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ASSESMENT OF INTEGRITY OF THE WELDED PIPES

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Abstract**—**The subject of work includes an analysis of integrity of the welded pipes made of steel API J55 of the high frequency contact welding (HF). Experimental testings of the mechanical properties of the based materials are performed on tubes removed from exploitation after 70 000 hours of work. The impact of damage type of the surface of crack on the integrity of pipe is tested by hydrostatically pressure of tube with an axial surface crack in the base material. The behaviour of fracture was tested using a modified compact testing tubes on tightening (CT), with an initial crack in the base material, welded joint and heat affected zone (HAZ). The critical value of the stress intensity factor C_{Ic} is determined on the basis of the critical value of J integral of the J_{Ic}.

In addition to the experimental research, based on the obtained values for C_r and S_r using the fracture analysis diagram (FAD) is carried out an assessment of the integrity of welded pipes with an axial surface crack on the outer surface.

Keywords**—**axial surface crack, high frequency contact welding, fracture analysis diagram (FAD).

I. INTRODUCTION

Reliability of the pipeline system is important not only due to of exploitation, but also due to the preservation of the living environment. For these reasons, the researches were carried out related to the evaluation of fracture resistence of the welded tubes and analyzed the integrity of the pipeline using the fracture analysis diagram (FAD). Pipelines used in exploitation may be made of a seam or a seamless pipes [1,2]. Specification of the pipeline, prescribed by API 5CT standard, mainly involves the proporties of the pipeline, such as the dimensions of pipes and fittings, pipeline resistence to internal and external pressure, as well as mechanical characteristics and chemical composition.

Some of the developed standards and recommendations that have been considered are dealt with the impact of extensive cracking on the integrity of pipes that are loaded on the internal pressure and bending [3]. However, the welded tubes may have an axial surface cracks on the internal and/or external surface, and subjected to various stresses, including the external and internal pressure, as well as the axial load (e.g., due to the weight of construction)

Methods for the assessment of damage to the pipes under pressure are important due to the maintenance of security and stability of pipelines in plants [4-9]. An essential part of the pipe's integrity is how to efficiently and accurately estimate tha maximum allowable pressure and determine the parameters of mechanical fracture, such as the stress intensity factor (K_{Ic}) and J-integral of damaged pipes. Unlike the internal circular and axial semi-elliptical surface cracks [4-15,17], a very limited number of studies is in the area deals with determination of K_{Ic} and J-integral for pipes with external axial semi-elliptical surface cracks [13]. So far, there have been no detailed 3D finite element analysis (FEA) for a wide range of surface cracks on the external part of the pipe. The performed analysis were mainly related to the use of 3D elastoplastic finite element analysis to determine the J integral for circular [16] and axial surface cracks on the inner surface of the tube [17].

In some diagrams of fracture analysis (FAD), the limit load of cracked pipe is used to define Lr parameter that represents the value of the plastic collapse [18]. Moreover, when the structural assessment integrity is done using the R6 method [19], the reference stress is defined by the limit load. Here, the limit load is usually estimated on damage in high strength steels [20,21]. A large number of existing solutions to pressure limit of the damaged pipes is developed analytically and empirically, on the basis of the data obtained by testing [20]. These solutions were usually too conservative, but the degree of conservatism cannot be quantified. Recently, based on the finite element analysis were developed the terms to determine the pressure limit of cylinders with an external axial semi-elliptical surface cracks [21]. However, the proposed terms relate to the very limited number of sizes of damage as shown in [22], and hence it is preferred that extension of testing to be aimed to find new solutions.

In this paper, is performed an analysis of the integrity of welded pipes with axial surface crack made of API-J55 steel. The analyzed pipe was in exploitaion and was removed during the process of reparation, after a period of operation of about 70 000 hours (8 years). This period is much shorter in comparison with the projected operating life, that is up to 30 years.

The study of modified CT test tubes, indirectly (through the critical value of J integral of the J_{Ic}) determine certain critical values of the stress intensity factor K_{Ic}. Based on the critical values of the stress intensity factor K_{Ic} for base material, HAZ and weld metal are calculated the critical crack lengths.

For the assessment of the pipeline's integrity is applied the fracture analysis diagram (FAD). Based on the obtained values for C_r and S_r in the fracture analysis diagram (FAD) is plotted the point, which is located in a safe part of the diagram. Taking into account the conservatism of FAD analysis in all its aspects, it can be concluded that the protective welded pipes are safe not only from brittle fracture, but also from the plastic collapse.

II. THE EXPERIMENTAL PROCEDURE

The presented study in this paper was conducted in order to assess the integrity of the tubes, after a period of about 70 000 working hours (8 years).

