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THE EFFECTS OF DYNAMIC LOAD ON BEHAVIOUR OF WELDED JOINT A-387 Gr. 11 ALLOYED STEEL

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The in-service behaviour of alloyed steel A-387 Gr. 11 Class 1, for pressure vessels, used for high temperature applications, depends on the properties of its welded joint, with parent metal (BM), heat-affected-zone (HAZ) and weld metal (WM), as constituents. Charpy testing of BM, WM and HAZ, together with, determination of the parameters of fatigue-crack growth and fatigue threshold ΔK_{th} was used, in order to understand, how heterogeneity of structure and different mechanical properties of welded joint constituents affect on crack initiation and propagation.

Key words: alloyed steel A-387 Gr. 11, fatigue, impact energy, Paris relationship

INTRODUCTION

Exploitation properties of A-387 Gr. 11 Class 1 alloyed steel, designed for manufacture of pressure vessels operating at elevated temperatures and pressures, largely depend on properties of the critical zones of a welded joint. Heat-affected zone (HAZ) and weld metal (WM) are latent locations of crack initiation, i.e. the locations where local brittle zones to whom crack initiation is attributed could be formed [1].

For better understanding of the causes and modes of crack initiation and crack growth in welded joints of steel designed for operation at elevated temperatures and under high pressure, it is necessary to establish how the heterogeneity of structure and mechanical properties of a welded joint affects crack initiation and growth, and to quantify the parameters controlling local-strain behaviour and crack growth.

The aim of this investigation is to assess the effects of heterogeneity of structure and mechanical properties of base metal and components of the welded joint of A-387 Gr.11 Class 1 steel on crack initiation and growth, as well as on the parameters of fatigue-crack growth (da/dN and ΔK_{th}) at elevated temperature of 540 °C, based on the results obtained [1].

MATERIAL

For testing, the sample of a welded joint of A-387 Gr. 11 Class 1 steel, with weld metal in the middle (double U-shaped weld), was used, the dimensions of which were 350 x 500 x 96 mm. Chemical composition of A-387 Gr. 11 Class 11 is presented in Table 1 [2]. The procedure for testing at elevated temperature of 540 °C is defined by the standard EN 10002-5 [3]. The results of tensile test of mechanical properties of A-387 Gr. 11 Class 1 steel at operating tempera-ture are presented in Table 2 [2].

Table 1 **Chemical composition of tested material [2]**

Chemical composition / mas. %						
C	Si	Mn	P	S	Cr	Mo
0,15	0,29	0,54	0,022	0,011	0,93	0,47

Table 2 **Results of tensile test [2]**

$R_{p0,2}$ / MPa	R_m / MPa	A / %
220	280	36

Welding of sheets new and exploited BM was conducted in two phases, as follows:

– root run – by manual arc procedure, using a plated electrode LINCOLN Sl 19G (AWS: E8018-B2),
– filling – by arc welding using powder protection, where the wire designated as LINCOLN LNS 150 and powder LINCOLN P230 were used as filler metals.

Chemical composition of used electrode LINCOLN Sl 19G (FM A) and wire LINCOLN LNS 150 (FM B) according to attest documen-tation is presented in Table 3. Main mechanical properties according to attest documentation are presented in Table 4.

Table 3 **Chemical composition of filler metal [4]**

Filler Metal	Chemical Composition / mass %						
	C	Si	Mn	P	S	Cr	Mo
FM A	0,08	0,045	0,35	0,025	0,025	1,10	0,50
FM B	0,11	0,18	0,37	0,020	0,020	1,04	0,47

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Table 4 Mechanical properties of filler metal [4]

Filler Metal	$R_{p0,2}$ / MPa	R_m / MPa	A / %	KV / J
FM A	505	640	23	> 95
FM B	490	610	26	> 100

RESULTS AND DISCUSSION

Testing by bending induced by impact effect of force on notched specimen can provide an explanation of material behaviour for disrupted strain. Determination of operation leading to fracture under established test conditions most frequently is used for current control of quality and homogeneity of the material, as well as of its treatment. This test procedure provides the possibility to establish susceptibility to brittle fracture, i.e. susceptibility to the increase of brittleness during exploitation (aging) [5].

