CAPABILITIES OF THE METHOD FOR EVALUATION OF STRESSED-DEFORMED STATE AT INSPECTION OF NUCLEAR POWER FACILITIES

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1. Introduction

There is a need in nuclear power engineering to introduce new testing methods and instrumentation to improve industrial safety as well as to increase operation life of pipelines and equipment. For instance, research [1] show that 6% of failures in WWR-C reactor operation for the period over 40 years belong to failures of pipelines and equipment in the primary loop since during long-term operation these units are subjected to intensive cyclic, thermal and mechanical loads such as oscillating pressure and temperature drops in the working media, vibrations. These loads can lead to irreversible degrading changes in physical and mechanical properties of the construction material what, in its turn, shortens operational life or results in failures accidents. There is no doubt that degrading processes at initial stages develop in limited areas as localized increases of stress then developing into larger defects. That is why safe life time of units and equipment is restricted by the resource of these localized areas; probability of their appearance is higher in initially strained areas of a unit such as in weld joints, bend-stressed areas and in locations of acceptable assembling or construction defects.

Inspections of nuclear power facilities are performed with conventional non-destructive testing methods focused mainly on identification of discontinuity flaws in weld joints, bulk metal and build-up welding. Evaluation of local stress levels is still only possible either with simulation models [2] or based on destructive testing which required cutting off samples directly from metal construction.

Capabilities of modern testing methods employed for identification and assessment of stressed-deformed state are mainly determined by NDT instrumentation and its applicability. In the majority of cases, instruments and methods used to reveal technological and construction concentrators of mechanical stress and to assess rates of these stress are widely employed in oil and gas industry for ferromagnetic materials [3]. These methods are still rarely used in nuclear power engineering for testing of non-ferromagnetic construction alloys and steels due to lack of accumulated experimental data [4, 5] on applicability of the methods for a wide range of material types.

Present paper reports on research which involved diagnostics and assessment of stressed state in weld joints and bulk metal of the primary loop pipelines and heat exchangers of the WWR-K reactor employing magnetic-anisotropy and scanning flaw detector.

2 Main results and discussion

2.1 Determination of critical values for parameters of stress concentrators in constructions of austenitic and aluminum alloys.

For investigation we have chosen the heat exchangers and pipelines of the primary loop of cooling system of the WWR-K reactor (in operation since 1967). The pipelines ∅219x12mm and the heat exchangers are made of austenitic stainless steel 1Cr18N9Ti, the pipelines ∅371x10 – of aluminum alloy SAB-1. During operation, pipeline walls are subjected to cyclic temperatures in the range 10 – 55^oC, pressures 1.2 – 3.5 kg/cm^2 of the desalinated water and are exposed to radiation. So, we selected potentially unsafe parts of the pipelines at bends and in the areas where several welds come together. Assessment of stressed state was performed for the weld joint zones and in the bulk metal employing a magnetic anisotropy scanning flaw detector «StressVision 2» with scan step of 40 mm. Measurements with this instrument made it possible to get the distribution of stressed state parameters in the bulk metal, weld joint and its vicinity. Upon processing the software «StressVision 2» made us possible to create the maps of difference in principal mechanical stress (DPMS), DPMS gradients, distribution maps for coefficients of local mechanical stress concentration (MSC) and mechanical stress non-uniformity coefficients (HSC) which were then used to plot isolines[1] with maps of stressed state parameters.

Evaluating acceptable values for DPMS, MSC, and HSC we based on the assumption that irreversible changes in deformed metal materials start after the material reached its yield stress and disruption becomes possible with certain local concentration of mechanical stress and gradient of main mechanical stress differences; the disruption process in elastictico-plastic solids therefore starts when the condition (1) below is violated [6]:

$$\begin{Bmatrix} (\sigma_1 - \sigma_3) \le \sigma_T \\ \text{MSC} \approx 1 \\ \text{HSC} \approx 1 \\ \text{G} \approx 0 \end{Bmatrix} \qquad (1)$$

where ($\sigma_1 - \sigma_3$) – difference of main mechanical stress (DPMS), i.e. a parameter characterizing upper and lower limits of normal stress across sections with zero tangential stress.

σ_T – yield stress;

G – DPMS gradient characterizing stress decrease rate as a function of distance along given directionж

MSC – coefficient of mechanical stress concentration, a ratio of stress in a given point to stress at the same point at zero local stress concentration;

HSC – coefficient of mechanical stress non-uniformity.