Properties of API J55 steel were determined in samples taken from the tubes produced by HF welding. The tested tubes were of Ø139,7 mm diameter and nominal wall thickness of 6,98 mm. The chemical composition of API-J55 steel is given in Table.

Table I: Chemical composition of API J55 steel [mas. %]

C	Si	Mn	P	S	Cr	Ni	Mo	V	Cu	Al
0.2924	0.233	0.963	0.013	0.0216	0.0995	0.0579	0.0123	0.003	0.131	0.025

**Ceq=[C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15]= =[0.2924+0.963/6+(0.0995+0.0123+0.003)/5+(0.0579+0.131)/15]=0.49*

2.1. Mechanical properties

Positions of extraction samples for the determination of mechanical properties of the base material and welded joints of the longitudinally welded pipes are defined by the standard [23].

The shape and dimensions of samples for testing of tensile proporties are defined by the standard [24]. The measurement process is performed by electromechanical equipment for testing of SCHENCK-TREBEL RM 100, in the control of deformation (elongation) with the speed of introduction of the load of 5 mm/min.

The results obtained by testing of tensile proporties of the samples of base material parallel to the direction of rolling, are shown in Table II and the test diagram is presented in Fig. 1.

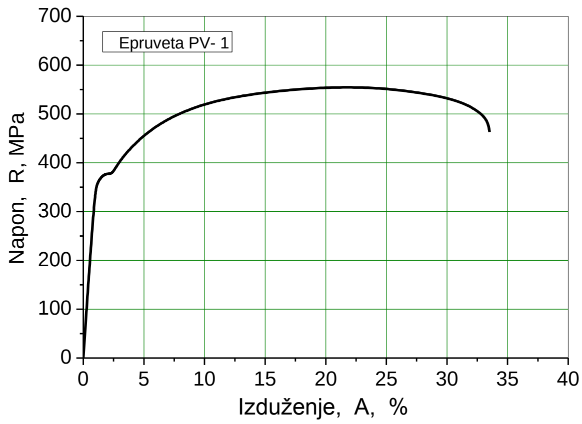

Fig. 1: Diagram of stress – percentage elongation, test tube PV–1, tube from exploitation, 20 °C

Table II: Tensile properties of the base material, parallel to the rolling direction.

Material	Test tube	Temperature	R_e	R_m	A
		[°C]	[MPa]	[MPa]	[%]
Exploitated	PV	20	380	562	33
Standard API 5CT			379-552	> 517	

2.2. Resistance to breakage

The welded pipes under the pressure may be very sensitive to cracks and their stable or unstable increase. Therefore, it is very important to determine reliable criteria for assessment of the remaining useful life of pipes under the pressure with cracks in the base material and the welded joint. For a better understanding of the initiation and increase of cracks in welded pipes, which are subjected to high pressures and chemically aggressive working environment, the control parameters of the behavior of materials around the tip of cracks and resistance to breakage should be expressed quantitatively. Thus, the critical values of the stress intensity factor K_{IC}, the resistance curves of crack increase (J-Δa), are experimentally examined [25].

2.2.1. Testing of the modified (CT) test tubes

Testing of the modified (CT) test tubes, were conducted at room temperature on a machine SCHENCK-TREBEL RM 100. The thickness of the modified (CT) test tubes is d = 6,98 mm (equal to the thickness of the pipe wall) [25]. Indirectly (through the critical values of J integral of the J_{Ic}) are determined critical values of the stress intensity factor K_{Ic}, which are calculated by means of the formula 1 and are given in

Table III:

$$K_{Ic} = \sqrt{\frac{J_{Ic} \cdot E}{1 - v^2}} \quad (1)$$

By using the formula:

$$K_{Ic} = 1{,}12 \cdot \sigma_c \cdot \sqrt{\pi \cdot a_c} \quad (2)$$

And taking into account values of stress, $\sigma = \sigma_c$, (where σ_c is stress at breakage), were calculated approximate values of critical crack length (a_c), for OM, HAZ and WM.

Table III: Values of K_{Ic} – pipe from exploitation

Marks of test tubes	Temperature [°C]	J_{Ic} [kN/m]	K_{Ic} [MPa m$^{1/2}$]	a_c [mm]
BM-NR-E	20	35.8	91.4	14.4
HAZ-NW-E		48.5	106.4	19.6
WM-NW-E		45.7	103.3	18.5

Based on the obtained values of K_{Ic} for base material, HAZ and welded joint, the lowest resistance to to creation and increase of crack has the basic material.