Impact testing of the notched specimens in base metal (BM), weld metal (WM) and heat-affected zone (HAZ) on the side of exploited BM in 540 °C, was conducted in order to dete-rmine total impact energy, as well as the components of the energy crack initiation and crack propagation. Test procedure and the shape and dimensions of the specimens, are defined by standard EN 10045-1 [6]. Position of the notch relative to the welded joint is defined by the standard EN 875 [7]. The testing itself was conducted on instrumented Charpy pendulum. The results of testing are presented in Table 5.

Table 5 **The values of impact energy for tested BM and welded joint**

Spec. Design.	Tot. Impact Energy, A_{uk} / J	Energy of Crack Initiat. A_I / J	Energy of Crack propag. A_P / J
BM-1	119	51	68
BM-2	109	49	60
BM-3	115	50	65
WM-1	141	62	78
WM-2	132	59	73
WM-3	137	60	77
HAZ-1	96	44	52
HAZ -2	79	39	40
HAZ -3	85	42	43

Typical diagrams force-time and energy–time obtained by testing of the specimens designated by BM-1, WM-1 and HAZ-1 at operating temperature are given in Figures 1 through 3.

Structural life is expressed through crack driving time. To determine exploitation life means to predict crack driving time. Thus it has been concluded that sharp stress concentrators under conditions of variable loading after certain number of cycles result in crack initiation and its propagation if the fatigue threshold, ΔK_{th}, is exceeded. As the structure under certain loading conditions, as a rule, would not be jeopardized until the crack reaches critical dimensions, exploitation of a pre-cracked structure can be allowed even during the period of crack growth, on condition that it had already been subjected to preliminary analysis. Knowledge on the crack -growth rate and its dependence on affecting loading is essential for the decision on further exploitation [8].

Considering the fact that the stress field at the crack tip is characterized by singularity, it would be best to express the effect of the stress-rate through the stress-intensity factor.; as this is the case of variable loading, varying from highest to lowest value it would be most appropriate to describe it by the range of the stress-intensity factors, ΔK.

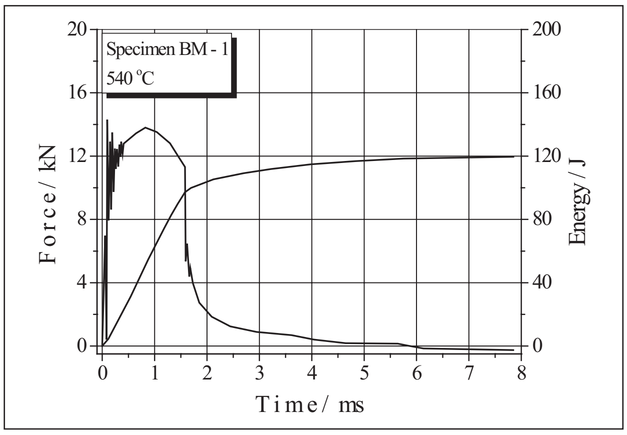

Figure 1 Diagrams obtained by impact testing of the specimen BM-1 [1]

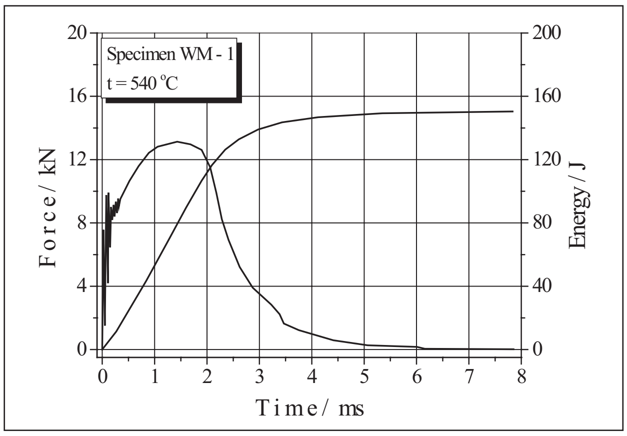

Figure 2 Diagrams obtained by impact testing of the specimen WM-1 [1]

