

ECF22 - Loading and Environmental effects on Structural Integrity

Experimental and numerical investigations of the critical values of J -integral for the steel of steam pipelines

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Abstract

Steel grade 14MoV6-3 is a low-carbon microalloyed steel with addition of chromium and molybdenum. This grade is designed mainly for power industry applications, withstanding operating at elevated temperatures. In this paper, mechanical properties of steel grade 14MoV6-3 and methodology of calculation of critical values of the J -integral are presented. The level of damage is determined by analyzing the virgin material of the same grade. The focus of presented investigation is on the experimental J -integral determination, where critical values of the J -integral (J_{IC}) are compared with the values obtained by using the finite element methods (FEM). FEM model was defined on the basis of experimental conditions and obtained numerical values should confirm our experimental results.

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Keywords: steel for elevated temperature application; mechanical properties; J -integral; FEM; crack.

1. Introduction

Steam pipelines belong to the highly reliable structures, which operate in complex conditions exposed to the effects of creep and low-cycle thermal fatigue at elevated temperature. For this reason, the steam pipeline, i.e. steam pipeline material, together with its welded joints, is subject to damage that accumulates during exploitation and which can lead to fracture. The basic property of steel for the steam pipelines is creep and fracture resistance during the prescribed time. [1]

Steel grade 14MoV6-3 is a low-carbon microalloyed steel with addition of chromium and molybdenum. This grade is designed mainly for power industry applications, withstanding operating at elevated temperatures. Crack resistance

can be evaluated by different fracture mechanics parameters. Three of them are in general use: stress intensity factor K_I , crack opening displacement (COD) and J -integral. It is to notice that their critical values: plane strain fracture toughness K_{Ic} , critical COD and J_{Ic} , a measure of fracture toughness, can be used as material properties of homogeneous material. The standards for their determination by testing are well defined, applying quasi-static loading. [2]

In this paper, mechanical properties of steel grade 14MoV6-3 and methodology of calculation of critical values of the J -integral are presented. The main idea of the present work is to determined experimental J -integral, where critical values of the J -integral are compared with the values obtained by using the finite element methods. FEM model was defined on the basis of experimental conditions in programe Ansys, and we confirm our experimental results.

2. Material

The study was carried out on the 14MoV6-3 ferritic-pearlitic steel, a structural alloy designed for the use od power generation applications at elevated temperatures. Chemical composition of the steel was determined in HBIS GROUP Serbia Iron & Steel d.o.o. Belgrade, by applying the OES method according to the standard SRPSC.A1.011:2004 and using the ARL 4460 device. The chemical composition and mechanical properties are shown in Tabs 1 and 2, respectively.

Table 1. Chemical composition of the tested material

| C | Si | Mn | P | S | Cu | Al | Cr | Mo | Ni |
|--------|--------|--------|--------|--------|-------|--------|--------|--------|-------|
| 0.1216 | 0.3745 | 0.6478 | 0.0055 | 0.0117 | 0.076 | 0.004 | 1.042 | 0.2429 | 0.280 |
| V | Ti | Nb | Co | W | B | Sn | N | Pb | |
| 0.1616 | 0.002 | 0.003 | 0.010 | 0.0151 | 0.000 | 0.0048 | 0.0057 | 0.004 | |

Table 2: Mechanical properties of tested material

| Yield stress $R_{p0.2}$, MPa | Tensile strength R_m , MPa | Elongation A, % | Total impact energy, Eu, J |
|----------------------------------|---------------------------------|--------------------|-------------------------------|
| 320 | 460 | 27.19 | 99.12 |

3. Calculation of J -Integral

The investigation of fracture mechanics parameters, in this case J_{Ic} , was conducted on a 14MoV6-3 steel specimen in the presence of a crack-type defect, as the most dangerous of all the defects in the structural materials. Fracture toughness testing were performed using three-points bend, 17.6 mm thick specimens (SENB), figure 1, to according the standard ASTM E1820 [b]. The distance between the specimen supports was 128 mm.