III. Assessment of integrity of the pipe with an axial surface crack

The testings were conducted in a vessel under the pressure, with an axial surface crack in the base material, Fig. 2. The vessel is made of parts of the welded parts from exploitaion. On the outer surface of the tube with an electro-erosion is made an axial surface crack in the base material of dimensions: a=3,5 mm and 2c=200 mm.

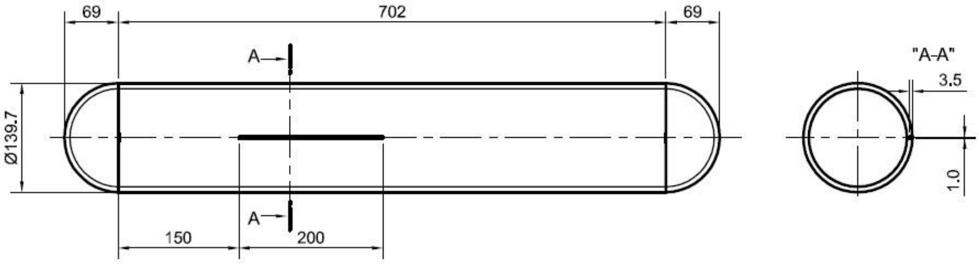

Fig. 2: The vessel with an axial surface crack on the outside

Tube prepared for testing by hydro static pressure is shown in Fig. 3.

Pressure testing was increate successively in steps from 1 MPa to a pressure of 8 MPa, followed by 0,5 MPa to a pressure of 22 MPa, whereby by means of measuring strap LY 11-6/120, of HBM manufacturer, were registered deformations on the measuring points [26].

Diagrams of the strain depending on the pressure testing p are shown in Fig. from 4 to 7.