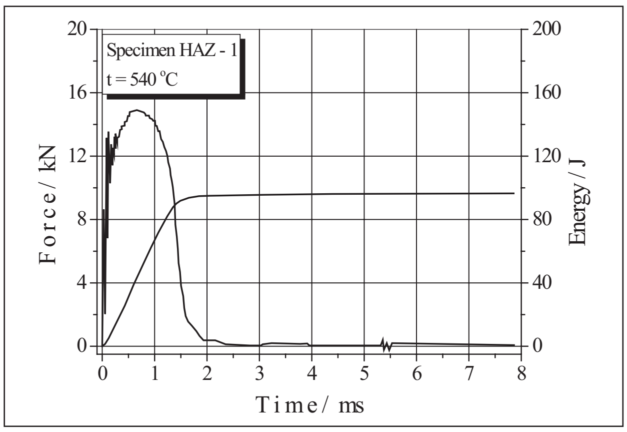

Figure 3 Diagrams obtained by impact testing of the specimen HAZ-1 [1]

This is the basis of the Paris' dependence, which is the foundation of the standard for determination of the parameters of fatigue-crack growth Standard ASTM E 647-00 [9] regulates the measurement of fatigue-crack growth rate, da/dN, propagating from a pre-crack, as well as calculation of the range of the stress-intensity factors, ΔK.

Therefore, it is reasonable to compare the crack-growth rate, da/dN, with ΔK, in a form defined by Paris [10]:

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

For determination of the parameters of fatigue-crack growth and fatigue threshold ΔK_{th} at operating temperature of 540 °C, modified CT-specimens were used. During the testing, the specimens were in a high-temperature chamber, placed on a high-frequency pulsator. The test itself was conducted in force control.

In Table 6, the values obtained for the parameters of Paris' equation, coefficient C and exponent m, as well as for fatigue threshold, ΔK_{th}, for all tested specimens are presented.

Table 6 **Parameters of the Paris' law**

Spec. Design.	ΔK_{th}, / MPa m$^{1/2}$	C	m
BM–1	5,7	$3,11 \cdot 10^{-13}$	4,08
BM–2	5,9	$2,79 \cdot 10^{-13}$	4,13
BM-3	5,9	$2,97 \cdot 10^{-13}$	4,07
WM–1	6,3	$3,27 \cdot 10^{-13}$	4,14
WM–2	6,2	$3,41 \cdot 10^{-13}$	4,06
WM-3	6,3	$3,36 \cdot 10^{-13}$	4,03
HAZ–1	6,1	$3,38 \cdot 10^{-12}$	3,17
HAZ–2	6,0	$3,31 \cdot 10^{-12}$	3,28
HAZ-3	6,0	$3,55 \cdot 10^{-12}$	3,35

As one can see from the results presented, the location of the notch and crack initiation affect both the values of fatigue threshold, ΔK_{th}, and parameters of fatigue-crack growth [11].

Typical diagrams fatigue-crack growth rate da/dN – variation of the range of the stress-intensity factor ΔK for the specimens with fatigue-crack tip in BM, WM and HAZ are shown in Figures 4 through 6.

From the results obtained, one can see that the specimens with a crack in base metal have the lowest fatigue-crack growth rate, da/dN. For the same range of the stress-intensity factor, ΔK, fatigue-crack growth rate, da/dN, increases in the specimens with a crack in weld metal, especially in the specimens with a crack in HAZ.

Maximum growth rate of fatigue crack can be expected at the level of the range of the stress-intensity factors approximating fracture toughness at plane strain, as brittle fracture is attained at that level [11].

However, in spite of the differences, both the specimens with cracks in BM and the components of the welded joint of WM and HAZ had rather low growth rates of fatigue cracks in general, which favoured the assessment on good properties of this material and components of the welded joints in presence of the crack-type defects affected by variable loading [11].

