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Cracking threshold of the welded joints subjected to high-cyclic loading

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1. Introduction

Parts of large-size mining-industry equipment, which exceeds 10 m in size, are produced for a particular purpose from welded elements. The longevity of such parts exceeds 25 years, and the number of loading cycles enters the giga-cyclic range ($N>10^8$ cycles) [1]. Welded joints are weak points in steel constructions, under the sway of cyclic load, corrosion and temperature fluctuation. Different defects in the welded joint and nearby determines the strength to cyclic loading. The durability of the equipment depends on the pattern of crack formation and propagation in these structural elements. Cracks may lead to the failure of the cracked elements or even to collapse of the structures. A large number of fatigue damage cases in welded elements and structures were reported. One of the main operational and technological requirements to welded joints is the compliance of their strength with basic metal.

Modern calculating methods used at initial stages of the crack formation are insufficiently reasoned. Supposedly, the fracturing changes its character. The time of the crack formation determines the longevity of the whole structure. The compatibility of strength, durability and resistance to dynamic loads in a particular material requires additional investigation. In many cases, the applicability of a material depends on such characteristic as impact ductility, brittleness, critical temperature and resistance to formation and propagation of cracks.

Cyclic strength of the welded joints was thoroughly analyzed in [2-6], where tensile deformations in various areas of the weld were considered. Well-known works [3-6] consider the impact of heat-treatment and nonuniformity of the microstructure of welded joints on their static and cyclic strength. Defects of various sizes and forms are found in the welded joints. Welding defects may be external (defects of the joint line) and internal structural defects and flaws of heterogeneous nature. External defects: deepened holes in the basic metal, craters, burned holes and pits in the line of the joint can be defected by visual inspection or by optical devices. Internal defects (inserts of slag, metal inserts, pores, nonwelding, cracks, nonfusion, etc.) can hardly be detected by nondestructive control methods because of their small size. Identified defects or operating cracks can be removed mechanically, i.e. by repairing the welded seam.

The principles of fracture mechanics [6-8] are applied to evaluate the strength of joints, depending on the nature of the load. The loading of structural elements of mineral mills and problems associated with the formation and propagation of cracks are discussed in [1-8].

2. The experiment

The paper presents the data on fracture toughness to cyclic loads of double-welded, heat-treated and rewelded joints. For experimental-analytical research, three 30 mm thick welded steel plates were chosen. (Fig. 1). Weld quality was checked by nondestructive (optic, ultrasonic and luminescent-magnetic) methods. The joints without defects in the weld were selected. One of the plates has double-V welded joint, the other one – heat-treated joint. In the weld of one of the plates, using nondestructive methods, defects of various forms were detected. The part of welded joints, where the defects were found, was removed by mechanical cutting and the joint was rewelded. No defects were found after repeated checking. Then, the surfaces of the plates were milled to the width of 26 mm. Chemical composition of the welded joints is:

- of the plate: C – 0.05-0.06%, Mn – 0.82-0.85%, Cr - 0.10-0.12%, Ni - 0.20-0.22%, Si - 0.27-0.29%, Mo - 0.05-0.54%, Cu - 0.032-0.034%;
- of the weld: C – 0.03-0.04%, Mn – 1.20-1.25%, Cr - 0.036-0.038%, Ni - 0.078-0.084%, Si - 0.30-0.32%, Mo - 0.030-0.034%, Cu - 0.18-0.21%.

Scheme of cutting specimens from all plates are shown in Fig. 2.

Microstructure of all the plates was studied at 6 points as indicated in Figs. 3-6. The microstructure: a) basic metal – pearlite, ferrite; b) transitional layers – ferrite, pearlite, carbide; c) weld – pearlite, ferrite, (nonhomogeneos material).