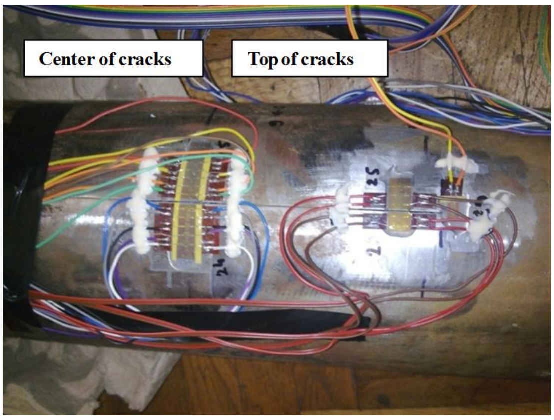

Fig. 3: Appearance of pipes prepared for testing

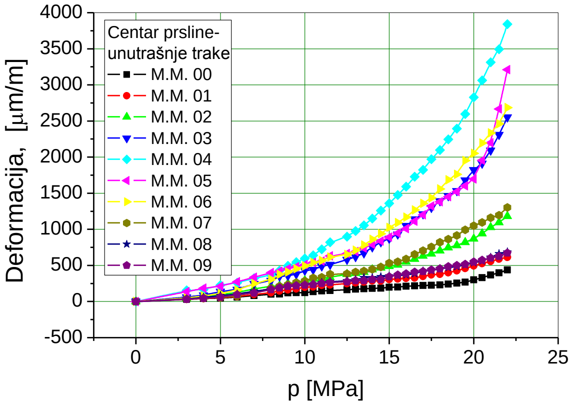

Fig. 4: Dependence of the strain from pressure, inner straps - middle of crack

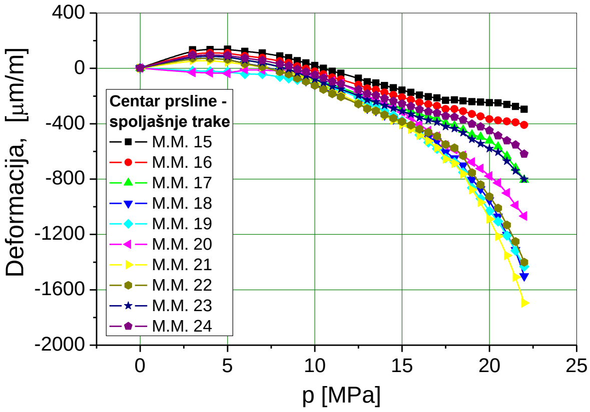

Fig. 5: Dependence of the strain from pressure, inner straps - middle of crack

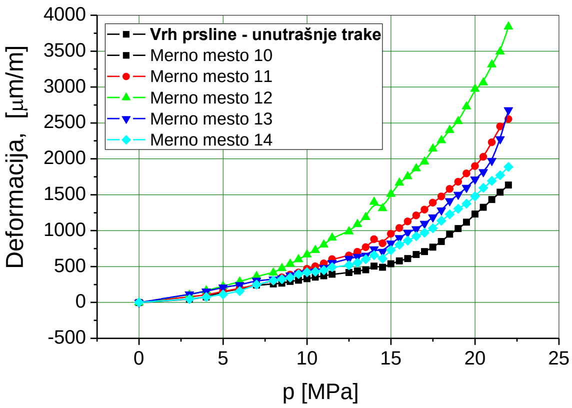

Fig. 6: Dependence of the strain from pressure, inner straps – crack tip

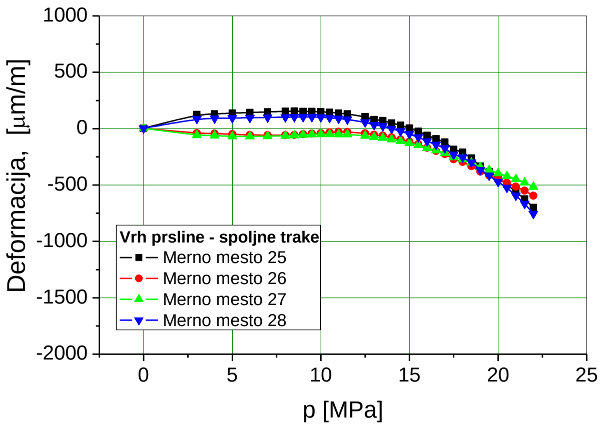

Fig. 7: Dependence of the strain from pressure, outer straps – crack tip

3.1. Fraction analysis diagram - FAD

Structures made of tough material are not subject to brittle fracture, but they can be broken plastically if overloaded. The mechanism of plastic fracture (collapse) is not included in the project CTOD curve, and to its analysis is required a more general approach. Therefore, is introduced the concept of the two criteria fracture in order to describe the mutual influence of brittle fracture and plastic collapse, realized through the fracture analysis diagram (Failure Assessment Diagram - FAD) [27]. The starting point of this diagram is modified strip model for flow through cracks in an infinite plate, which connects the effective stress concentration factor K_{eff} with the remote stress [28]:

$$K_{eff} = \sigma_Y \sqrt{\pi a}\left[\frac{8}{\pi^2}\ln\sec\frac{\pi}{2}\frac{\sigma}{\sigma_c}\right]^{1/2} \tag{3}$$

In a real structure the yield stress σ_Y should be replaced by stresse collapse σ_C, which in addition of the material, depends on the geometry of the structures, including cracks. The next step in the modification of FAD is the expression of the effective stress intensity factor in dimensionless form as K_{eff}/K_I:

$$\frac{K_{eff}}{K_I} = \frac{\sigma_c}{\sigma}\left[\frac{8}{\pi^2}\ln\sec\frac{\pi}{2}\frac{\sigma}{\sigma_c}\right]^{1/2} \tag{4}$$

As a final step, are defined the dimensionless variables, $S_r=\sigma/\sigma_c$ i $K_r=K_I/K_{Ic}$, which represent the abscissa and ordinates of the modified FAD, Fig. 5, and the equation becomes:

$$K_r = S_r\left[\frac{8}{\pi^2}\ln\sec\left(\frac{\pi}{2}S_r\right)\right]^{-1/2} \tag{5}$$

If the material is fully tough, construction is going to be broken by plastic collapse S_r=1, while the fracture of the structure of a fully brittle material K_r=1. In all other cases, there is the interaction between plastic collapse and brittle fracture, and the K_r and S_r are less than 1, and pairs of matching values represent the limit curve, which is presented in Fig. 8. It is assumed that K_{eff} is equal to toughness of the fracture material, K_{Ic}, so C_r, is determined according to the formula:

$$K_r = \frac{K_I}{K_{Ic}}$$

For the calculation of S_r are taken only the primary stresses, for the secondary stresses do not impact to the collapse of the structure.

Using the manual of, K_I-factor, for the geometry from Fig. 2 is given by the following formula:

$$K_I = \sqrt{\frac{\pi a}{Q}}\,\frac{pR_i^2}{R_o^2\ R_i^2}\,2G_0 + 2\frac{a}{R_i}G_1 + 3\left(\frac{a}{R_i}\right)^2 G_2 + 4\left(\frac{a}{R_i}\right)^3 G_3$$

(6)