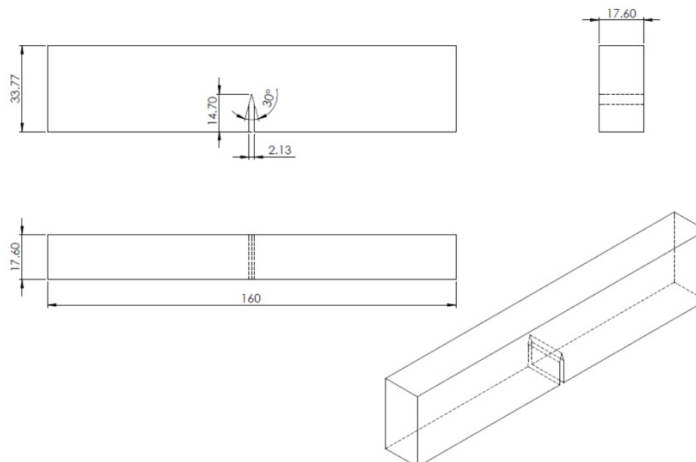


Figure 1. Dimensions of the SENB specimen for fracture mechanics testing

Table 3. Geometric measures of the specimen for J-integral determination

| Material | W (mm) | B (mm) | S (mm) | a ₀ (mm) | a _f (mm) |
|----------|-----------|-----------|-----------|------------------------|------------------------|
| 14MoV6-3 | 33.77 | 17.60 | 128 | 16.83 | 21.52 |

Table 3 provides data for: W - specimen height; B - specimen width; S - spacing between supporting rolls; a₀ - the initial length of the notch obtained by preliminary fatigue of the specimen; a_f - the finite length of the notch measured after the final test. Three-point bend (SENB) specimens were tested at the temperature of 150°C. Fracture toughness, K_{Ic}, a measure of fracture toughness, J_{Ic}, is determined based on J-integral critical value, by testing according to ASTM E899-06 standard [3]:

$$K_{Ic} = \sqrt{\frac{J_{Ic} \cdot E}{1 - \nu^2}} \tag{1}$$

where: E – elasticity modulus, and ν – Poisson’s ratio.

For the determination of the J-integral a single specimen testing method by successive partial unloading was applied. By data pairs applied force, F, crack opening displacement, δ, the points of basic relationship curve were obtained, Figure 2a. The procedure for the determination of critical value, as measure of the fracture toughness, J_{Ic}, requires the design of resistance curve (J-R curve), shown in Figure 2b, in which crack increase is determined based on compliance change.