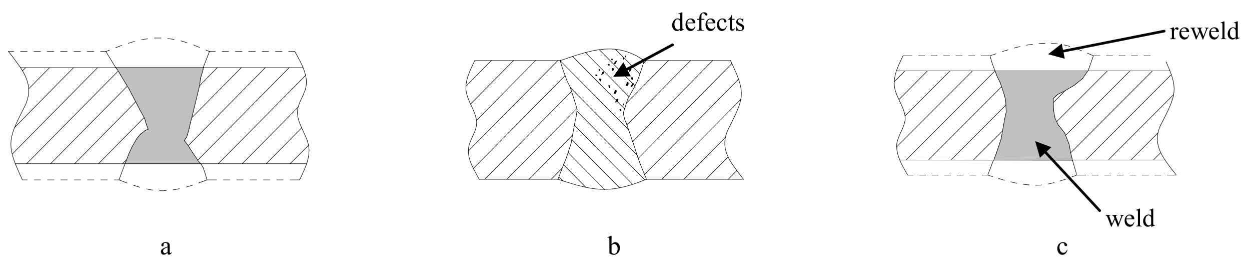
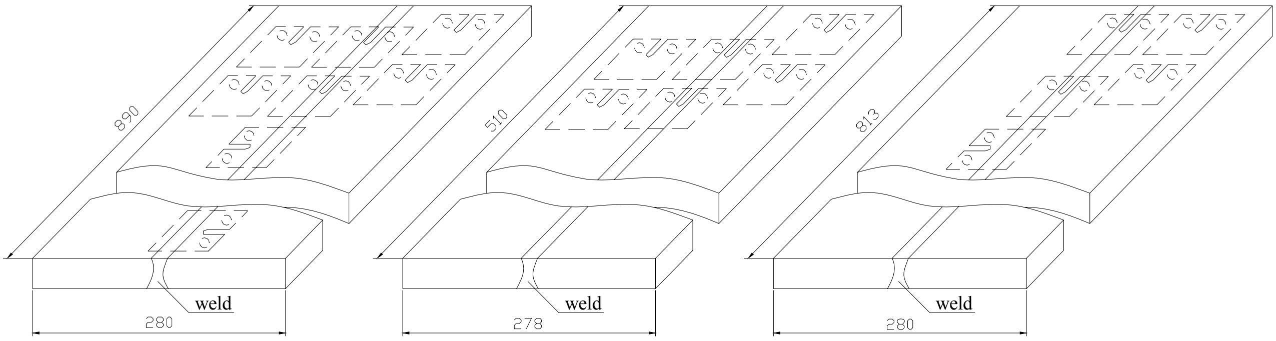


Fig. 1 Welded plates: a – double welded plate, heat treated plate; b – welded plate with defects; c – rewelded plate



a b c

Fig. 2 Scheme of cutting specimens from plates: a – double welded plate; b – heat treated plate; c – rewelded plate

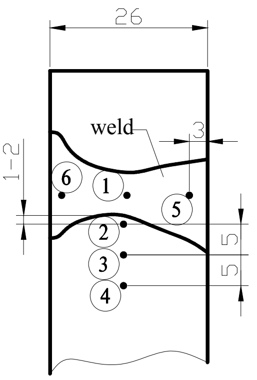
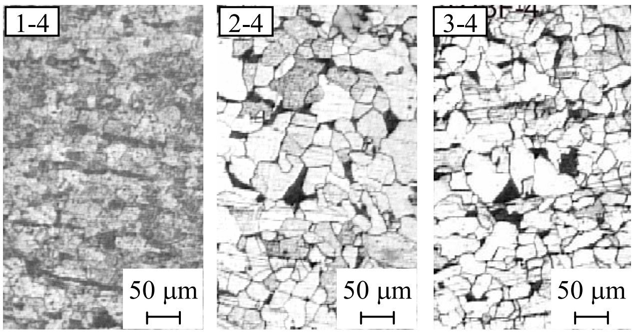
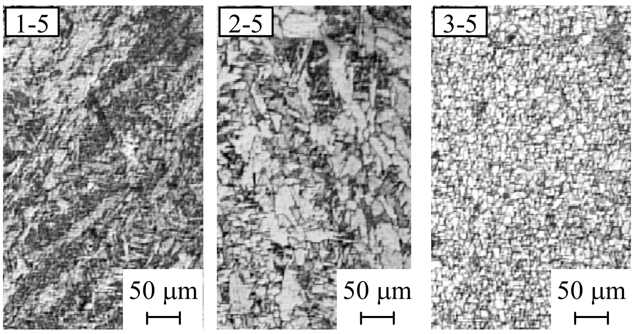


