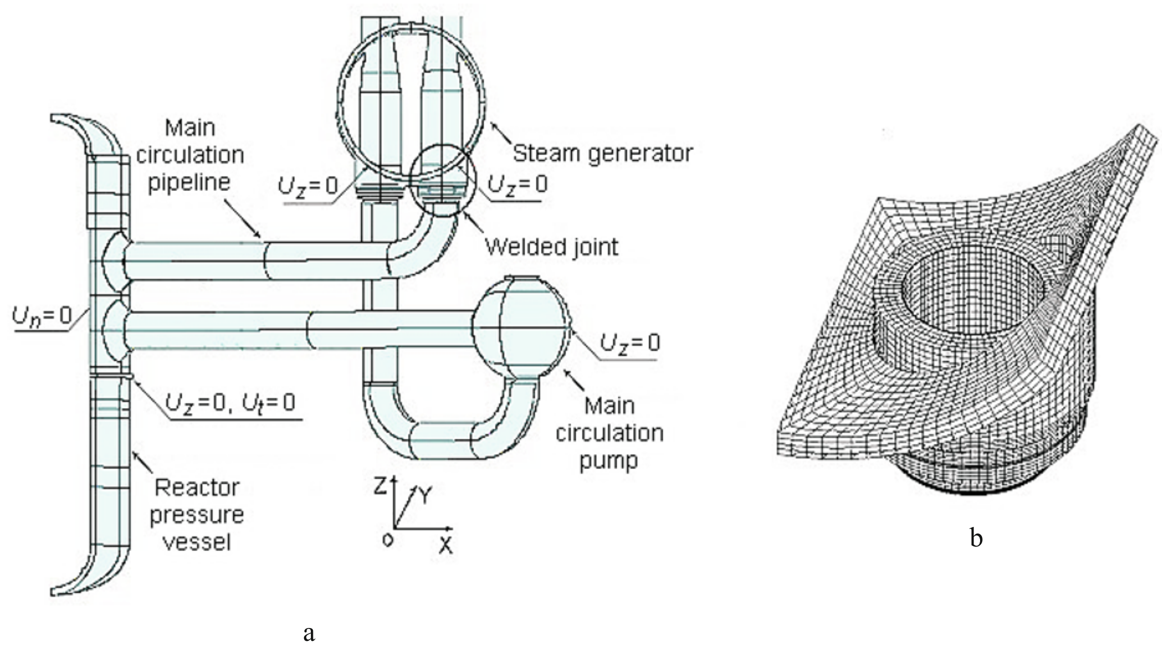

Fig. 1. Computational model of RP loop (a) and welded joint (b).

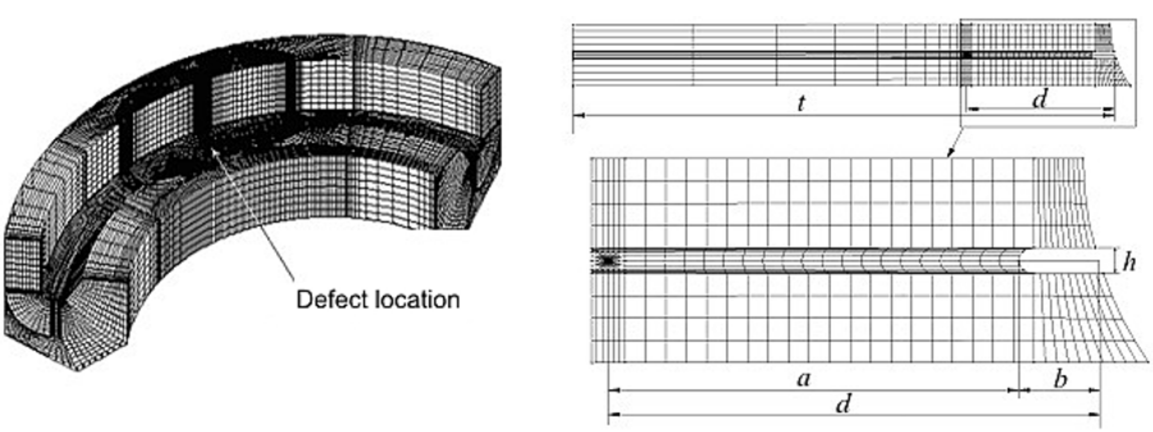

Fig. 2. Finite element model of a fragment of the welded joint with a defect at the cavity tip.

there one can also find the data on the determination of the most critical geometry of the defects of given type with respect to the maximum SIF values.