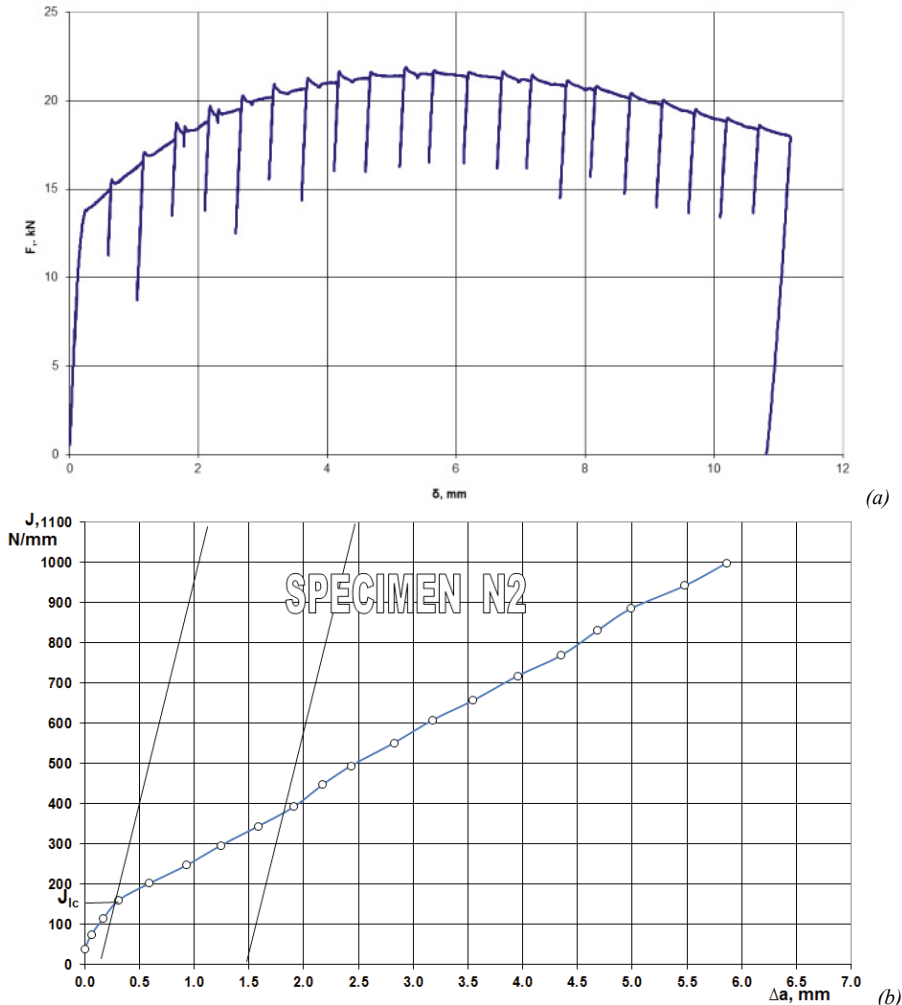


Figure 2. Diagrams F – δ (a) and J – Δa (b) for the specimen N2

In a single specimen test, the specimen is unloaded in intervals to about 30 % of the actually attained level of force chosen by experience with the type of material. Based on the change of line slope of the compliance, C , with crack extension, the crack increase, Δa , between two successive unloadings, corresponding to the attained value of force, is determined as [4]:

$$\Delta a_i = \Delta a_{i-1} + \left(\frac{b_{i-1}}{\eta_{i-1}} \right) \cdot \left(\frac{C_i - C_{i-1}}{C_{i-1}} \right)$$

The next steps are the determination of critical value, J_{Ic} , and use of this value in Eq. (1) for the calculation of the fracture toughness, K_{Ic} , according the single specimen compliance method. The values in Tab. 4, critical J -integral, J_{Ic} , and the values of critical stress intensity factor, K_{Ic} , were obtained from the diagram J - Δa by the described regression analysis procedure. For the modulus of elasticity a value of 190 GPa was taken, while the Poisson's coefficient for this grade of steel was 0.3.

Table 4. Results of testing the critical J-integral, J_{Ic} , and the critical stress intensity factor, K_{Ic}

| Designation | Testing Temperature, °C | Critical J-integral J_{Ic} , N/mm | Critical stress intensity factor, K_{Ic} , MPa m ^{1/2} |
|----------------|-------------------------|-------------------------------------|---|
| N ₂ | 150 | 158 | 181 |

4. Numerical assessment of specimen j-r curve

The investigation was limited to SENB specimen analysis subjected to mode I type of loading for 14Mov6-3 steel material. The variation of specimen J-R curve is dependent on the standard fracture specimen geometry. Therefore, the geometry of SENB specimen used in the present study is kept same as used in the experiments. The mesh was constructed with four-noded quadrilateral elements (2-D 4-Node Structural Solid) available in ANSYS 19.1, figure 39. The size of the element is increased in the region away from the crack tip.