It is known that disruption is a multi-stage process and each stage has certain set of values for MSC, HSC and gradients which were determined for carbonaceous ferromagnetic steels [7]. Experimental determination of critical values in anomalously stressed zones of construction material is needed for austenitic and aluminum alloys; a decision on possibilities for further operation is to be taken upon reaching of these critical values.

Norms for the acceptable values of the parameters of stress concentrators for austenitic stainless steel and aluminum alloy SAV-1 were determined based on data obtained in model experiments aimed at determination of characteristics for stressed state in bended metal plates. For that, 5 mm-thick aluminum and stainless steel (Cr18N10Ti) were laid out with a grid of 40x40 mm. Then the plates were step-by-step deformed to certain bend angles; scanning of deformed plates with the flow detector «StressVision-2» was performed after each loading step. To reduce boundary effects interfering with real pattern of stress distribution, the surface at scanning was arranged 40 mm away from plate boundaries. Distribution maps for main mechanical stress differences and their gradients, MSC and HSC were plotted for each scan run to assess the values of stress concentrators

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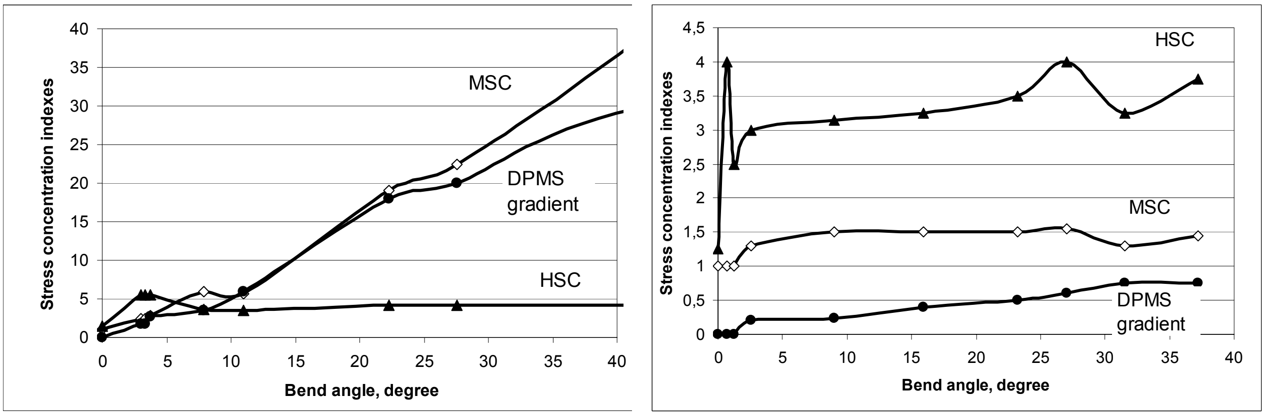
[1] Isoline – a line on a material surface linking all points of equal or constant stress [8].

in vicinity of the bend. It has been revealed (see Fig.1) that MSC and DPMS gradient are sensitive characteristics for bending of aluminum while HSC is that in case of austenitic stainless steel. Comparative analysis of data on stressed state parameters for different disruption stages obtained by the designer of scanning flow detector "StressVision-2" for carbonaceous steels [7] and data at Fig.1 has made it possible to assess provisional critical values for stressed state parameters which, when revealed, would require additional diagnostics with non-destructive methods.



a b

Fig. 1. MSC, HSC indexes and DPMS gradient in the zone of mechanical stress concentration versus bend angle for aluminum (a) and steel plate (b)

Further, inspecting pipelines and primary loop of the WWR-K nuclear reactor we paid particular attention to those areas with stressed conditions above experimentally assessed conditional critical values presented in Table 1.

Table 1. Provisional critical values for stressed state of aluminum and stainless steel

	Aluminum and aluminum alloys	Stainless austenitic steel
MSC	3	1.5
HSC	4	3
DPMS[2] gradient	5	0.4

2.2 Assessment of stressed-deformed state of pipelines and heat exchangers of WWR-K reactor primary loop

Bend areas, welds of the pipelines and adjacent areas were studied employing magnetic-anisotropy scanner-flow detector «Stressvision-2». Based on measurements, mechanical stress concentrator distributions, stress heterogeneity coefficients and mechanical stress gradients were plotted to evaluate conditionally dangerous areas.