Computational Procedure. Calculations of the stress state of welded joint have been conducted in the elastoplastic formulation using three-dimensional model of the reactor plant (RP) loop. The computational model of RP (Fig. 1a) consists of an SG shell with nozzles Du 1200 and Du 800, "hot" and "cold" headers of coolant, main circulation pipeline, main circulation pump and 1/4 part of the reactor shell with nozzles Du 850.

The procedure of SIF calculation of the welded joint (Fig. 1b) involves two stages. At the first stage, the elastoplastic stress-strain state is determined for the finite element model of RP loop under operational loads considering residual manufacturing stresses within the welded joint No. 111. At the second stage, SIF is calculated for the model of a fragment of the welded joint with a postulated defect in the maximum tensile axial stresses zone determined at the first stage (Fig. 2). The displacements determined from the elastoplastic calculation of the model of RP loop are taken as the boundary conditions for the fragment of the welded joint with an embedded defect.

In the calculation of the stress-strain state the temperature-dependence of physical-mechanical properties of metal of the RP loop elements is considered. The following cycle of operational loading is simulated: hydraulic testing (HT) – unloading – normal operating conditions (NOC). The fields of residual stresses and strains obtained

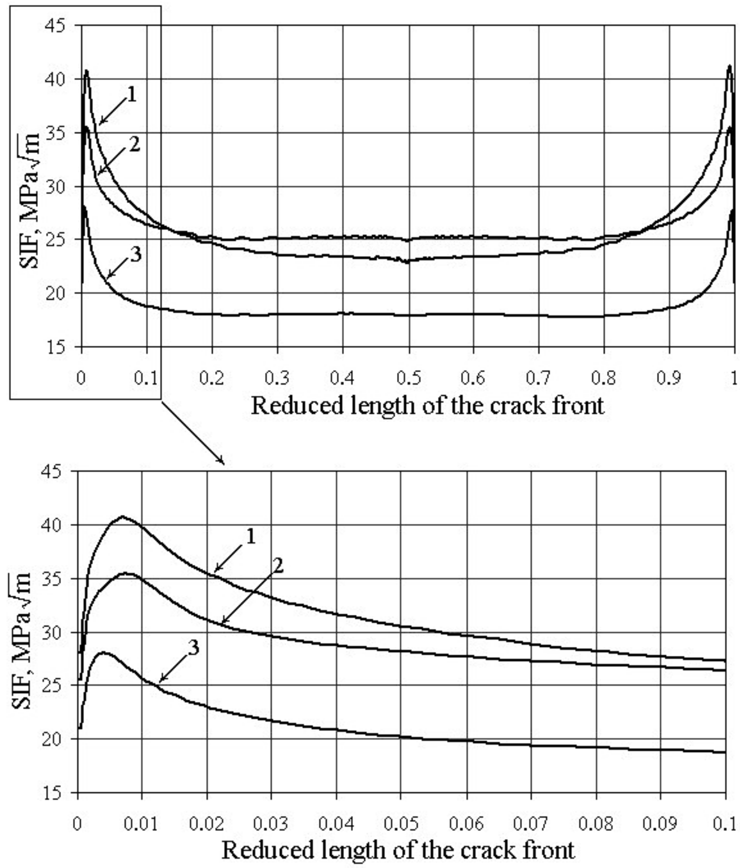

Fig. 3. Distribution of SIF along the crack front: (*1*) NOC after TT and HT, (*2*) NOC after HT, (*3*) NOC under single loading.

from the computational simulation of manufacturing operations of welding and thermal treatment (TT) are taken as the initial state. For HT the primary and secondary pressures are assumed to be 24.5 MPa and 10.78 MPa, respectively, whereas for NOC – 16.0 and 6.0 MPa, respectively.