Fig. 3 Points for analysing the microstructure



a b c

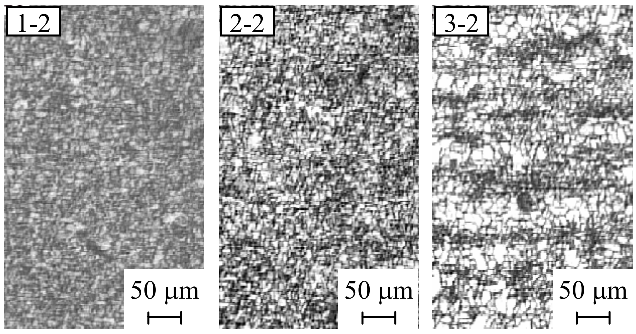
Fig. 4 Microstructure of basic metal: a – double welded plate; b – thermal treated plate; c – rewelded plate



a b c

Fig. 5 Microstructure of welded joint: a – double welded plate; b – thermal treated plate; c – rewelded plate

Cylinder samples (the initial diameter d_0 = 10mm, original gauge length L_0 = 40mm) made of the basic metal and weld seam were investigated to establish the mechanical properties (according LST EN 10002-1:2003 en). Table 1 presents the main properties of the basic and weld metals.



a b c

Fig. 6 Microstructure of thermal effect zone: a – double welded plate; b – thermal treated plate; c – rewelded plate

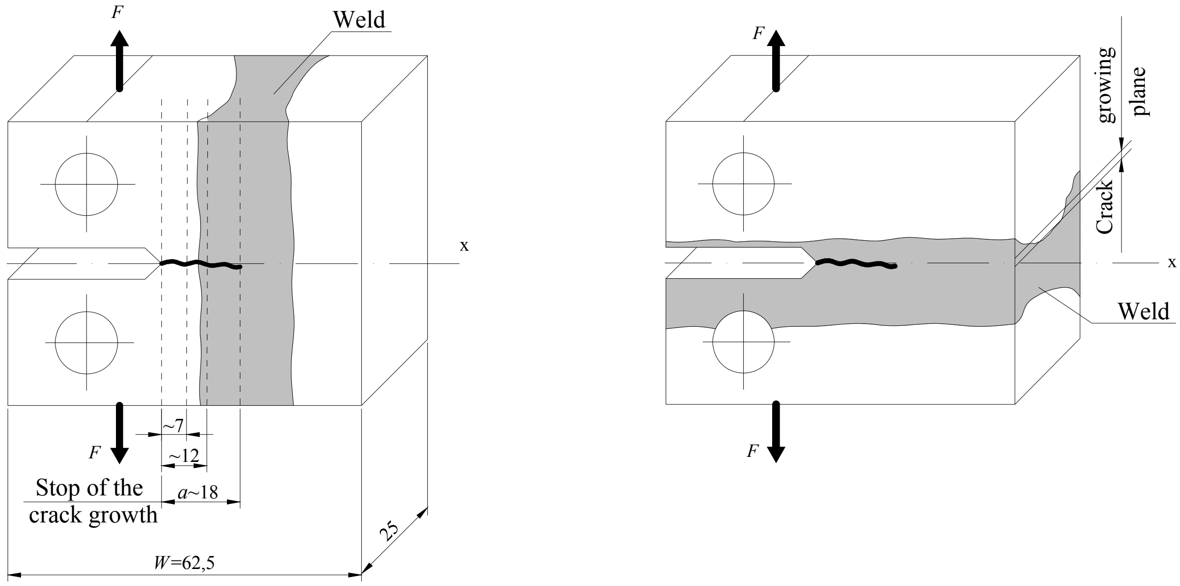
Table 1

Mechanical properties of the plate and the weld

Indexes	Plate 1, 2, 3	Weld 1, 2, 3
Hardness (BHN)	126-131	147-159
Lower yield strength R_{eL}, MPa	260-278	360-370
Upper yield strength R_{eH}, MPa	274-301	380-385
Tensile strength R_m, MPa	416-428	440-475
Modulus of elasticity E, GPa	210-215	211
Percentage reduction of area at fracture Z, %	66.6-74.5	75-78
Percentage elongation at fracture A_t, %	34.8-40.4	33.9-35

For determining the dependence of crack growth rate on the range of stress intensity factor, the methods of ASTM E 647-00 were applied and modified. Compact specimens (CT) were cut out of steel plates under the investigation with a slot orientated differently to the plate and weld axes. For producing diagrams, 2 – 6 compact samples of each plate and welded joint were tested.