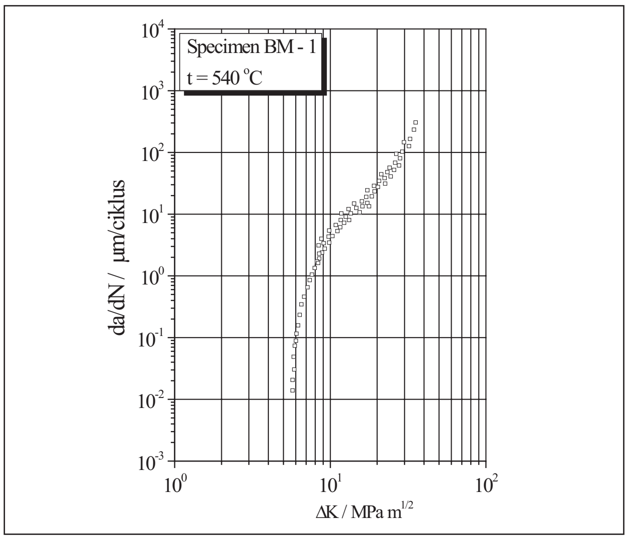

Figure 4 Diagram da/dN - ΔK for specimen BM [1]

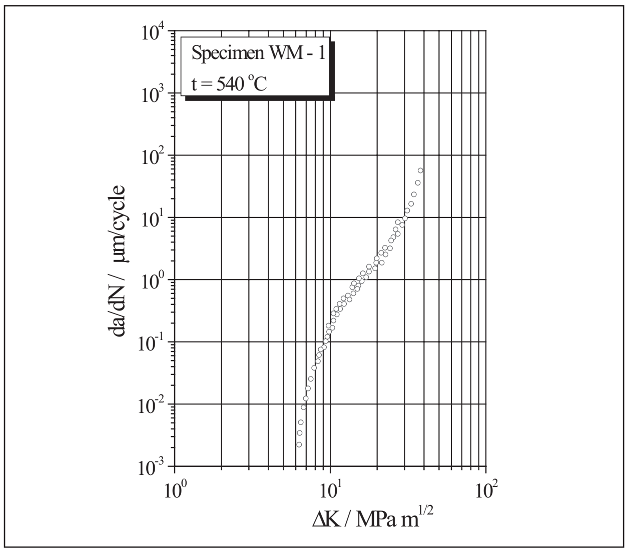

Figure 5 Diagram da/dN - ΔK for specimen WM [1]

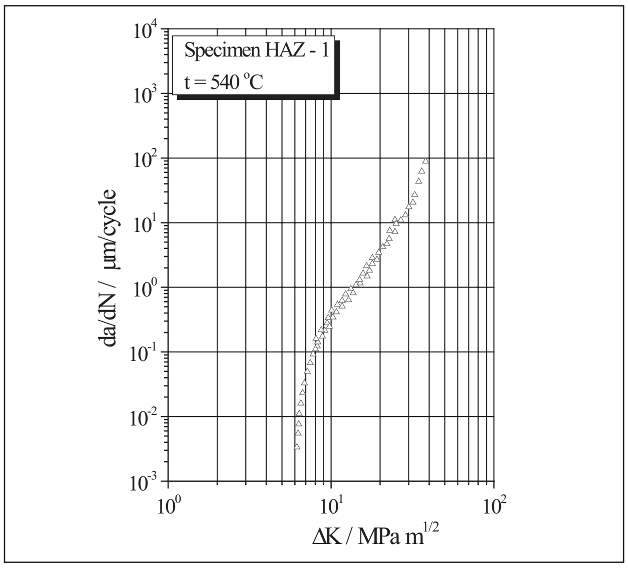

Figure 6 Diagram da/dN - ΔK for specimen HAZ [1]

Successful application of A-387 steel and its maximum creep resistance require guaranteed mechanical

