Analysis and simulation of kinetics of elasto-plastic weld failure in structures at cryogenic temperatures

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Abstract. The article presents the results of solving one of the fundamental problems in the field of increasing strength, service life, survivability, reliability and safety of welded joints in critical structures. A model for simulation of elasto-plastic welds failure in steel structures at cryogenic temperatures was developed. It proposed clarifying calculation and experimental methods for analysis and simulation of failure mechanisms taking into account types of forming defects. In addition, effect of heating and cooling cycles, kinetics of elasto-plastic deformation as well as fields of residual stresses and strains were used to predict the results.

1. Introduction
Technologies of welding parts with inhomogeneous physical and mechanical properties require development of theoretical approaches to their analysis and simulation using the general theory of elastic-plasticity. This will increase strength, service life, survivability, reliability and safety of welded joints of critical structures. In particular, one of the urgent problems is development of algorithms for calculating strength and survivability taking into account multidirectional kinetics of fracture of welded structures at cryogenic temperatures. To solve it, prediction of crack resistance of welds should be done considering initial differently oriented defects such as semi-elliptic cracks. It is also necessary to simulate effects of heating and cooling cycle, kinetics of elastic-plastic deformation under loading, fields of residual stresses and strains, as well as dependences of these parameters on temperature. Inability to obtain accurate analytical solutions on distribution of physical and mechanical properties over all volume of welded joints necessitates experimental studies.

2. Materials and experimental procedure
The studies were carried out on two types of welded plates along the weld (WS) and fusion line (FL). Schemes of the samples are shown in Figure 1. The samples were tested for eccentric tension according to current standards. Width of the welds was 20…100 mm, the temperature range was 77…295 K.

The plates were welded using gas tungsten arc welding with filler wire. The number of discontinuities formed using this method is much less than when using shielded metal arc welding. This is especially important for the operation of structures in high vacuum and low temperature conditions. In addition, the mechanical properties of the weld metal are more stable. In turn, this ensures stable values of the maximum level of stress intensity factor (\( K_c \)) for a material of a given thickness.
Figure 1. Scheme of welded plates with crack-like discontinuities such as lack of fusion: 
a – samples with a symmetrical weld; b – samples with an asymmetric weld.

Due to the large cross-section of the welds, multilayer welding was done. The cross-section of each bead was 15…40 mm² (depending on the welding mode and dimensions of the samples). The number of layers in the welds was up to 100…150. Heat input \( \frac{q}{v} \), determined using the equation \( \frac{q}{v} = J \cdot U \cdot \eta_0 \) (where \( J \) is welding current; \( U \) is arc voltage; \( \eta_0 = 0.75 \)), was in the range of 756…1133 mm.

Repeated thermo-deformation effect of welding cycles on steels such as 18%Cr-8%Ni type caused precipitation of chromium carbides. This process most intensively occurs in the temperature range of 873…1123 K. The reason for this is the fact that the filler wire does not contain titanium which accelerates carbide formation. After 3…4 multiple exposures, the effect of thermal welding cycles on welded metal at cryogenic temperatures decrease below critical level [1]. Therefore, each subsequent weld bead was deposited after cooling the previous one to 373 K.

3. Statement and solution of the problem
A crack begins to propagate when stress intensity factor reaches a certain critical value. The deformation criterion of failure is determined by the following equation [2–3]:

\[
\overline{K}_{ac} = K_{ac}^\alpha,
\]

where \( \overline{K}_{ac} \) is the relative coefficient of intensity of elasto-plastic deformations; \( K_{ac}^\alpha \) is the relative critical coefficient of intensity of deformations; \( \alpha = I, II, III \) is the type of crack (normal, transverse or longitudinal).

According to [2-3], the relationship with the force criterion is governed by the dependence \( \overline{K}_{ac} = K_{ac}^{P_\alpha} \), where \( K_{ac}^{P_\alpha} \) is the stress intensity factor and \( P_\alpha \) is the parameter of deformation fracture criteria. It is obvious that the force fracture criterion for mixed-type cracks is represented by the function \( F(K_{ac}, K_{se}) = 0 \), where \( K_{se} \) is the critical stress intensity factor. The Irwin’s force fracture criterion and the critical value criterion for the invariant J-integral

\[
J = \int_{\Gamma} \frac{1}{2} \sigma_{ij} \varepsilon_{ij} \, dx - T_i \frac{\partial u_i}{\partial x_i} \, ds = J_i,
\]

are equivalent, since the relations of the deformation theory of plasticity are the same as the relations of nonlinear elasticity (\( T_i \) are the stresses applied to the crack faces; \( u_i \) is the displacements; \( \sigma_{ij} \) and \( \varepsilon_{ij} \) are the components of the stress and strain tensor).