The obtained distribution of residual and operating stresses along the circumferential coordinate within the line of the fillet region of the internal surface of the cylindrical part of nozzle Du 1200 at a distance of 20 mm from the bottom of the pocket, as well as on the internal wall of the nozzle throughout the height from the pocket bottom has been presented earlier in [6].

A defect in the form of a cavity with a semi-elliptical crack at the tip in the fillet region and oriented along the circumferential coordinate has been simulated. The thickness t of the nozzle wall within the defect zone is 73.14 mm. The following parameters of the cavity and crack are accepted: cavity height $h = 1.25$ mm, cavity depth $b = 3.25$ mm, depth of the cavity with a crack $d = 18$ mm, crack depth $a = 14.75$ mm, and ratio between the crack half-axes $a/c = 1/3$. The cavity length along the circumferential coordinate exceeds the larger crack half-axis significantly.

Calculation Results. Figure 3 illustrates the distribution of SIF values along the crack front for operational loading. Additional calculations under single loading were performed under NOC to perform the assessment of the influence of consideration of residual stresses at the welded joint No. 111 and history of thermomechanical loading on the calculated SIF values.

The analysis of the results of calculations shows that for the loading cycle, at which residual stresses are calculated, the maximum SIF values are 40.5 MPa$\sqrt{\text{m}}$. Neglecting residual stresses from TT causes a decrease of the maximum values of SIF up to 35.5 MPa$\sqrt{\text{m}}$. Under single loading SIF values are equal to 28 MPa$\sqrt{\text{m}}$, which is lower by 47% than the SIF values for the loading cycle with consideration of residual stresses after TT.

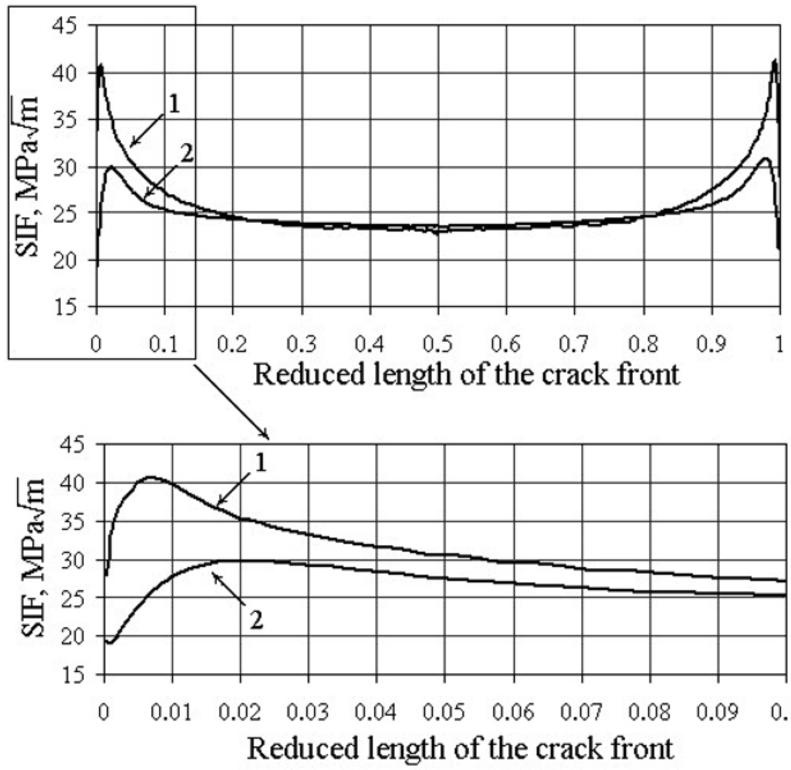

Fig. 4. Distribution of SIF along the crack front for the cavity with a crack (*1*) and the crack (*2*).

Thus, neglecting residual stresses within the loading cycle results in a considerable decrease of the maximum SIF and, consequently, in non-conservative assessment of the fracture resistance for the welded joint.

A comparative analysis of the calculated SIF for the cavity with a crack and the crack was carried out. It was accepted that the defect depths were equal to 18 mm at a ratio between the crack half-axes $a/c = 1/3$. Here, the crack depth at the cavity tip is 14.75 mm. Figure 4 shows the distribution of SIF along the crack front for NOC.