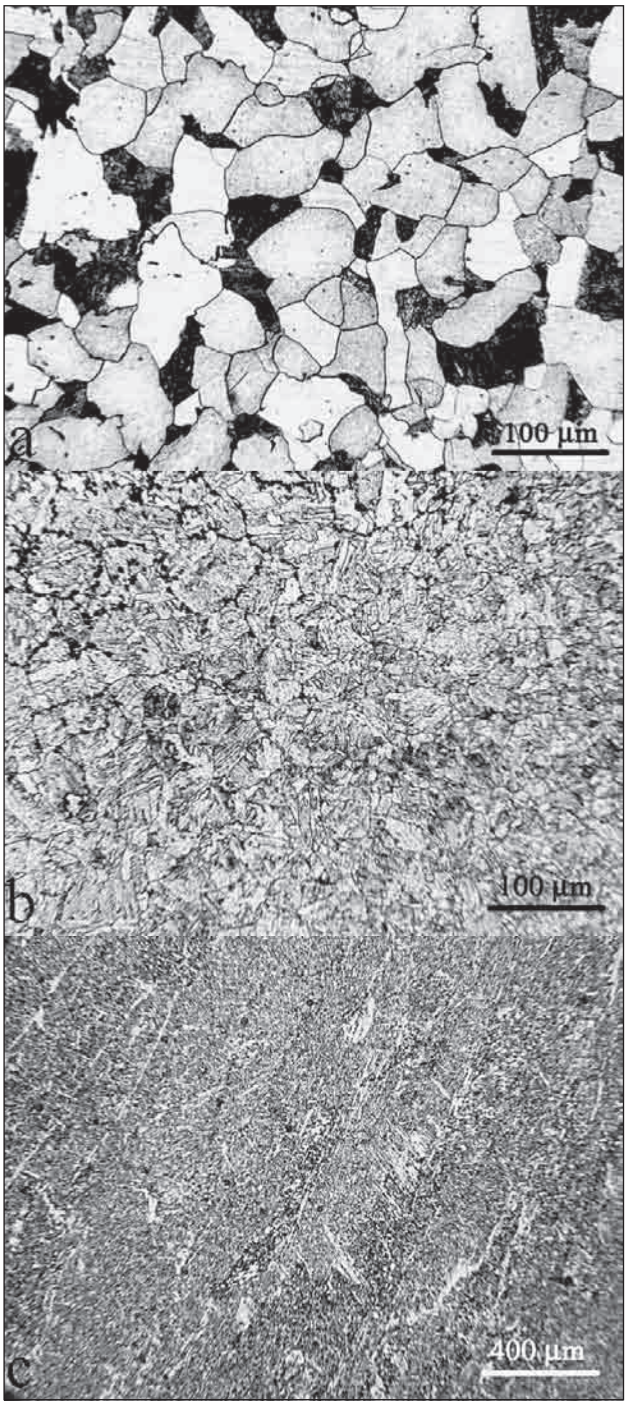

Figure 7 Microstructure of a) BM, b) HAZ and c) WM [1]

properties at elevated temperatures (max. 550 °C) and creep resistance at operating temperature during the period of exploitation that can significantly exceed 100 000 hours.

Microstructure of basic metal is ferrite and perlite, Figure 7a. In heat-affected zone micro-structure are consists of ferrite, beinite and perlite, Figure 7b. In heat-affected zone, beinite forms because of higher cooling rate of a part of base metal that was heated to austenitisation temperature during welding. Beinite content decreases with increase of the distance from the joint line. The structure of weld metal where the coarse dendrites formed because of the water-bath size, due to the dimensions of the welded plates, is shown in Figure 7c [1].

