INDICES OF PORE FORMATION IN HEAT TREATMENT OF WELDED ASSEMBLIES FROM STEELS SUSCEPTIBLE TO TEMPERING CRACKING

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It is well-known fact that the welded joints from heat-resistant steel of 10GN2MFA type, widely used in power engineering, have a tendency to formation of tempering cracks. Aim of the present work was a grounded explanation of reasons of crack appearance as well as understanding of mechanisms of their preventing based on pore formation in material creep. It is shown in the work using published experimental data of Prof. I. Hryvnak on this problem and attracting modern statements of mechanism of poor formation in plastic deforming (strain ageing) that mechanism of section loss near the grain boundary in HAZ metal becomes significantly apparent in two-hour holding at 700–600 °C temperature due to pore formation at relaxation of high tempering residual stresses. Efficiency of heat treatment (relaxation of high residual stresses related with manufacture and, in particular, with repair of critical structures from considered steel) is rapidly reduced at tempering temperatures below 600 °C. Therefore, existing anxieties related with effect of modes of high tempering on appearance of tempering cracks in HAZ at fusion welding of specified type of steel are grounded enough and require particular attention to problems of determination of permissibility of corresponding repairs and development of suitable technologies on modes of post-weld heat treatment. This allows significantly reducing operation expenses. 8 Ref., 2 Tables, 3 Figures.

Keywords: *tempering cracks in HAZ of low-alloy steel, strain ageing, relaxation of residual stresses, grain-boundary diffusion, pore formation*

Tempering (reheating) or strain ageing cracks are one of the most character defects of welded structures manufactured from some modern low-alloy Cr–Mo steels. These defects have intercrystalline character (Figure 1) and appear, as a rule, in the HAZ in coarse grain areas. Effect of chemical composition of steel on tendency to formation of tempering cracks is determined by equation based on the results of experiments for low-alloy steel with maximum 1.5 % Cr [1]:

Figure 1. Appearance of cavities on initial stage of tempering crack formation in HAZ metal (×2000)

$$\Delta G = \mathrm{Cr} + 3.3\mathrm{Mo} + 3.1\mathrm{V} + 10\mathrm{C} - 2. \qquad (1)$$

If $\Delta G > 0$, then steel is susceptible to formation of tempering cracks. Besides the chemical composition, an appearance of the tempering cracks is affected by mode of reheating (high tempering), namely time of material holding at high temperature promoting its strain aging. Figure 2 shows the data of Prof. Hryvnak [2] concerning the effect of temperature of two-hour holding in reheating of the specimens of 10GN2MFA steel welded joint from near-weld zone ($\Delta G = 0.8$–1.4) on value of nominal (applied) tensile stresses, necessary for obtaining of studied failure (see Figure 1). It can be seen that the temperature of two-hour holding provides significant effect on minimum allowable value of applied stresses at which formation of tempering cracks takes place (see Figure 2).

The failures were observed at 700–580 °C tempering temperature and 280–380 MPa nominal stresses, and there were no studied failures at temperatures below 550 °C even with nominal stresses above 625 MPa.

Consideration of only grain-boundary diffusion of additives and corresponding grain boundary embrittlement can not explain these facts. It can be assumed that process of nucleation and growth of pores, related with relaxation of sufficiently high residual welding stresses, and corresponding growth of creep deformations due to residual elastic deformations after welding have certain effect here. Series of works [1, 2 etc.] studied such a mechanism of strain ageing of material in the near-weld zone connected with development of diffusion plasticity (creep) deformations in relaxation of residual elastic deformations after welding. Certain degradation of properties of studied steel is possible in power engineering, where 10GN2MFA type steel is widely used (steam generators, circulation pipeline of WWER-1000 etc.) at total duration of holding of welded assemblies at high temperatures (above 580 °C) in process of manufacture and repair (in particular, when technological process of welding is alternated with intermediate tempering).

This work makes an effort of obtaining of grounded solution for given problem based on modelling of mechanism of pore formation in material creep.

