FATIGUE OF HIGH STRENGTH STEEL WELDMENT IN PRESSURE VESSELS APPLICATION

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Abstract

The application of high strength steels in design of heavy duty welded structures requires the data about the properties in different loading condition. This is of importance for pressurized equipment, but also for other industrial branches (cranes, earth moving machines). The behaviour under variable loading can annul the benefits of high strength, and for that it has to be analyzed. The testing results of high strength steel NIONIKRAL 70 (nominal yield stress 700MPa) and its MMAW welded joints under variable loading are presented and discussed. Fatigue crack growth rate is determined by precracked specimens testing. The difference in crack growth rate properties between parent metal, weld metal and HAZ is less expressed compared to other properties of high strength steel welded joint.

1. Introduction

The requirement for cost reduction in pressure vessel manufacturing can be fulfilled by application of steels of increased strength (450 to 700 MPa yield strength) compared to mild structural steels (235 to 355 MPa). Benefit in strength increase can be expressed in reduced pressure vessel wall thickness, followed by significant reduction in welded joint cross-section, welding consumables and time necessary to produce welded joints.

The choice of steel for a given application should be logically based on cost and on properties. The relevant cost, however, is that of the fabricated product rather than of the unwelded steel. Thus, the choice should fall on the steel that gives the cheapest fabricated product with adequate properties. The design properties which should be considered are the yield stress, creep strength where applicable, fracture toughness and fatigue properties, together with the availability of weld metals with adequate properties.

Design against brittle fracture should normally be the basis of fracture initiation, although in certain highly critical components a propagation criterion may be justifiable to give an extra margin of safety. The chance of brittle fracture failure will almost certainly not depend upon the properties of the parent material but on those of the weld metal and heat-affected zone, since in most cases these regions are less tough than the parent material. It is strongly recommended that general yielding or linear elastic fracture mechanics tests be carried out, as appropriate, on welded joints and that the minimum toughness be specified on the basis of the largest defect which could remain undetected in the structure. The fracture mechanics results enable a relationship between defect size, material thickness and toughness to be established [1,2].

Regions of stress concentration are provided by a change in section, by a welded connection, e.g. where nozzles are introduced into a pressure vessel, or by the overfill of a butt weld. Should a defect of some kind exist at a geometrical stress concentration, its effect will be amplified.

The great majority of service failures involve the initiation of cracking at defects situated in regions of stress concentration. In welded structures defects are almost always involved. It is therefore necessary not only to design against overload but also to avoid the possibility of low stress failure by brittle fracture, fatigue, creep and corrosion.

The welding problems if they result in weld defects, increase the risk of service failure by increasing the local stress concentration. It is important to avoid cracking problems but it would be unrealistic to imagine that, by taking the utmost care during welding, all cracks and defects at welds could be eliminated. However, by maintaining an adequate degree of control by non-destructive testing, it should be possible to ensure that defects exceeding some maximum size will be absent. Special care is required for application of high strength steel in pressurized components exposed to variable loading. Elevated strength does not reflect to fatigue properties and other influencing factors must be considered in order to increase fatigue strength in that case. It is much more important to reduce stress concentration level, especially for welded joints of high strength steel, when exposed to variable loading. The necessary data for fatigue crack growth are not available still, and experimental part of this work is directed to get more data for crack growth behaviour of high strength steel weldments. In general, two aspects are interesting behaviour of smooth specimens in different variable load level, e.g. low and high cycle fatigue and behaviour of notched (or precracked) specimens, e.g. fatigue crack growth [3].

In this paper we will show the influence of the presence of crack on the growth parameters of fatigue crack in the base metal, the weld metal (WM) and the heat-affected-zone (HAZ) of the welded steel joint NIONIKRAL-70.

2. Material

The experiments had been performed with high strength steel NIONIKRAL-70 (NN70) weldments, of HY100 steel class. This steel is mainly used for pressure vessels manufacturing and in shipbuilding, e.g. for submarines. The chemical composition and mechanical properties are shown in Tables 1 and 2, respectively.

