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Original scientific paper

Experimental Determination of the Critical Value of the J-Integral that Refers to the HSLA Steel Welded Joint

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Abstract: Fracture mechanics, as a scientific discipline dealing with the study of cracks in welded structures, has defined parameters and introduced new test methods in order to better determine the tendency to crack growth, critical conditions for rapid fracture development, material resistance to rapid crack propagation and better definition of other parameters for assessing the behaviour of the material and the safety of the structure in the presence of cracks. In this paper, the focus is on determination of the parameter of elastic-plastic mechanics of J-integral, more precisely, on examination of the critical value of J-integral (J_{Ic}) of the welded joint of HSLA steel. The position of the tip of the fatigue crack and the properties of the region where fracture propagation occurs are main indicators of influence of the heterogeneity of the NN-70 welded structure and mechanical properties. Resistance to cracking in the welded joint shows that the heterogeneity has a major impact on the resistance to crack initiation and propagation, in elastic as well as in the plastic region.

Keywords: elastic-plastic fracture mechanics parameters; HSLA steel; J-integral; welded joints

1 INTRODUCTION

Using the stress intensity factor, K_I as a parameter of linear elastic fracture mechanics, it is not possible to describe the stress and strain field or using its critical value, K_{Ic} to define the fracture toughness in the crack tip area when a plastic zone of significant size appears [1].

The impact of plastic strain around the crack tip is very important for materials with pronounced plasticity, which include high-strength low-alloy steels used for welded structures.

Therefore, it is necessary to introduce parameters that are not limited by the linear-elastic behaviour of the material, so that the research of the plastic behaviour of cracked materials, which deals with elastic-plastic fracture mechanics, introduced the following two parameters [2, 3]:
- crack tip opening displacement CTOD (δ) and
- J-integral.

The analysis of fatigue parameters has to be possible even after the occurrence of significant plastic strains. Standards that refer to experiments carried out in order to determine the size of plastic strains have to be adequate. There are two significant problems in applying these parameters to the analysis of the behaviour of welded joints in the form of limited ability to detect defects in terms of their size and position as well as heterogeneity of microstructure and mechanical properties [4].

Since it is not certain how the crack will develop during the passage through the different constituents of the welded joint, it is necessary to examine the location of the crack tip as one of the significant problems. Due to the different mechanical properties, the conditions of crack growth will be different [5]. However, the mentioned problems are not difficulties in the experimental determination of fracture toughness in critical regions of the welded joint, but rather in the interpretation of measured values.

The possibility of additional analysis of the complete crack growth, stable and unstable, more precisely elastic-plastic behaviour of the crack material, is provided by the J-integral.

In addition to the disadvantages that δ brings with it, it is quite logical to introduce another elastic-plastic parameter fracture mechanics, J-integral. This was crucial for the progress of this scientific field as well for contributing to the new practical methods for analyzing and reliably predicting processes damage to components and structures. Generally, the J-integral can be applied to cases of large plastic deformations. Analogous to δ, in this case the criterion fracture is reduced to a comparison of the crack growth force and the properties of the material, calculated by J-integral:

$$J \geq J_{Ic} \tag{1}$$

Procedure for determining J_{Ic} using the *J-R* curve (J-Δa dependence) consists of the value of the J-integral for uniform crack increase Δa, which for each load /unload point can be defined based on the total of elastic and plastic components [6, 7]:

$$J_{(i)} = J_{\mathrm{el}(i)} + J_{\mathrm{pl}(i)} \tag{2}$$

Elastic component of J-integral from the Eq. (2):

$$J_{\mathrm{el}(i)} = \frac{K_i^2 \cdot \left(1-\nu^2\right)}{E} \tag{3}$$

where are: E - elasticity modulus, K_i - stress intensity factor and ν - Poisson's ratio.

Plastic component of J-integral [8] from the Eq. (2):

$$J_{\mathrm{pl}(i)} = \left[J_{\mathrm{pl}(i-1)} + \frac{\eta_{i-1}}{Bb_{i-1}} A_{\mathrm{pl}}{}^{i-1,1}\right]\left(1-\frac{\gamma_{i-1}}{b_{i-1}}\left(a_i - a_{i-1}\right)\right) \tag{4}$$

where are: $A_{\mathrm{pl}}{}^{i-1}$ - the increment of plastic zone under *a* load-displacement record from step i – 1 to i, b and η are constants, g - geometry factor defined in standard ASTM E813, B-full thickness of specimen.