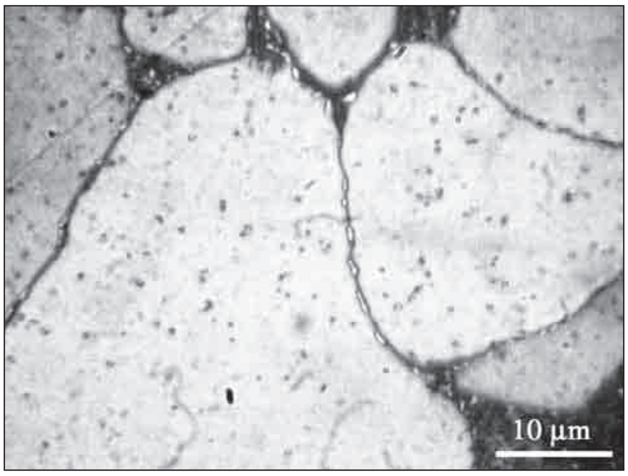

Figure 8 Microstructure of exploited BM [1]

Technique of colour-metallography (by pre-cipitation of interferential film) with BERAHA solution at larger magnification (2000 x) has made it possible to detect structural modifi-cations. Namely, the period of exploitation exceeding 30 years at temperatures above 500 °C in presence of stresses strongly affected separation of carbides at the boundaries and inside ferritic grain, Figure 8.

CONCLUSION

Based on the tests conducted, one could conclude the following:

Total impact energy obtained by testing of the specimens sampled from the zone of exploited welded joint and tested at operating temperature depends on the spot of notch engraving. The highest value of total impact energy is that of the specimens with a notch in WM, slightly lower is that of the specimens with a notch in BM, and the lowest value of total impact energy is that of the specimens with a notch in HAZ. The values of total impact energy, the components, energy of crack initiation and energy of crack propagation are primarily affected by heterogeneity of structure, and this effect is most prominent on the specimens with V-notch in the heat-affected zone (HAZ), as here the heterogeneity of structure is highest.

The values obtained for fatigue threshold, ΔK_{th}, and fatigue-crack growth rate, da/dN, are directly related to the location of fatigue-crack tip. The specimens with fatigue-crack tip in BM are most resistant to pre-crack growth. It is obvious that ferritic-perlitic structure predominant in BM results in higher resistance to activation of present crack, too, which reflects in lower value of fatigue-crack growth rate, da/dN.

(Exploitation conditions (operating tempera-ture) additionally decrease resistance of a crack to propagation under variable loading, which can have decisive effect on assessment of integrity and remaining life of the reactor itself. This increase of fatigue-crack growth rate, da/dN, is directly related to the structural modifications occurring in exploited material.

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REFERENCE

[1] M. Burzić, Uticaj eksploatacionih uslova na integritet i preostali vek posuda pod pritiskom, Doktorska disertacija, Univerzitet Novi Sad, (2008).
[2] ASME Boiler and Pressure Vessel Code an International Code, MATERIALS Part-A Ferrous Material Specification, (2001).
[3] EN 10002-5, Tensile testing of metallic materials. Method of test at elevated temperatures, (1992).
[4] Lincoln Electric, Welding Handbook, (2006).
[5] M. Burzić, Analysis of Crack Parameters of Welded Joint of Heat Resistant Steel, Structural Integrity and Life, 8(2008)1, 41-54.
[6] EN 10045-1, Mechanical Testing of Metals; Charpy Pendulum Impact Test; Parts 1 and 2 Terms and Definitions, Test Method, (2004).
[7] EN 875, Welded Joints in Metallic Materials - Specimen, Location and Notch Orientation for Impact Test, (1995).
[8] M. Burzić, Z. Burzić, J. Kurai, Dž. Gačo, Fatigue behaviour of alloyed steel for high temperature, First Serbian Congress on Theoretical and Applied Mechanics, Kopaonik, Serbia, (2007), 1085-1090.
[9] ASTM E647-00, Standard Test Method for Measurement of Fatigue Crack Growth Rates, Annual Book of ASTM Standards, 03.01(2000).
[10] P. C. Paris, and F. Erdogan, A Critical analysis of crack propagation laws, Journal of Basic Engineering, 85(1963), 528-534.
[11] M. Burzić, R. Prokić-Cvetković, B. Grujić, I. Atanasovska, Ž. Adamović, Safe Operation of Welded Structure with Cracks at Elevated Temperature, Strojniški vestnik - Journal of Mechanical Engineering 54(2008)11, 807-816

Note: The responsible translator for English language is Anđa Zorica, Belgrade, Serbia