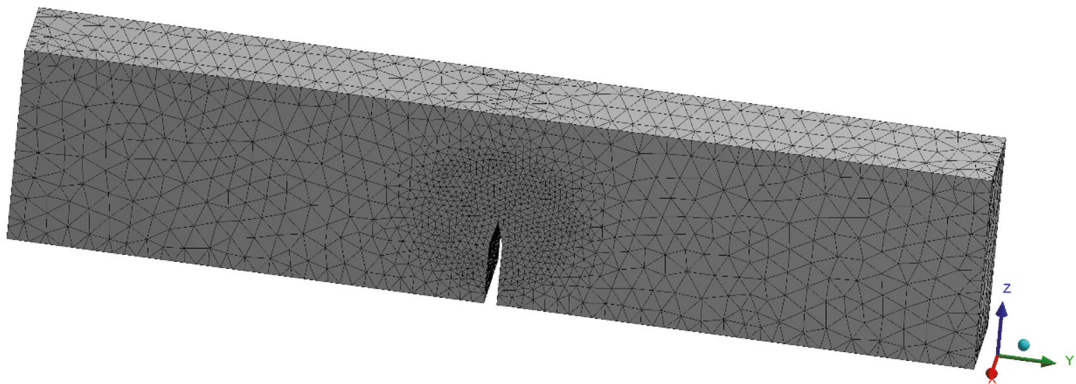


Figure 3. Typical FEM mesh used for SENB damage model

For a 2-D problem, the domain integral representation of the J -integral is given by:

$$J = \int_A \left[\sigma_{ij} \frac{\partial u_j}{\partial x_1} - W \delta_{1i} \right] \frac{\partial q}{\partial x_i} dA + \int_A \alpha \sigma_{ii} \frac{\partial \theta}{\partial x_1} q_1 dA - \int_A \sigma_{ij} \frac{\partial \varepsilon_{ij}^0}{\partial x_1} q_1 dA - \int_C t_j u_{j,1} q_1 dS \tag{2}$$

where:

- σ_{ij} = stress tensor
- u_j = displacement vector
- W = strain energy density
- δ_{ij} = Kronecker delta

- x_i = local coordinate axis
- q = crack-extension vector
- α = coefficient of thermal expansion
- ε_{ij}^0 = initial strain tensor
- t_j = crack face traction
- A = integration domain
- C = crack faces upon which tractions act

The direction of q is the x axis of the local coordinate system ahead of the crack tip. The q vector is chosen as zero at nodes along the contour Γ , and is a unit vector for all nodes inside Γ except the midside nodes, if there are any, that are directly connected to Γ . The program refers to these nodes with a unit q vector as *virtual crack-extension nodes* [5]. Virtual crack-extension nodes are one of the most important input data elements required for J -integral evaluation. It is also referred to as the crack-tip node component. For a 2-D crack problem, the crack-tip node component usually contains one node which is also the crack-tip node. The first contour for the area integration of the J -integral is evaluated over the elements associated with the crack-tip node component. The second contour for the area integration of the J -integral is evaluated over the elements adjacent to the first contour of elements. This procedure is repeated for all contours. To ensure correct results, the elements for the contour integration should not reach the outer boundary of the model (with the exception of the crack surface). The program calculates the J -integral at the solution phase of the analysis after a substep has converged, then stores the value to the results file. The **CINT** command initiates the J -integral calculation and also specifies the parameters necessary for the calculation. Perform the J -integral calculation as follows [5]:

- Step 1: Initiate a New J -integral Calculation
- Step 2: Define Crack Information
- Step 3: Specify the Number of Contours
- Step 4: Define a Crack Symmetry Condition
- Step 5: Specify Output Controls

To determine the numerical specimen J-R curve, at the particular displacement, the area under the load displacement curve was taken as a numerical J -integral value and the total element failure was taken as corresponding increase in crack growth. The obtained FEM results of J-R curve assuming plane stress and plane strain conditions are then averaged to compare with experimental specimen J-R curve. The predicted FEM results, as a comparison with experimental results is given in fig 4, providing reasonably agreement of results.

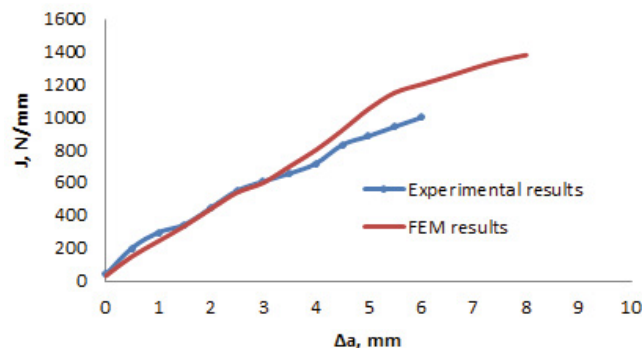


Figure 4. Comparison of experimental specimen J-R curve with FEM results, 2D model