Table 1 Chemical composition of tested material

C	Si	Mn	P	S	Cr	Ni	Mo	V	Al
0.1	0.2	0.23	0.009	0.018	1.24	3.1	0.29	0.05	0.08

Table 2 Mechanical properties of tested material

Yield stress $R_{p0,2}$, MPa	Tensile strength R_m, MPa	Elongation A, %	Impact energy, J		
			+20°C	-60°C	-100°C
735	807	19	240	115	85

Samples for investigation had been prepared by manual arc welding (MAW). Two plates of 18 mm thick, had been prepared for asymmetric 2/3 X welded joint by edge machining on one side. The chemical composition and mechanical properties of the filler metal used, Tenacito – 80 electrode, are shown in Tables 3 and 4, respectively. Welding is performed with 2 mm gap, in six passes.

Table 3 Chemical composition of all weld metal, %

Electrode	C	Mn	Si	Cr	Ni	Mo
Tenacito-80	0.06	1.65	0.3	0.55	2.0	0.35

Table 4 Mechanical properties of all weld metal

Electrode	Yield stress $R_{p0,2}$, MPa	Tensile strength R_m, MPa	Elongation A, %	Impact energy, J		
				+20°C	-40°C	-60°C
Tenacito-80	710-770	770-830	18-20	50-80		35-65

3. Results and analysis of experimental results

Welded structures can contain small pre-existing cracks. They will propagate under repeated loads up to critical size, at which fracture occurs. In that case the entire life is spent in the propagation phase, and additional data of the crack growth rate behaviour is necessary for overall fatigue life computation. Since the zone ahead the crack tip, exposed to cyclic plasticity, is small, necessary plane-strain conditions is develop even for small thickness. and the data obtained by thin specimens can be applied quite generally.

Fatigue crack will initiate and propagate from severe stress raisers under variable loading after determined cycle number if the stress-intensity factor range, ΔK_{th}, for fatigue threshold is achieved. The structure can be used before growing crack reaches critical value, based on performed structural integrity analysis. Substantial data for the decision about extended service of cracked component is crack growth rate and its dependence on acting load. Standard ASTM E647 [6] defines testing of pre-cracked specimen for fatigue crack growth rate measurement da/dN, and calculation of stress intensity factor range, ΔK. Two basic requirements in standard ASTM E647 are crack growth rate above 10^{-8} m/cycle to avoid threshold ΔK_{th} regime, and testing with constant amplitude loading.

Fatigue crack growth rate testing is performed with notched and precracked SE(B) specimens (width W = 10 mm, thickenss B = 10 mm, span S = 4W) of base metal, weld metal and heat-affected-zone (HAZ), Fig. 1 [4,5].