Inspection of force and tailpipe of the primary loop made of aluminum alloy SAV-1 revealed the highest stress concentrations in vicinity of flange joints close to weld joints. Figure 2 represents layout of a scanned pipeline area and a map of DPMS, MSC distributions along with DPMS gradients: one can see that in the vicinity of the weld joint of a pipe (between the triple weld joint and the flanged joint) in the point with coordinates {1.5; 6.5} there is a stress concentrator; in the vicinity of this stress concentrator isolines changes its sign from negative to positive what tells us about the possibility for elastic deformation to appear there. In the vicinity of weld joint (a point with coordinates {5.5;4}) one can see a zone of stress concentration with MSC=2.6 and DPMS

[2]The method [8] employs three categories for DPSM gradients: low – 0-2, moderate 2-4, high >4.

gradients equal to 6, which are close to the provisionally critical values. At that the main flow of isolines forms symmetrical concentric ellipses where one should expect generation and development of orbicular defects in.

Weld joint scanning of units made of austenitic steel revealed a zone with increased stress concentration in vicinity of triple joint in the heat exchanger; further analysis of main mechanical stress gradients and their distribution showed that this defect is not a dangerous one. At inspection, particular attention was paid to those parts of steel pipelines subjected to vibration. So, we picked up a weld joint of a line to the circulation pump in the place of circular bend with maximal stress due to bend. Figure 3 below represents a scanning map showing several stress concentration zones in the region of the weld joint (horizontal line 5).