It is seen that for the crack the maximum SIF values are 30 $MPa\sqrt{m}$, whereas for the cavity with a crack they increase by 30% and are equal to 40.5 $MPa\sqrt{m}$, in other words, at the same depth the defect in the form of a cavity with a crack is more critical.

The distribution mechanism of SIF along the crack front, where the maximum values are near the cavity surface, facilitates crack propagation in the circumferential direction.

CONCLUSIONS

1. SIF of the welded joint between the header and shell of steam generator with the defect in the form of a cavity with a crack at its tip was determined in the process of simulation of the operating loading cycle.

2. The influence of residual stresses and history of thermomechanical loading on the calculated values of SIF at the crack tip was analyzed.

3. It is showed that neglecting residual stresses within the loading cycle leads to a decrease of the maximum values of SIF by 47% and, consequently, to non-conservative assessment of fracture resistance of the welded joint.

4. Based on the comparative analysis of the calculated SIF values for defects in the fillet region of the welded joint in the form of a cavity with a crack and the crack it was determined that at the same defect depth the maximum SIF values for the defect “cavity-crack” exceed the SIF values for the crack by 30%.

5. The distribution mechanism of SIF along the crack front facilitates its propagation in the circumferential direction.

REFERENCES

1. V. V. Panasyuk (Ed.), *Fracture Mechanics and Strength of Materials* [in Ukrainian], Vol. 7: I. M. Dmytrakh, A. B. Vainman, M. G. Stashchuk, and L. Toth, *Reliability and Lifetime of Structural Elements of Heat-and-Power Engineering Facilities*, Akademperiodika, Kyiv (2005).
2. A. F Getman, *Operating Life of Nuclear Vessels and Piping* [in Russian], Moscow, Énergoatomizdat, (2000).
3. Yu. G. Dragunov, O. Yu. Petrova, S. L. Lyakishev, et al., "Increase of reliability of operation of PGV-1000, -1000M steam generator nozzles," *Atom. Énergiya*, **104**, No 1, 9–13 (2008).
4. S. L. Lyakishev, N. B. Trunov, S. A. Kharchenko, et al., "Development and justification of measures for ensuring reliable and safe operation of welded joints No. 111 in PGV-1000M steam generator," in: Proc. of the VI Int. Conf. on *Safety of NPPs with WWER*, FGUP OKB "Gidropress," Podol'sk, Russia (2009).
5. N. B. Trunov, S. A. Kharchenko, N. F. Korotaev, and S. L. Lyakishev, "Results of activities on the investigation of reasons of damage of metal within the welded joint between the primary circuit nozzle and steam generator shell and development of compensating measures," in: Proc. of the VIII Int. Seminar on *Horizontal Steam Generators*, FGUP OKB "Gidropress," Podol'sk, Russia (2010).
6. A. Yu. Chirkov, V. V. Kharchenko, S. V. Kobel'skii, et al., "Stress-strain state of the coolant collector-to-nozzle welded joint in the PGV-1000M steam generator under the operating loads with consideration of residual manufacturing stresses," *Strength Mater.*, **45**, No. 4, 459–465 (2013).
7. *Software "Three-Dimensional Finite Element Modeling of the Thermal and hermostressed State of Components of Mechanical Engineering Structure (SPACE)"* [in Ukrainian], UkrSEPRO Conformity Certificate No. UA1.017.0054634-04 (2004).
8. S. N. Atluri (Ed.), *Computational Methods in the Mechanics of Fracture*, North-Holland, Amsterdam (1986).
9. S. M. Ban'ko, S. V. Kobel'skyi, and V. V. Kharchenko, "Numerical simulation of the stress state of a hollow cylinder with a defect in the form of a cavity with a crack," *Opir Mater. Teor. Sporud*, Issue 92, 157–169 (2014).
10. V. V. Kharchenko, S. M. Ban'ko, and S. V. Kobel'skyi, "Numerical solution of the problem on the fracture resistance of a hollow cylinder with a defect in the form of a cavity with a crack in the elastoplastic statement," *Opir Mater. Teor. Sporud*, Issue 93, 137–150 (2014).