J -integral for the 3-D model was also calculated in Ansys 19.1. In the case of the 3-D model, it is not possible to take into account the plasticity of the material, and therefore the value of the J integral is drastically lower and the match with the experiment is very poor, which is expected because the value of the J -integral depends to a large extent of the plastic component. In the 3D model, the value of the J integral is calculated across-based on the thickness of the specimen and we can see that the highest value is in the middle of the sample, Figure 5. In Fig. 6, dependence of the J integral and-on the crack increase in case of 3D model, Δa , is presented.

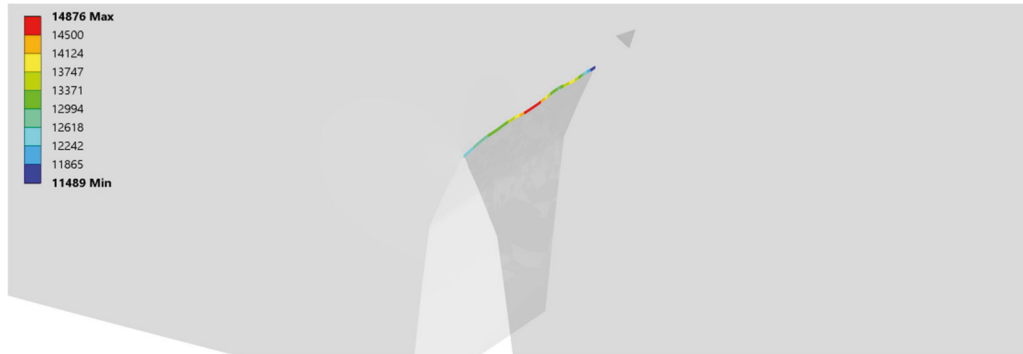


Figure 5. Distribution of the J integral in the case of crack opening displacement, 3D model

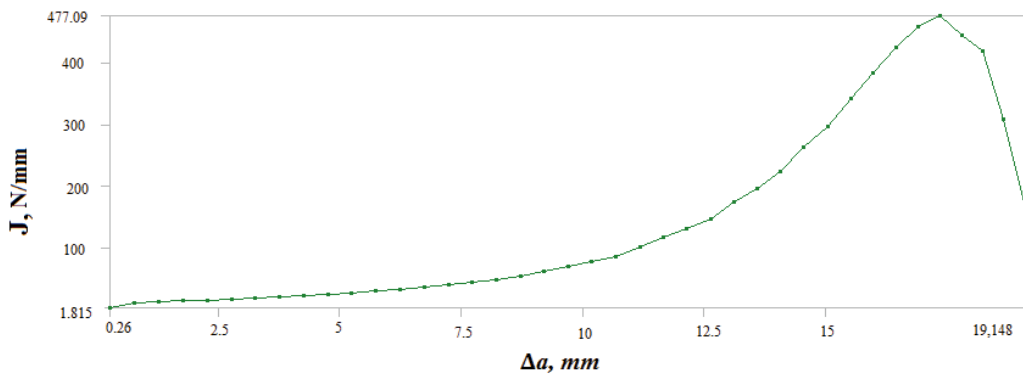


Figure 6. Diagrams $J - \Delta a$ for the 3-D model

5. Conclusions

Applied techniques in this experiment enabled the evaluation of parameters, important for the application of steel using on high temperature. The degree of damage to the steel of steam pipelines is determined by using the local approach to ductile fracture. The critical values of the J -integral are experimentally measured on SENB specimen and calculated by using the FEM. The agreement of records obtained by tensile testing of notched specimens give us the material characteristics, and with precisely describing material properties and experimental conditions, we are ready for modern computational methods, such as FEM. In the case of 2D models, the two results, experimental and numerical, coincide reasonably well with each other, while with the 3D model we cannot simulate plastic, so that the results are not valid.

Acknowledgements

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