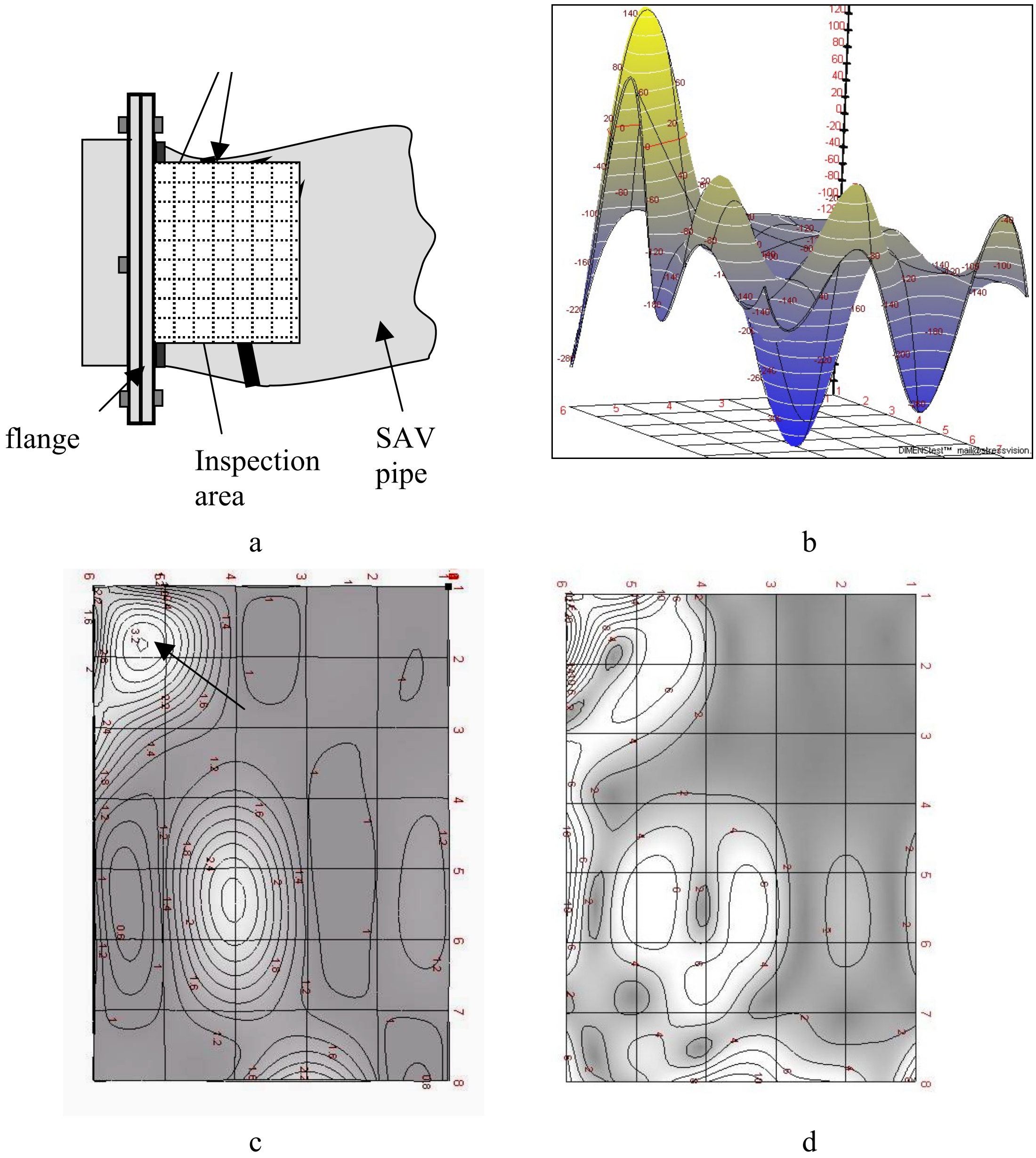


Fig. 2. Inspection layout (a) and distribution maps for main mechanical stress differences (b), mechanical stress concentration coefficient (c), DPMS gradients (d) in the material SAV-1 of the WWR-K reactor primary loop in vicinity of flange and weld joints.

At the 3-D map of DPMS (see Fig. 3-a) the region of minimal stress values belongs to the weld joint and the extremes – to the stress concentration zones. In the vicinity of the points[3] {5;4.5} and {5.5; 1.5} maximal values of MSC and HSC exceed those accepted and critical ones (see Table 1). Distribution maps for concentration coefficients and mechanical stress non-uniformity (see Fig. 3 b and c) the main flows of isolines crowding form concentric ellipses arranged along the weld axis: such pattern is typical for orbicular defects. Besides, the rate of DPMS change along the boundaries of local concentration is close to the critical values. Since inspection of the primary loop of WWR-K reactor employing the scanning flaw detector "StressVision-2" has been performed for the first time, proposed critical values for the parameters of stressed state need additional experimental verification. Based on the obtained results it has been proposed to perform additional investigation of the zones with increased concentration of stress employing other non-destructive methods.