Pore formation in creep results in reduction of net sections of structural elements, that naturally increases net stresses approximating them to critical ones. This sufficiently simple idea is used in development of corresponding solutions in material creep [3, 4 etc.] as well as at instanteneous plastic deformations [4–7 etc.]. Extent of reduction of net sections (1–S) of structural element in zone of potential crack formation (see Figure 1) can be approximately evaluated using data (see Figure 2) and applying dependence

$$\frac{1}{(1-S)}\alpha_\sigma = \frac{\sigma_{cr}}{\sigma_{test}}, \tag{2}$$

where S is the relative sectional area of structural element occupied by pores; α_σ is the stress concentration related with notch; σ_{test} are the testing stresses; σ_{cr} are the critical stresses at testing temperature (~20 °C). $\sigma_{cr} < 625$ MPa on results of tests (after high tempering at $T \leq 550$ °C) that allows getting an inequality from (2):

$$S = 1 - \frac{\sigma_{test}\alpha_\sigma}{\sigma_{cr}} > 1 - \frac{\sigma_{test}}{625}. \tag{3}$$

Data, given in Table 1, show that a mechanism of section loss in near-boundary zone becomes sufficiently apparent due to pore formation at relaxation of the residual welding stresses in a process of high tempering under condition of approximately similar level of embrittlement of grain boundary in HAZ metal on mechanism of grain-boundary diffusion at 700–550 °C of two-hour holding.

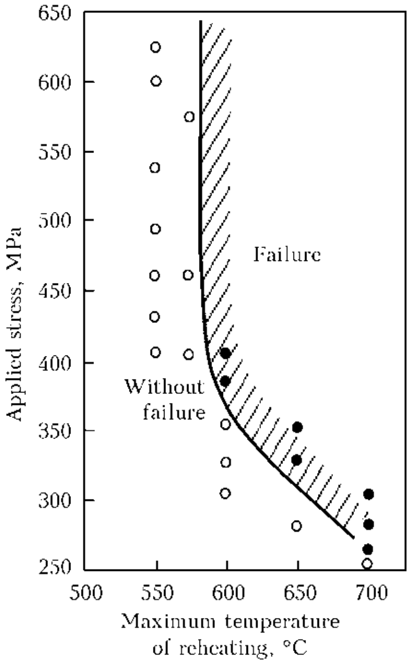

Figure 2. Effect of applied stresses and maximum temperature of reheating on tempering crack formation in specimens from 10GN2MFA steel with notch after simulation of heat cycle: T_{max} = 1300 °C; $\Delta t_{800-500}$ = 100 s; $\Delta G \approx 0.8$–1.4 (1)

Experimental data on relaxation of residual welding stresses in HAZ metal near fusion boundary in arc welding of studied steel (Figure 3) are given in work [2]. It follows from them that the residual stresses in considered zone reduced from corresponding yield point $\sigma_y(T)$ up to values indicated in Figure 3 and Table 2, respectively, depending on temperature of two-hour high tempering. Rates of deformations of diffusion plasticity $\dot{\varepsilon}^c_{ij} = \frac{d\varepsilon^c_{ij}}{dt}$ were calculated on these data [8] for four variants of temperatures of two-hour holding using sufficiently popular formulation:

$$\dot{\varepsilon}^c_{ij} = \Omega_1(\sigma_i)\Omega_2(T)(\sigma_{ij} - \delta_{ij}\sigma). \tag{4}$$

Here ε^c_{ij} are the components of tensor of creep deformations ($i, j = x, y, z$); σ_i is the intensity of stresses; $(\sigma_{ij} - \delta_{ij}\sigma)$ is the stress deviator [8]; $\Omega_1(\sigma_i)$ is the stress function; $\Omega_2(T)$ is the temperature function. At uniaxial tension in x-direction $\sigma_i = |\sigma_{xx}|$; $\sigma = \sigma_{xx}/3$.

Differential equation concerning the rate of stress relaxation at given constant temperature T will be obtained at isothermal holding under

Table 1. Estimation of relative area of section of structural element occupied by pores depending on tempering parameters

T, °C	σ_{test}, MPa	S
700	275	>0.56
650	325	>0.48
600	375	>0.40
550	625	>0

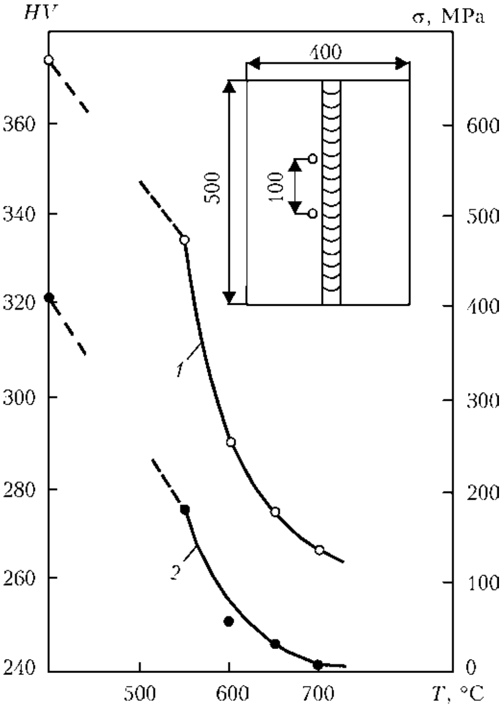

Figure 3. Effect of temperature of two-hour high tempering after welding on value of residual stresses (*1*) and hardness (*2*) in weld zone (on insert is a sample of joint with weld)