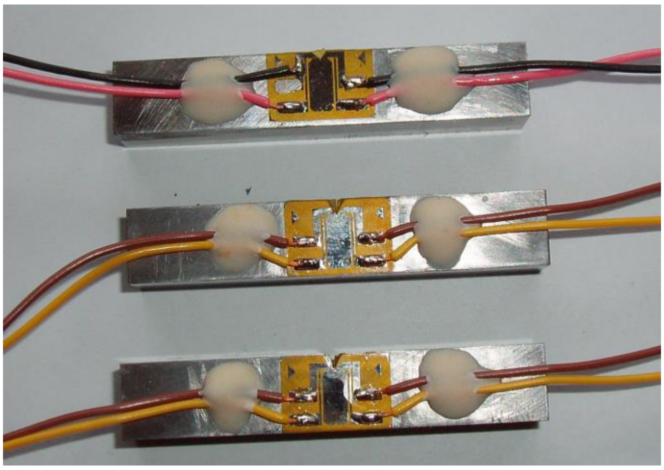
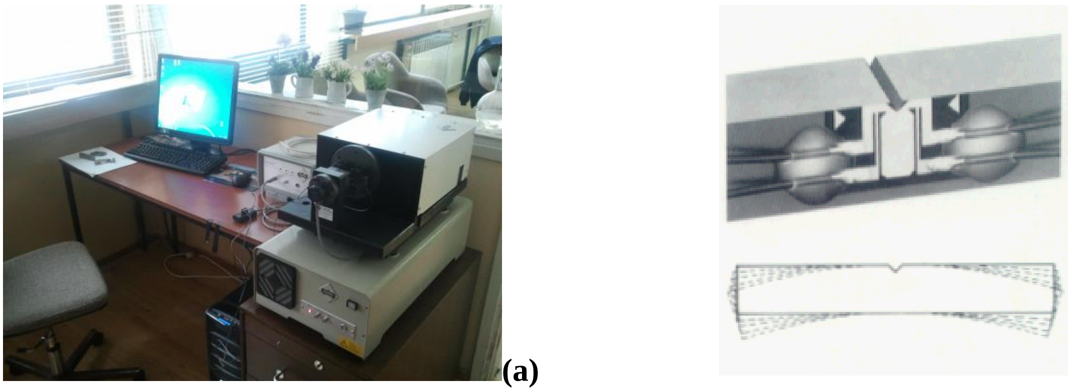


Fig. 1 SE(B) specimens for fatigue crack growth rate testing

Standard Charpy size specimens, pre-cracked in different welded joint regions, were tested under variable loading for determination of stress-intensity factor range at fatigue threshold, ΔK_{th}, and fatigue crack growth rate da/dN. Testing was performed in load control, by three-points bending on high-frequency resonant pulsator, Fig. 2. The specimen is part of the spring/mass system and affects by its stiffness the resonant frequency. The machine with notched impact test specimen runs with 200 cps. The system produce pure bending moment (Fig. 2b) and measure the crack length during test, simply and accurately, by the crack-gauge of special thin metal foil (Fig. 3) with electrical transducer bonded on a component. The change in gauge resistance by constant current excitation produces a DC output ΔU of infinite resolution. The photo-etched crack-gauge shape gives a strongly linear relationship gauges-output vs.crack length.

Generally, the installation of a crack-gauge to a specimen is identical to the well established used for foil-type strain gauges. The crack-gauge will be placed on the specimen in the correct position according to the reference marks. A suitable bonding jig should be used for curing to give a pressure of about 0.1-0.2 MPa.

Specimens with a machined notch will be stressed with a bending moment which is composed of a dynamic and a static part. Between the grips there is a constant bending moment. The fatigue crack growth tests had been performed on SE(B) specimens (single edge notch three points bending) at room temperature. All tests had been performed under the same ratio R = 0.1 of minimal and maximal load. During experiment number of cycles for every 0,1 mm crack growth has been automatically registered, enabling the design of relationship crack length a vs. number of cycles N.



(a) **(b)**

Fig. 2 High frequency bend fatigue testing system FRACTOMAT (a) with device CRACKTRONIC for crack length monitoring (b)

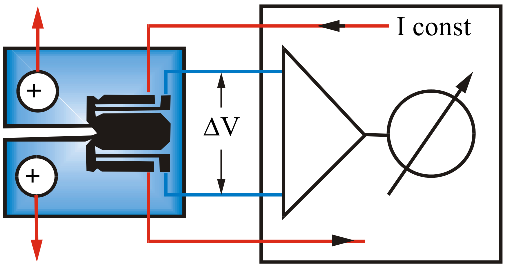


Fig. 3 Schematic diagram of crack gauge foil function

From the curve a vs. N it is possible to derive data, necessary for Paris law (Eq. 1). Knowing the initial, a_i and critical, a_c, crack sizes, the number of cycles to failure N_f can be calculated with the help of Paris law [7]

$$\frac{da}{dN} = C(\Delta K)^m \qquad (1)$$

Here, da/dN is the growth in crack size a per unit cycle, N is cycle number, C and m are constants obtained from experiments, $\Delta K = K_{max} - K_{min}$ is stress intensity factor range, change of stress intensity factor in the loading cycle, depending on crack size a. The stress range ΔK For SE(B) specimen can be calculated from formulae (2) and (3), for specimen width, W = 10 mm and thickness, B = 10 mm. In this formulae L is span, P is applied force, a is crack length.