These relations of the plastic and elastic components of the J-integral (2-4) are used for larger increments of crack length Δa (when determining the J-R curve, Δa is greater than 1,5 mm). Based on the change of inclination of the loosening curve C, which is directly related to crack growth, the increment Δa that occurs between two successive unloads and corresponds to the reached value of force is being determined [9]:

$$\Delta a_i = \Delta a_{i-1} + \left(\frac{b_{i-1}}{\eta_{i-1}} \right) \cdot \left(\frac{C_i - C_{i-1}}{C_{i-1}} \right) \tag{5}$$

Based on the calculated data (points), J-R curve can be created (J-Δa curve) using a fitted regression line, Fig. 1. Using the regression line, the J_{Ic} was obtained. After determining the J_{Ic}, the K_{Ic} can be determined very easily [8-11]:

$$K_{\mathrm{Ic}} = \sqrt{\frac{J_{\mathrm{Ic}} \cdot E}{1 - \nu^2}} \tag{6}$$

J-integral is, as a parameter of fracture ductility, more sensitive to non-homogeneity and asymmetry of behavior of the welding joint than other parameters, and therefore may have a significant influence on measurement uncertainty. The key question that arises when it comes to fracture ductility is at which level and under which conditions the lowest value of fracture ductility, which lies within very narrow margins, influences the behavior of the whole welding joint as part of the structure, and hence the behavior of the entire welded structure. Only intuitive answers can be given to a question formulated as this one, taking into account the contemporary level of knowledge. Stochastic approach to a problem that refers to the occurrence of fractures in welding joints enables the obtainment of exact instead of intuitive answers. This approach treats crack opening (δ) and fracture ductility K_{Ic} as stochastic variables, not deterministic. Safety level is, when it comes to this particular approach, being expressed numerically, by taking into account the probability that the failure of the structure will occur.