And a constant Q is calculated based on:

$$Q = 1 + 1,464\left(\frac{a}{c}\right)^{1,65}$$

Where the values of G_j depend on a/c, a/t and t/R_i and are given in literature [13]. Relevant values of G_j, for this study obtained by interpolation or extrapolation are:

$$G_0 = 1,584 \quad G_1 = 0,839 \quad G_2 = 0,600$$

$$G_3 = 0,480$$

In the initial depth a = 3,5 mm and crack length 2c=200 mm is obtained

$Q = 1,0058$ i $K_I = 32,067\ MPa\sqrt{m}$ and

$$K_r = \frac{K_I}{K_{Ic}} = \frac{32,067}{91,4} = 0,35$$

The stress in the cross-section $\sigma_n = 2pR/t$, where the factor 2 is taken due to the weakening of the cross-section with the crack length of 3,5 mm to a thickness of 6,98 mm (50%), and is obtained:

$$S_r = \frac{2\left(\frac{2pR}{t}\right)}{(R_{eH} + R_m)} = \frac{2\left(\frac{2\cdot 22\cdot 69,85}{6,98}\right)}{(380 + 562)} = 0,93$$

Based on the obtained values for C_r and S_r in the fracture analysis diagram (FAD) is plotted the point with coordinates (0,93; 0,35), which is located in a safe part of the diagram, Fig. 8.

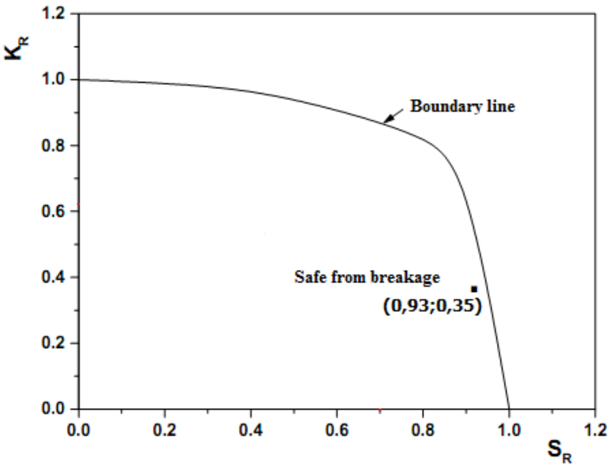

Fig. 8: Fracture analysis diagram (FAD) for tube

With an axial surface crack on the outer surface

In Table IV. Are shown the values of parameters C_r i S_r depending on the change in pressure. The values obtained for C_r and S_r are plotted fracture analysis diagram (FAD), Fig. 9.

Table IV: Values of the parameters of C_r and S_r depending on the pressure change

a [mm]	t [mm]	*p* [MPa]	C_r	S_r
3,5	6,98	22	0,35085	0,93485
3,5	6,98	20	0,31895	0,84987
3,5	6,98	18	0,28706	0,76488
3,5	6,98	16	0,25516	0,67989
3,5	6,98	14	0,22327	0,59491
3,5	6,98	12	0,19137	0,50992
3,5	6,98	10	0,15948	0,42493
3,5	6,98	8	0,12758	0,33995

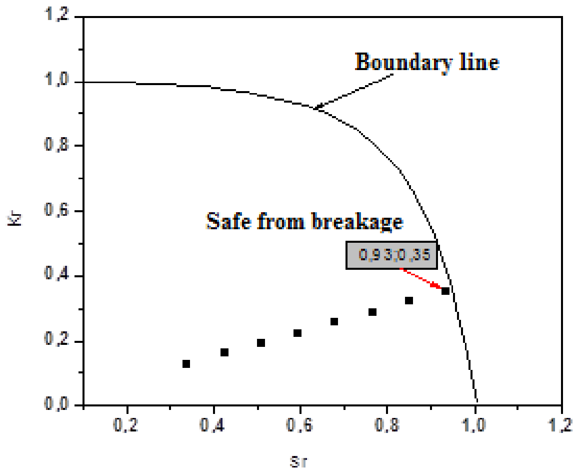

Fig. 9: Fracture analysisn diagram (FAD) for tube With an axial surface crack on the outer surface at various pressures

IV. Conclusion

In this paper, with the application of mechanics fracture is performed an assessment of the welded pipes integrity with an axial surface crack on the outer surface of tubes made of API-J55 steel.

Based on the critical values of the stress intensity factor K_{Ic} for base material, HAZ and weld metal are calculated the critical crack lengths. According to obtained results, the lowest resistence to creation and increase of cracks has the base material.

Taking into account the conservatism of FAD analysis in all its aspects, can be concluded that the welded pipes are safe not only from the brittle fracture, but also from the plastic collapse. It is important to note that fad provides a simple analysis of integrity that can reliably determine whether the welded pipe is safe from breakage, provided that the geometry and the load presented to the conservative way. On the other hand, if the integrity cannot be proved, it does not mean that the welded pipe is useless, but they need additional, more complicated analysis.

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