$$K_Q = \frac{F_Q L}{BW^{1,5}} \times f\left(\frac{a_o}{W}\right) \qquad (2)$$

$$f\left(\frac{a_o}{W}\right) = \frac{3\left(\frac{a_o}{W}\right)^{0,5}\left[1,99 - \left(\frac{a_o}{W}\right)\left(1 - \frac{a_o}{W}\right)\left(2,15 - \frac{3,93a_o}{W} + \frac{2,7a_o^2}{W^2}\right)\right]}{2\left(1 + \frac{2a_o}{W}\right)\left(1 - \frac{a_o}{W}\right)^{1,5}} \qquad (3)$$

Parameters C and n in Paris law (Eq. 1), together with fatigue threshold ΔK_{th} value are tabulated in Table 5 for base metal, in Table 6 for weld metal and in Table 7 for heat-affected-zone respectively. Obtained relationships da/dN vs. ΔK for base metal, weld metal and HAZ are given in Fig. 4.

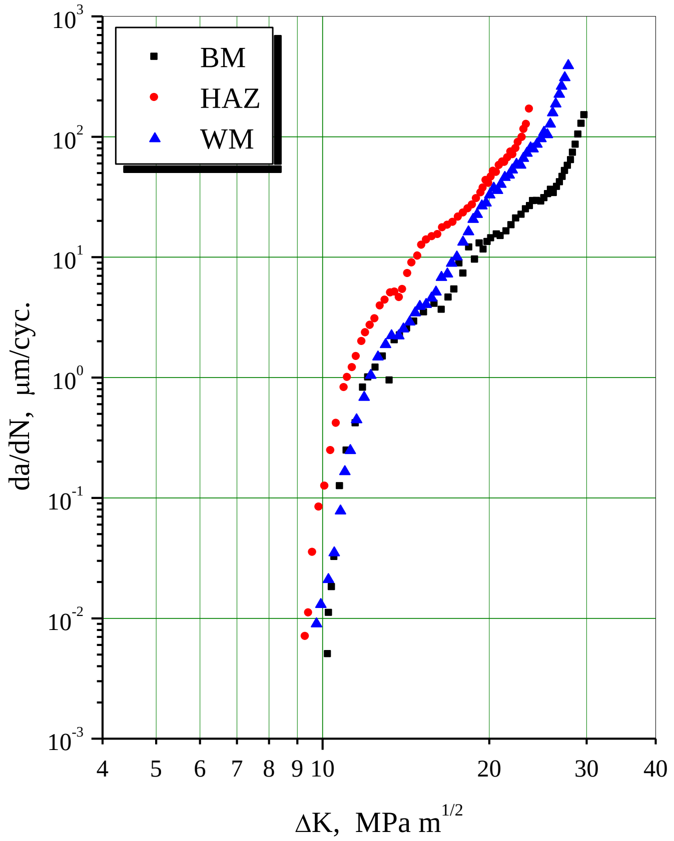


Fig. 4 Diagram da/dN - ΔK for BM, HAZ and WM

Table 5 Parameters C and m and fatigue threshold ΔK_{th} value for base metal

Zone of validity Paris equation	**C**	**m**	**Fatigue threshold. ΔK_{th}, MPam$^{1/2}$**
I	$3.98 \cdot 10^{-14}$	4.139	10.22
II	$1.67 \cdot 10^{-13}$	3.765	