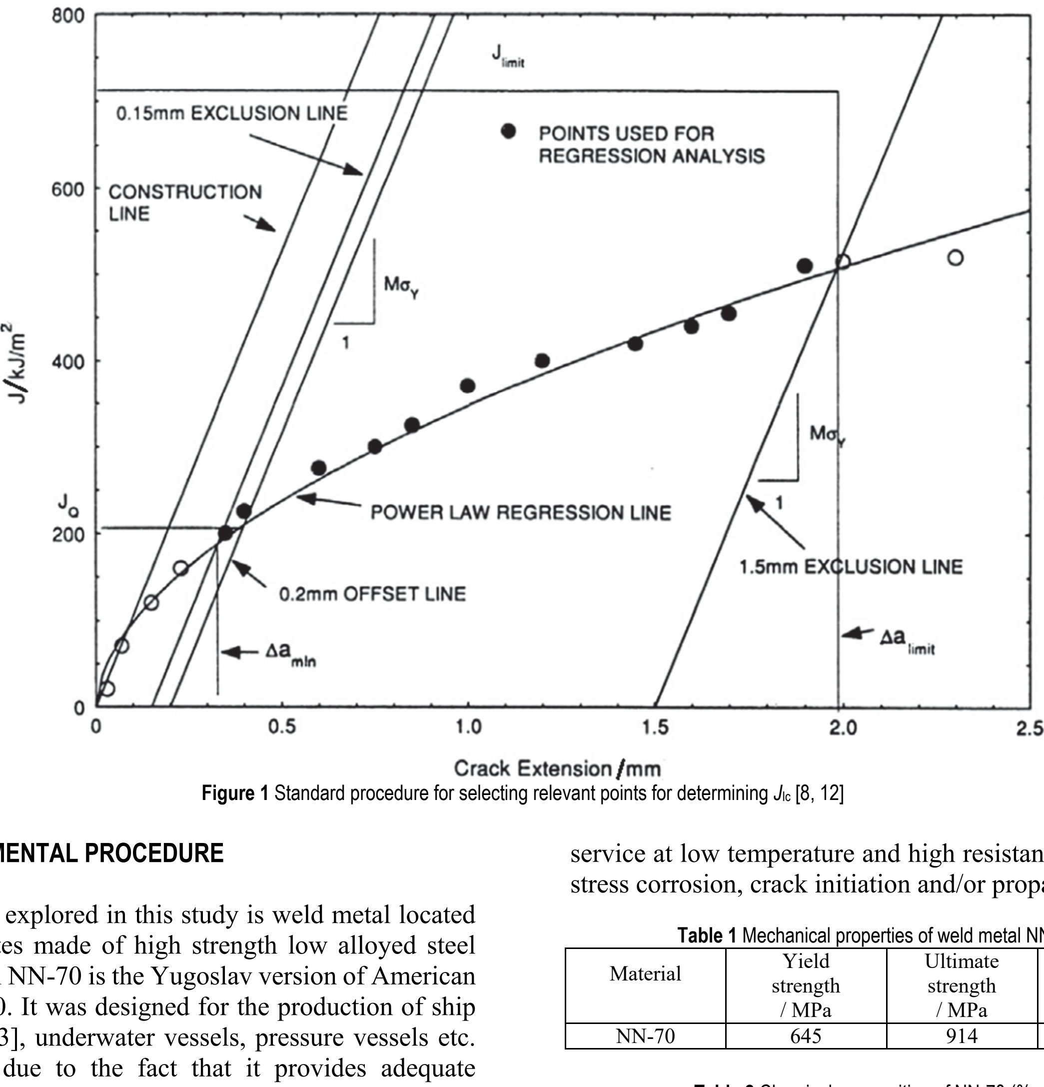


Figure 1 Standard procedure for selecting relevant points for determining J_{Ic} [8, 12]

2 EXPERIMENTAL PROCEDURE

Material explored in this study is weld metal located between plates made of high strength low alloyed steel NN-70. Steel NN-70 is the Yugoslav version of American steel HY-100. It was designed for the production of ship structures [13], underwater vessels, pressure vessels etc. by welding due to the fact that it provides adequate ductility, depending on accumulated strain that ultimately transforms into plastic strain. Mechanical properties of weld metal located between steel plates made of steel NN-70 are presented in Tab. 1, while its chemical composition is displayed in Tab. 2. Chemical composition was carefully chosen with the intention to provide optimal combination of strength, ductility, plasticity, normal service at low temperature and high resistance to fatigue, stress corrosion, crack initiation and/or propagation.

Table 1 Mechanical properties of weld metal NN-70

Material	Yield strength / MPa	Ultimate strength / MPa	Elongation / %
NN-70	645	914	22,4

Table 2 Chemical composition of NN-70 (% wt)

C	Si	Mn	P	S	Cr	Ni
0,106	0,209	0,220	0,005	0,017	1,258	2,361

Experimental evaluation of weldment fracture mechanics parameters, in this example critical J-integral J_{Ic}, has to be carried out at room temperature on 9 test specimens of welded joint NN-70 [14]. Taking into account the location of the fatigue crack tip, the following was examined:

- 3 notched specimens in the base metal (BM);
- 3 notched specimens in the weld metal (WM) and
- 3 notched specimens in the heat affected zone (HAZ).

The position of the tip of the fatigue crack and the properties of the area where fracture propagation occurs are major indicators of the effect of heterogeneity of the structure of the welded joint NN-70 and mechanical properties. Three point bending tests were performed on 9 specimens, in accordance with standard ASTM E399 [15].

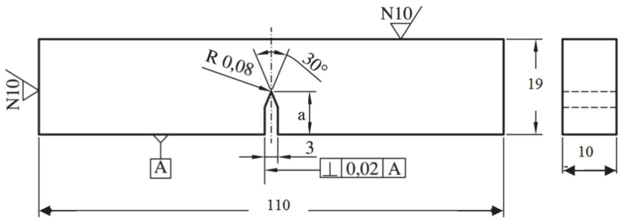
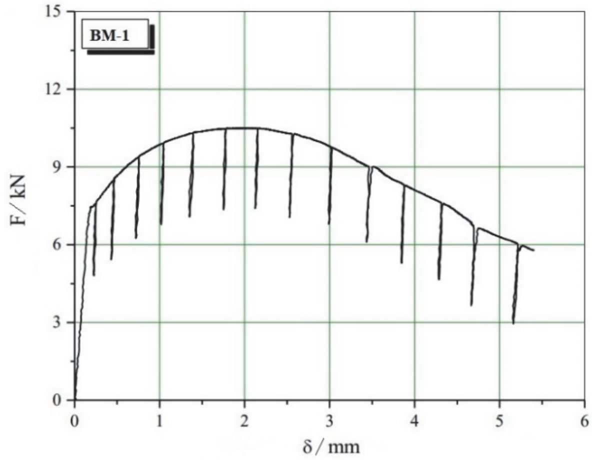