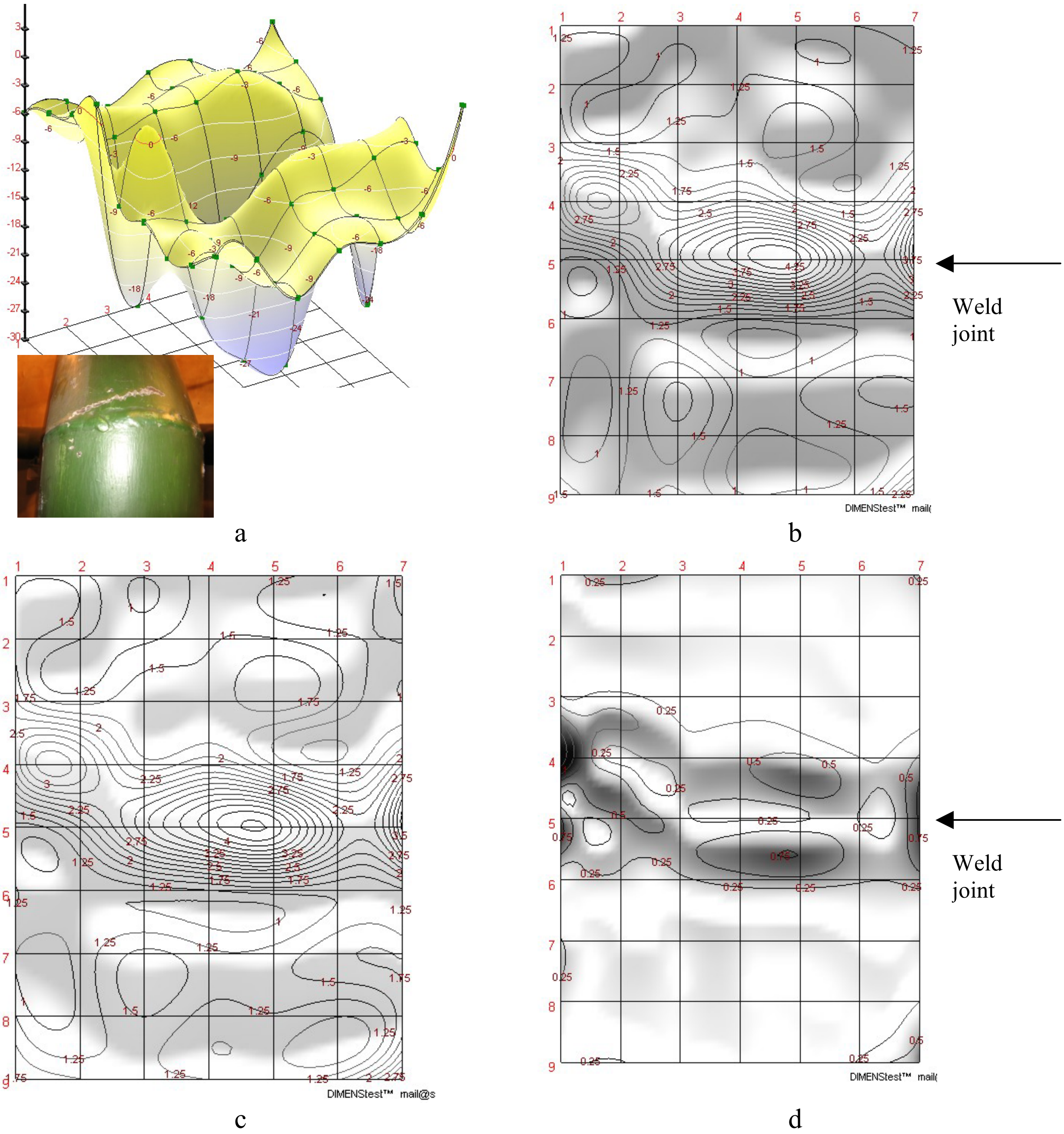


Fig. 3. Distribution maps for main mechanical stress differences (a), mechanical stress concentration coefficient (b), mechanical stress heterogeneity coefficient (c) and DPMS gradients (d) in the material 1Cr18N9T of the WWR-K primary loop in vicinity of the weld joint.

[3] First comes the horizontal coordinate, second – the vertical one.

Previously, employing radiography we revealed lack of fusion (up to 3 mm in depth and 1-2 mm in width) in the seam bottom due to poor welding and various defects in other weld joints. Based on the inspection performed, it was recommended to continue monitoring of these areas and to simulate defects proliferation at cyclic loads during "starts\stops" of the WWR-K reactor.

One should note that the method of «StressVision-2» instrument application for inspection of non-ferromagnetic metal constructions is still developing and the data obtained still need further discussion and verification by approved non-destructive testing methods.

2.3 Evaluation of the WWR-K reactor primary loop lifetime employing low-cycle fatigue criterion

Kinetics of crack development was simulated for the weld joint which binds the pipeline to the main circulation pump since there are the highest loads mainly due to bending. Assessing the crack kinetics we assumed that the weld joint has a circular crack of given depth equal to the depth of real incomplete fusion revealed and that the pipe experiences axial load since such load is more dangerous than bending moment. Incomplete fusion of 33 mm depth was considered as a crack, i.e. incubation period was taken zero what increases for several times the assurance coefficient in our calculations. Number of load cycles resulted in crack development from initial depth l_0 to a depth l_K has been determined from the crack development equation for cyclic loads which operates deformational criteria for disruption [9, 10]:

$$N = \frac{1}{C_0}\left[\frac{R+0.5\delta}{2B\Delta\sigma_H\sqrt{\pi\delta}(R-0.5\delta)}\right]^m \int_{l_0}^{l_k}\frac{(1-l/\delta)^m}{(l/\delta)^{mB}}dl$$

where C_0, m – material constants equal to $6.7\cdot10^{-11}$ and 3.53, respectively for Cr18N9T steel in the operation temperature range;

$\Delta\sigma_H$ – stress amplitude at outer surface of the pipe weld joint equal to 14.6 kgf/mm^2;

l_0 – initial crack depth equal to 3 mm;

$$B = 0.2777\left(\frac{R-0.5\delta}{\delta}\right)^{0.256}$$

where R=219 mm – pipe radius; δ= 12 mm – wall thickness.