condition that $\Omega_1(\sigma_i) = \sigma_i^n$ (n = 4–5) and $\dot{\varepsilon}_{xx}^c = \dfrac{1}{E}\dfrac{d\sigma_{xx}}{dt}$, where E is the elasticity modulus:

$$\frac{d\sigma_{xx}}{\sigma_i^{n+1}} = \frac{2}{3}E\Omega_2(T)dt;\quad \sigma_{xx} > 0. \tag{5}$$

Solving of (5) under condition that σ_{xx} are set at $t = 0$ and $t = 2$ h allows obtaining the values of function $\Omega_2(T)$, indicated in Table 2:

$$\Omega_2(T) = \frac{3}{2E(T)nt}\left[\frac{1}{\sigma_{xx}^n(t)} - \frac{1}{\sigma_{xx}^n(0)}\right], \tag{6}$$

$$\dot{\varepsilon}_{xx}^c(\sigma_{xx}) = \frac{2}{3}\sigma_{xx}^{n+1}(t)\Omega_2(T),\ 1/\text{h}. \tag{7}$$

If Rice–Tracy law of pore growth is used [5]

$$\frac{dl}{dt} = lK_1\dot{\varepsilon}_{xx}^c \exp\left(K_2\frac{\sigma_m}{\sigma_i}\right), \tag{8}$$

where l is the relative length of linear dimension of structural element occupied by pores; K_1 = 0.28; K_2 = 1.5, then considering (7) the following will be obtained at constant temperature:

$$\frac{dl}{l} = K_1\Omega_2(T)\left[\exp\left(K_2\frac{\sigma_m}{\sigma_i}\right)\right]\frac{2}{3}\sigma_{xx}^{n+1}(t)dt, \tag{9}$$

from which

$$\ln\frac{l^{(k+1)}}{l^{(k)}} = K_1\Omega_2(T)\frac{2}{3}\int\limits_{t_k}^{t_{k+1}}\sigma_{xx}^{n+1}(t')\exp\left(K_2\frac{\sigma_m}{\sigma_i}\right)dt', \tag{10}$$

where $l^{(k)}$, $l^{(k+1)}$ are the dimensions corresponding to points of time t_k and t_{k+1}.

At uniaxial tension σ_m/σ_i = 0.3 and, respectively,

$$l^{(k+1)} = l^{(k)}\exp\left[K_1\Omega_2(T)\frac{2}{3}e^{0.45}\int\limits_{t_k}^{t_{k+1}}\sigma_{xx}^{n+1}(t')dt'\right] \tag{11}$$

after integration in (11) will obtain

$$l^{(k+1)} = l^{(k)}\exp\left[K_1\Omega_2(T)\frac{2}{3}e^{0.45}(\bar{\sigma}_{xx}^{n+1})\Delta t_{k+1}\right], \tag{12}$$

where $\bar{\sigma}_{xx}^{n+1}$ is the average σ_{xx}^{n+1} value in $\Delta t_{k+1} = t_{k+1} - t_k$ interval.

Since the kinetics of stress change $\sigma_{xx}(t)$ in Δt_k interval at $t_k = 0$ and $t_{k+1} = 2$ h can arbitrarily change in the limits from $\sigma_{xx}(0) = \sigma_y(T)$ up to $\sigma_{xx}(t) \approx 0$ at $t = 2$ h in the real welded joint (depending on conditions of fastening and geometry of joint) then $\bar{\sigma}_{xx}^{n+1} = [0.5\sigma_y(T)]^{n+1}$ at $n = 5$ can be used for evaluation of growth of initial linear dimensions of porosity l_0, related with heating and stress relaxation.

It can be seen on results of calculation (see Table 2) that relation $l(t)/l_0$ can significantly change depending on temperature under specified conditions.