Figure 2 Fracture mechanics test specimen (SEB) [15]

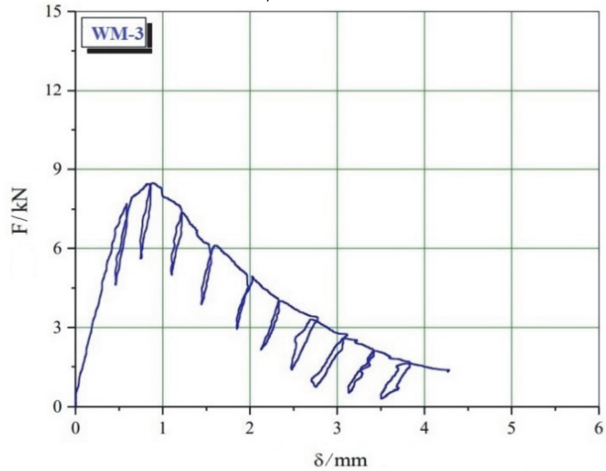
This test, at room temperature, is performed with the electromechanical testing machine SCHENCK TREBEL RM 100, Fig. 3. The crack tip opening is obtained by special extensometer, with a measuring accuracy of ±0,001 mm [3, 16]. Also, this test is performed using the ASTM E1820 standard [17] for sampled notched specimens in the base metal and heat affected zone and BS 7448-Part 2 standard [18] for sampled notched specimens in weld metal. The ASTM E1820 standard is used for the entire calculation.

Figure 3 Electromechanical testing machine SCHENCK TREBEL RM100

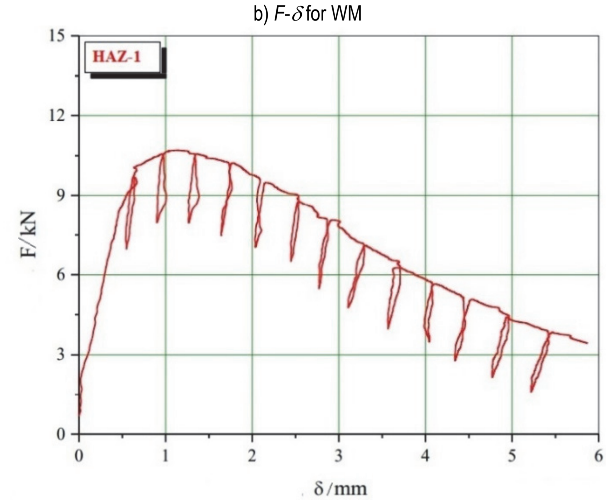
A single specimen test method characterized by successive partial unloading is used for determination of fracture mechanics parameters. Points that define the base dependency curve are obtained from the following data pair: applied force (F) - crack tip opening (δ), as can be seen in Fig. 4. The procedure for determination of critical value of J_{Ic} which refers to the measure of fracture toughness, requires the creation of the resistance curve (J-R curve), shown in Fig. 5, where the crack increase is determined on the basis of change of inclination [9, 14].