Calculated kinetics of the crack at cyclic load are presented at Fig.4 which shows that stable crack development can be limited within the depth 4 mm at 6,400 load cycles. According to [2,10] and taking into account increased safety requirements we accepted the load factor for stress to be $n_\sigma=2$; corresponding assurance factor for the number of cycles for Cr18N9Ti-type steels can be taken as $n_N=11{,}6$. Taking into account the assurance factor for the number of cycles and our calculations (see Fig.4), acceptable number of load cycles for the selected weld joint comprised 550. Therefore, calculations performed for the specific weld joint taking into account assumptions made (which, actually, increase safety factor) can be extended to the whole primary loop pipeline of the reactor WWR-K at operational variations of temperatures not more than 40^o with the number of "start-stops" up to 550. These calculations agree well with literature data, so calculations of reactor pipeline life time performed for the steel 12ChN10Ti employing various criteria for low-cycle fatigue assessed the lifetime of pipelines to be in the range 470 [2] to 6,000 cycles determined based on energy criteria [11].

By the present time, the primary loop pipelines has already used 35% of its calculated resource in terms of the number of cycles; so, some increase in stress levels in the regions with defects is expected at higher number of "star-stops".

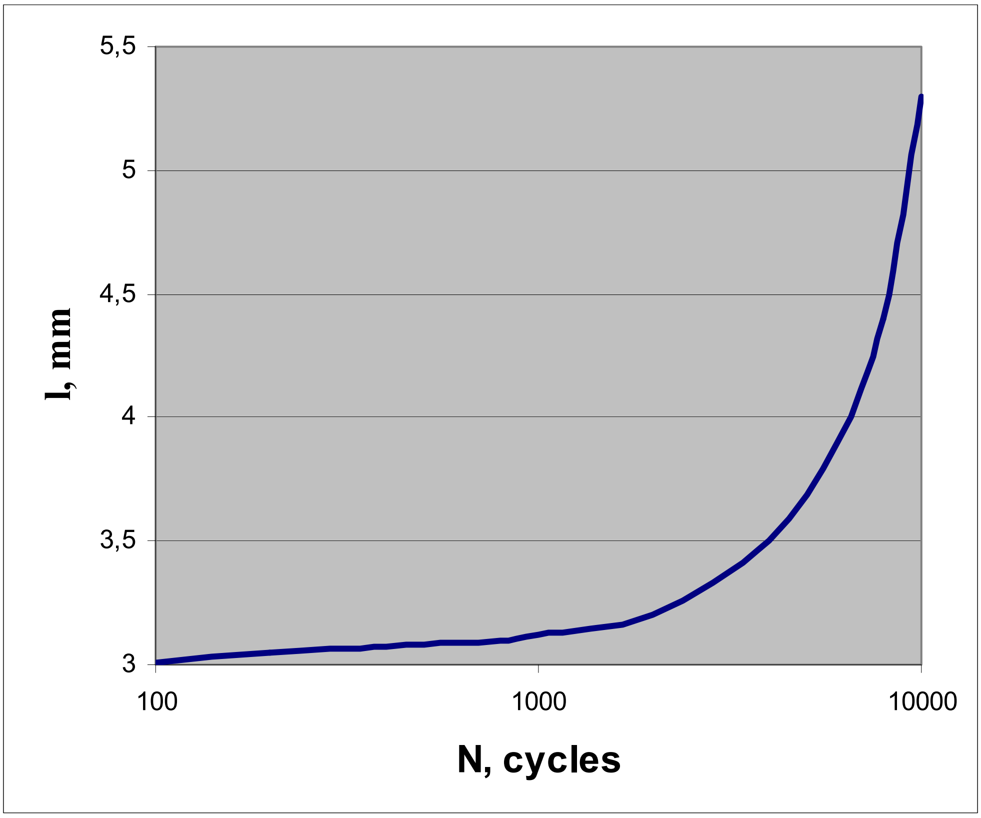


Fig. 4. Calculated kinetics of fatigue crack at cyclic load

3 Conclusions

Present paper reports on research outcomes of stressed state in weld joints of primary loop pipelines and heat exchangers of the reactor WWR-K (in operation for 40 years). Novel use of a magnetic anisotropy scanning flaw detector «StressVision-2» made us possible to reveal zones of increased concentrations of mechanical stress in weld joints and metal constructions of the WWR-K reactor primary loop made of austenite steel 1Cr18N9Ti and aluminum alloy SAV-1. While the proposed method needs further development for assessment of stressed-deformed states, the results make it possible to reduce inspections and testing with other NDT methods (RT, UT) and to pay more attention at regular monitoring to specific parts pipeline and equipment units of nuclear power facilities with increased stress concentrations.

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