When it is considered that l_0 value taking into account stage of heating and instantaneous plasticity deformations at stage when $\sigma_{xx}(t) > \sigma_y(T)$ can be significant, and value of loss of net section S is related with $l(t)$ by dependence

$$S = 1 - 2l(t) = 1 - 2l_0\omega \tag{13}$$

Table 2. Temperature function $\Omega_2(T)$ for variants of two-hour high tempering

T, °C	$E\cdot10^{-5}$, MPa	$\sigma_y(T)$, MPa	σ, MPa (t = 0)	σ, MPa (t = 2 h)	$\Omega_2(T)$, $\text{MPa}^{-(n+1)}\cdot\text{h}^{-1}$ (n = 5)	$l(t)/l_0 = w$ (t = 2 h)
700	1.60	120	120	12	$3.77\cdot10^{-12}$	1.10847
650	1.65	250	250	35	$1.73\cdot10^{-14}$	1.03939
600	1.70	300	300	60	$1.13\cdot10^{-15}$	1.00756
550	1.75	330	330	180	$0.43\cdot10^{-17}$	1.00005

(x values are given in Table 2), then necessary data (see Table 1) on l_0 are determined from condition $l_0 = \frac{1 - S}{2\omega}$ (13), from which at

$$T = 700\ ^\circ\mathrm{C},\ l_0 \approx 0.44/2.29 = 0.198;$$
$$T = 650\ ^\circ\mathrm{C},\ l_0 \approx 0.52/2.10 = 0.25;$$
$$T = 600\ ^\circ\mathrm{C},\ l_0 \approx 0.6/2.09 = 0.298;$$
$$T = 550\ ^\circ\mathrm{C},\ l_0 \approx 1.0/2.0001 = 0.5.$$

Such tendency of l_0 dependence on temperature of two-hour high tempering is sufficiently logic since provides theoretic confirmation of existing anxieties relatively to effect of mode of reheating for welded structures from steel of 10GN2MFA type [2].

Therefore, performed calculations allow stating that the welded joints from heat-resistant low-alloy steel of 10GN2MFA type have high susceptibility to strain ageing at tempering temperatures above 600 °C. Efficiency of heat treatment that provides relaxation of high residual stresses related with manufacture and, in particular, repair of critical parts from this steel (for example, in power engineering, equipped with corresponding equipment of Russian production) rapidly reduces at tempering temperatures below 600 °C. Hence, corresponding attention should be made to problems of determination of allowable boundaries of respective repairs and development of adequate technological modes of postweld heat treatment. This will allow significantly reducing costs for equipment operation.

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NEWS

System of Monitoring the Technical State of Pipelines Based on Software and Hardware Means

Decision on extension of operating life should be taken in a differentiated manner, allowing for the features of operation of each individual section and its technical condition. This condition, as well as transition from traditional standard repair and maintenance of the pipeline to operation based on the technical condition, predetermined the block diagram of the monitoring system suggested by the E.O. Paton Electric Welding Institute together with the Institute of Geography and G.S. Pisarenko Institute for Problems of Strength, which includes the database on the condition of individual pipeline sections and analytical block for taking the respective decisions.

The database is formed on the basis of the data obtained from technical documentation and during inspections, and is designed for storage of all the currently available data on pipelines, including the data on crossings, pipe laying, soil types, electrochemical protection potentials, state of insulating coating, detected defects, use of pipeline fittings, working parameters, topographic maps of pipeline corridors, etc. Database interface enables the user to view various data types, making enquiries, and editing the available data.

The core of the analytical block is the model of assessment of relative risk, allowing for the consequences of a probable accident in each specific pipeline section. This model uses database information and allows establishing an acceptable risk level for the operator under the conditions of limited technical and financial resources.

Distinctive features of the monitoring system are the possibility of evaluation of hazards and risk of accidents in the pipeline taking into account:

- prediction of residual life based on statistical methods of processing of results of examination in test holes;
- determination of stress-strain state of typical pipeline elements by FEA, also in the presence of surface noncrack-like defects;
- assessment of the condition of insulating coating based on application of above-route method;
- assessment of near surface part of the lithosphere in pipeline route regions.

Based on continuous collection, accumulation, processing and analysis of information on the actual condition of the pipeline, the system allows determination of the possibility of further operation of both the individual sections, and the pipeline as a whole, and taking the appropriate preventive and corrective actions in time. As a result, the level of safe operation of the real pipelines is significantly increased due to prompt acquisition of visual reference information and expert evaluations based on the procedure of assessment of the residual life and problem-oriented software.