As a result of the studies, a functional change in the average integral values of the yield strength of the welded joints \( \sigma_{ij} \) was determined as dependences on temperature. They are described by the
obtained empirical linear functions. Yield strength of the weld \( \sigma_{TW} = f_1(T) \) is represented by equation (2):

\[
\sigma_{TW} = h_1 + h_2 T.
\]

Yield strength of the fusion line \( \sigma_{TF} = f_2(T) \) is represented by equation (3):

\[
\sigma_{TF} = h_1 + h_2 T,
\]

where \( h_1 = 583 \cdot \text{MPa} \), \( h_2 = -0.8 \cdot \text{MPa/K} \), \( h_3 = 557 \cdot \text{MPa} \), \( h_4 = 0.76 \cdot \text{MPa/K} \).

Based on the experimental results, dependences of the relative critical stress intensity factors \( K_{Cj} = K_c / \sigma_0 = f(T,t) \) as functions of temperature \( T \) and weld thickness \( t \) were obtained. They are determined by equation (4) for the weld, equation (5) for the fusion line.

\[
K_{CW} = (k_1 + k_2 \cdot T) - (k_3 + k_4 T)(t - k_5)^2,
\]

where \( k_1 = 0.086 \cdot \sqrt{m} \), \( k_2 = 4.4 \cdot 10^{-4} \cdot \sqrt{m / K} \), \( k_3 = 18.53 \cdot 4^4 m \), \( k_4 = 0.123 \cdot 4^4 \sqrt{m / K} \), \( k_5 = 0.07 \cdot m \).

\[
K_{CL} = (k_6 + k_7 \cdot T) - (k_8 + k_9 T)(t - k_3)^2,
\]

where \( k_6 = 0.053 \cdot \sqrt{m} \), \( k_7 = 5.1 \cdot 10^{-4} \cdot \sqrt{m / K} \), \( k_8 = -14.1 \cdot 4^4 m \), \( k_9 = 0.22 \cdot 4^4 \sqrt{m / K} \).

Figure 2a shows the results of \( K_{Cj} \) for the welded joint of the 18%Cr-9%Ni steel. Figure 2b gives the limit of fracture function \( f_F = f(K_{CW},T,t) \) for a wide class of welded joints of austenitic stainless steels such as 18%Cr-9%Ni type. Dots located below this fracture surface provide operational parameters for the corresponding structural parts. The coefficients of equations (4) and (5) \( k_i \) for \( i = 1, 2, 3, \ldots, 9 \) depend on the type of welding and the parameters of the mode:

\[
f_F = f(K_{CW},T,t) = K_{CW} - (k_1 + k_2 \cdot T) - (k_3 + k_4 T)(t - k_5)^2 = 0
\]
It follows from the analysis of the data presented in Figure 2 that the weld has higher $K_{cj}$ values compared to the fusion line. There is a decrease in the level of $K_{cj} = K_{cj}(t)$ with a decrease in temperature from 295 K to 77 K. In the graph presented, an extreme thickness range can be observed after which a monotonous decrease in $K_{cj}$ occurs. This parameter tends to values that make it possible to form the condition for the maximum reduction in plastic deformations during failure by normal breakaway:

$$K_C \rightarrow K_{IC}.$$  \hfill (7)

Discontinuities in welds (both initial and emerged during operation) can be modeled as surface semi-elliptical cracks in the metal. When calculating the stress-strain state near their contour, it is important to take into account the anisotropy of physical and mechanical properties of the material and kinetics of residual stresses [4–7]. This was done by the finite element method using ANSYS MECHANICAL software [8]. The relative stress factors along the contour of the cracks were determined. Their maximum dimensions are regulated according to criterion (8), if condition (9) is fulfilled based on equations (4), (5) and (6).

$$K_u < K_{uc}.$$  \hfill (8)

Figure 3a shows the function of the intensity of the relative deformations vs. relative distance from the crack contour $\bar{e} = f(r/T)$.

Based on the deformation criteria of failure [2, 3] and taking into account [5–7], the calculation of the relative strain intensity factors for misoriented surface semi-elliptic cracks can be obtained by equation (10):

$$\bar{K} = \frac{(2\pi)^{1/4}}{\bar{e}_u[f(r/L)]^{1/4} \beta^* \sin^2 \beta^*}. \hfill (10)$$

The relative coefficient of strain intensity for the first fracture model $\bar{K} = K^*$ was calculated taking into account the relative elasto-plastic strains $\bar{e}^*_{in} = \bar{e}^*_i$ directed along the axis of the first principal stress. In this case, $\sigma_{in}$ and $\bar{e}_{in}$ are relative nominal stresses and elastic-plastic deformation in the weld; $\beta^*$ is the angle of inclination of the crack plane to the direction of the first principal stress.