Table 6 Parameters C and m and fatigue threshold ΔK_{th} value for weld metal

Zone of validity Paris equation	**C**	**m**	**Fatigue threshold. ΔK_{th}, MPam$^{1/2}$**
I	$8.38 \cdot 10^{-15}$	4.798	9,11
II	$3.30 \cdot 10^{-19}$	8.462	
III	$7.93 \cdot 10^{-15}$	5.078	

Table 7 Parameters C and m and fatigue threshold ΔK_{th} value for heat-affected-zone

Zone of validity Paris equation	**C**	**m**	**Fatigue threshold. ΔK_{th}, MPam$^{1/2}$**
I	$1.90 \cdot 10^{-20}$	10.259	8,51
II	$4.63 \cdot 10^{-12}$	2.667	
III	$2.90 \cdot 10^{-16}$	6.403	
IV	$7.87 \cdot 10^{-13}$	3.560	
V	$1.48 \cdot 10^{-16}$	6.505	
VI	$1.74 \cdot 10^{-14}$	4.929	

When welded steel structures are exposed to variable loading of high level it is necessary to reduce stress concentration as much as possible. Performed experiments have shown that this can be achieved by complete machining of welded joints.

The stress-intensity factor range ΔK characterizes the cyclic stresses and strains ahead of the crack tip and uniquely characterize the crack growth rate through a relationship such as Eq. 1. Since the zone ahead of the crack which experiences cyclic plasticity (i.e. the fatigue plastic zone) is very small, plane-strain conditions can develop even for small thicknesses. This is an important conclusion since it means that data can be obtained from thin specimens and applied quite generally. In regime I of Paris relation the crack growth rate is low since the threshold for crack propagation is approached. In regime II the so-called Paris law (Eq. 1) is obeyed, while in regime III the crack growth rate increases above that predicted by the Paris equation since the fracture toughness of the material is approached and there is local tensile overload fracture. Material behaviour in regime I can be considered in the similar way as endurance limit, because in both case there is no crack growth.

The life of components containing pre-existing flaws can be in principle computed using fracture mechanics concepts. For complex load/crack geometries and stress patterns, the equations for ΔK are complex. In addition, the da/dN vs. ΔK relationships may be quite complicated (or perhaps not even available in functional form). Such conditions do not lead to easily evaluated integrals for the fatigue life.

It is interesting that the difference in fatigue threshold value, the value of stress intensity factor range, ΔK_{th}, at which existing crack will not grow is not significant it is 10.22 MPa $m^{1/2}$ for base metal, 9.11 MPa $m^{1/2}$ for weld metal and 8.51 MPa $m^{1/2}$ for heat-affected-zone. Fatigue crack growth rate in different welded joint regions, expressed by different values of parameters C and m in Tables 5 through 7 can indicate critical region.

4. Conclusion

It is necessary to have fatigue properties of high strength steel for intented application in manufacturing of pressure vessel, exposed to variable loading, because fatigue strength of high strength steel is not superior compared to mild structural steel in the same level as it is the case with the strength. This situation is even more expressed for welded joints, because it is generally accepted that development of fatigue crack in that case is achieved only through crack propagation stage and not through crack initiation stage. Experimental data for fatigue crack growth are required for pressure vessel application.

Having in mind that fatigue crack initiated from defect in welded joint, next experiments are performed for crack growth rate analysis in base metal, weld metal, heat-affected-zone. Obtained results revealed that fatigue threshold is, as expected, the lowest in the HAZ, then in weld metal, with highest value in base metal. This can be taken as reason for next analysis in how to improve fatigue behaviour of welded joint. The differences in rang II of Paris equation are more expressed. Slope of the curve for base metal agrees well with reference data, but in weld metal and in the HAZ is remarkable change in coefficient m (tangent of the curve slope), indicating significant difference in fatigue crack growth rate in different microstructures, present in these constituents. General conclusion is that high strength steels can be applied in pressure vessel design after taken measures for improvement of fatigue properties of their welded joints.

5. References

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