a) F-δ for BM



b) F-δ for WM

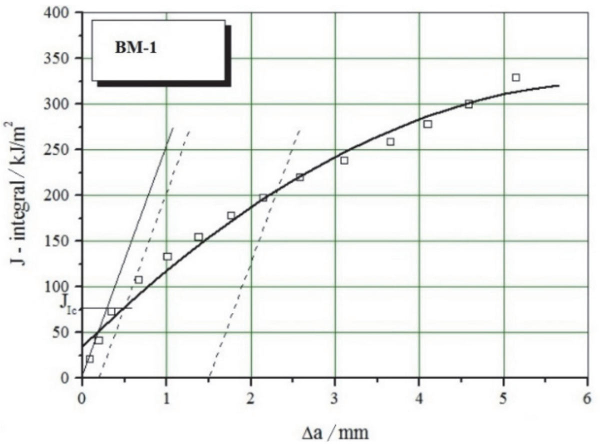


c) F-δ for HAZ

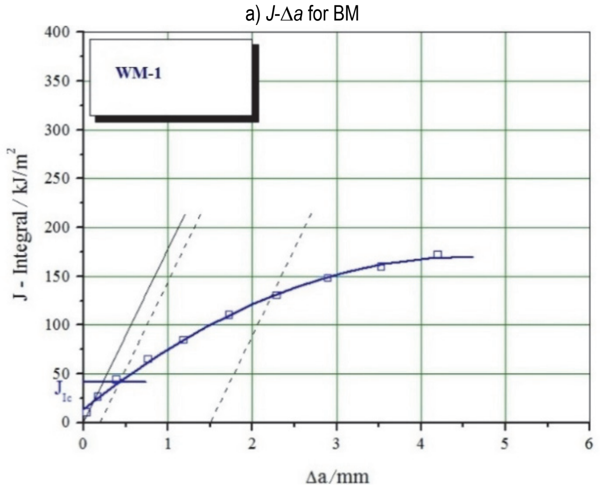
Figure 4 Examples of F-δ diagrams of notched specimens in BM (base metal), WM (weld metal) and HAZ (heat affected zone)

From the diagrams shown above (Fig. 5), created through the application of regression analysis which is described in the introduction of this paper, critical values of J_{Ic} were obtained.

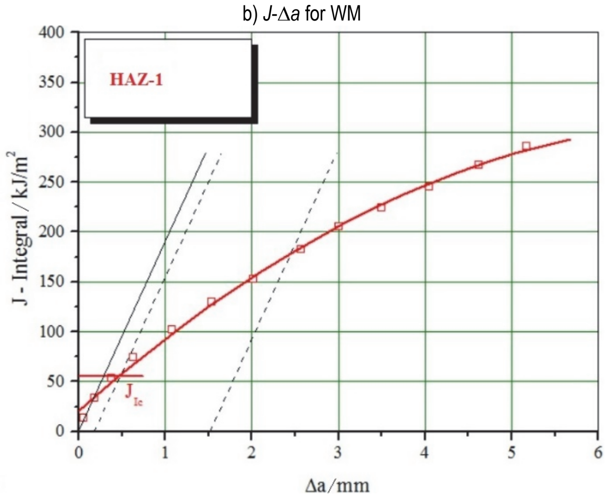
After the obtainment of values of critical J_{Ic} integral, values of critical stress intensity factor or fracture toughness at plain strain K_{Ic} can be determined in accordance with Eq. (6).



a) *J*-Δ*a* for BM



b) *J*-Δ*a* for WM



c) *J*-Δ*a* for HAZ

Figure 5 Examples of *J*-Δ*a* diagrams of notched specimens in BM (base metal), WM (weld metal) and HAZ (heat affected zone)

Table 3 Values of the fracture mechanics parameters J_{Ic} and K_{Ic}

Specimen	Critical J-integral, J_{Ic} / kJ/m^2	Critical stress intensity factor, K_{Ic} / MPa.m$^{1/2}$
BM-1	77,4	133,6
BM-2	82,1	137,6
BM-3	81,4	137,1
WM-1	41,7	96,6
WM-2	44,9	100,2
WM-3	43,8	99,0
HAZ-1	55,4	113,1
HAZ-2	50,6	108,1
HAZ-3	58,5	116,2

Results of critical J-integral, J_{Ic}, and critical stress intensity factor, K_{Ic} (the fracture mechanics parameters) were obtained through tests and are shown in Tab. 3.

3 CONSLUSION

On the basis of tests performed on specimens extracted from base metal, weld metal and heat affected zone of welded joint of HSLA steel NN-70, welded by manual metal arc welding, it can be seen that specimens taken from base metal have the highest J_{Ic} values. Mean value of J_{Ic} for base metal is 80,3 kJ/m^2, for heat affected zone 54,8 kJ/m^2 and for weld metal 43,5 kJ/m^2. Highest mean value of K_{Ic} is observed in the base metal specimens - 136,1 MPa.m$^{1/2}$, in relation to heat affected zone specimens - 112,5 MPa.m$^{1/2}$ and weld metal specimens - 98,6 MPa.m$^{1/2}$.

Therefore, crack resistance in the welded joint of steel NN-70 to crack growth is highest in the base metal, which could be expected due to the heterogeneity of the structure and test conditions when it comes to weld metal and heat affected zone. More precisely, crack resistance in the welded joint created between plates made of steel NN-70 shows that the non-homogeneity of the welded joint has a huge influence on the resistance to crack growth, in elastic as well as in the plastic region.

Consequently, the main goal of such tests is a highly reliable product. This feature is also important in agricultural technology and tests like these can be very useful. Agricultural machines and vehicles have been used for many years in difficult terrain conditions and mostly steel is still the basic construction material [19, 20].

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