![Figure 3](image-url)

**Figure 3.** Distribution of relative strains near the contour of a semi-elliptical crack vs. relative distance (a) and finite element model of the crack (b)
As a result of solving the elasto-plastic problem using the deformation criteria of fracture [2-3], the relative intensity coefficient of deformations was obtained for the crack with the parameters \( a = 0.001 \text{ m}, \ b = 0.0015 \text{ m}, \ b/a = 2/3, \ t = 0.025 \text{ m} \). On the surface, they are significantly larger than the critical coefficient of strain intensity \( K_{\text{c}} = 0.017 \) at \( T = 77 \text{ K} \). The results of this study are consistent with [2–18].

4. Conclusion

The paper presents a refinement methodology for prediction allowable critical dimensions of initial and operational semi-elliptical inclined surface cracks. It is based on the above mentioned factors of nonlinear boundary loading conditions. In addition, fracture toughness dependences of the studied steels were presented as a limit of a function depending on cryogenic temperatures and thickness of welded joints. Basic concepts and a general methodology for the refinement calculation of strength and survivability of welded joints of critical structures were formulated on the basis of the deformation criterion of failure. A model for simulation of these processes was also proposed for determining an equivalent coefficient of strain intensity along a front of cracks during inelastic deformation.

References

[1] Makarov I I, Grudzinsky B V 1975 Effect of thermal diffusion welding cycle on the ductility of welds at cryogenic temperatures Automatic welding 9 38–42 (in Russian)
[2] Makhutov N A 1981 Deformation Criteria of Failure and Strength Analysis (Moscow: Mechanical engineering) (in Russian)
[3] Makhutov N A 2005 Structural strength, Service Life and Technogenic Safety (Novosibirsk, Science) (in Russian)
[4] Makhutov N A, Makarenko I V, Makarenko L V 2017 Calculation and experimental analysis of the stress-strain state for inclined semi-elliptical surface cracks Inorganic Materials 53 1502–05
[5] Makhutov N A, Makarenko I V, Makarenko L V 1999 Kinetics of residual stress fields in inhomogeneous austenitic steels during elastoplastic deformation Factory laboratory 65 40–4 (in Russian)
[6] Makhutov N A, Makarenko I V, Makarenko L V 2004 Investigation of spatial mechanical heterogeneity of welded joints of austenitic stainless steels Factory laboratory 70 39–49 (in Russian)
[7] Makhutov N A, Makarenko I V, Makarenko L 2004 Effect of anisotropy of physical and mechanical properties on kinetics of cracks in austenitic steels Strength issues 1 113–9 (in Russian)
[8] 2010 ANSYS. Structural Analysis Guide (Canonsburg: SAS IP, Inc)
[9] Lach R, Grillmann W 2017 Mixed mode fracture mechanics behaviour of PMMA Macromol Symp 373 1–6
[10] Wei Z, Deng X, Sutton M A, et al. 2011 Modeling of mixed-mode crack growth in ductile thin sheets under combined in-plane and out-of-plane loading Eng. Fract. Mech. 78 3082–101
[11] Chen X, Deng X, Sutton MA, et al. 2014 An inverse analysis of cohesive zone model parameter values for ductile crack growth simulations Int. J. Mech. Sci. 79 206–15
[12] Wang Y J, Ru C Q 2016 Determination of two key parameters of a cohesive zone model for pipeline steels based on uniaxial stress-strain curve Eng. Fract. Mech. 163 55–65
[13] Zhao G H, Zhao L, Zhang Y X, et al. 2018 Finite element analysis of dynamic fracture behaviour of drill pipe under various impact loads Mechanika 24 404–11
[14] Li W, Siegmund T 2002 An analysis of crack growth in thin-sheet metal via a cohesive zone model Eng. Fract. Mech. 69 2073–93
[15] Wang Y J, Ru C Q 2016 Determination of two key parameters of a cohesive zone model for pipeline steels based on uniaxial stress-strain curve Eng. Fract. Mech. 163 55–65
[16] Daimon R, Okada H 2014 Mixed-mode stress intensity factor evaluation by interaction integral method for quadratic tetrahedral finite element with correction terms Eng. Fract. Mech. 115 22–42