The schemes of crack propagation of the samples are shown in Fig. 7.



a b

Fig. 7 Scheme of crack propagation: a - crack is perpendicular to the weld; b - crack is along or near the weld

3. Analysis of experimental results

The range of stress intensity factor was calculated according ASTM E 647-00 to the following formula

$$K = \left(F / BW^{1/2}\right) f(\lambda) \quad (1)$$

$$\lambda = a / W \quad (2)$$

$$f(\lambda) = \left[(2+\lambda)/(1-\lambda)^{3/2}\right] \times$$
$$\times\left(0.866 + 4.64\lambda - 13.32\lambda^2 + 14.72\lambda^3 - 5.6\lambda^4\right) \quad (3)$$

where $\Delta K = K_{max} - K_{min}$ is stress intensity factor range; $r = F_{min} / F_{max} = K_{min} / K_{max}$ is stress ratio; K_{min} and K_{max} are minimum and maximum stress intensity factor in the cycle of loading.

Nominal stresses in the top of the crack

$$\sigma = F / A + M / Z = (F / B)\left[(4W + 2a)/(W-a)^2\right] \quad (4)$$

or

$$\sigma = (2F / BW)(2+\lambda)/(1-\lambda)^2 \quad (5)$$

where F are axial force; $M = F\left[a + (W-a)/2\right]$ is bending moment; $A = (W-a)B$ is area of netto cross-section; $Z = \left[(W-a)^2 B\right]/6$ is section modulus; a is crack length.

Experiments are performed using the regulation methodology, when the cycle asymmetry is $r \approx 0$. On purpose to apply the experimental data for practical calculation, the variation of the cycle asymmetry coefficient must be estimated.

Cracking thresholds at different cycle asymmetry coefficients interrelate such dependence

$$\Delta K_{th} = \Delta K_{th0}(1-r)^{\gamma} \quad (6)$$

where ΔK_{th} is threshold stress-intensity range, ΔK_{th0} is limit interval of the stress-intensity factor, when $r = 0$, γ - a coefficient, which depends on the material and fluctuates from 0.5 up to 1.

The cracking threshold, when $r = 0$, can be calculated by

$$\Delta K_{th0} = \frac{\Delta K_{th}}{(1-r)^{\gamma}} \quad (7)$$

The cracking threshold stress-intensity range at any positive cycle asymmetry coefficient can be calculated as follows

$$\Delta K'_{th} = \Delta K_{th}\left(\frac{1-r}{1-r_{th}}\right)^{\gamma} \quad (8)$$

where r is current cycle asymmetry, r_{th} is cycle asymmetry, at which the cracking threshold was established.

The stress range that is in accordance with the threshold stress-intensity factor range and estimate cycle asymmetry

$$\Delta\sigma'_{th} = \frac{\Delta K_{th}}{\sqrt{\pi a}}\left(\frac{1-r}{1-r_{th}}\right)^{\lambda} f(\alpha) \quad (9)$$

The formula is valid when $r > 0$.

The stress intensity threshold ΔK_{th} was established in the case of stress ratio $r \approx 0.05$. The diagrams of crack growth rate versus the range of stress intensity factor were compiled and the stress intensity threshold ΔK_{th} was defined. The diagrams of the crack growth rate versus the range of stress intensity factor are shown in Figs. 8-15.

The dependences between the crack growth rate and stress intensity factor range for CT specimens of double welded joints, when fatigue crack growth is perpendicular to the weld, are: ΔK_{th} = 14 - 20 MPa$\sqrt{\text{m}}$ at $v = 10^{-10}$ m/cycle and ΔK_{th} = 13.6 - 20.2 MPa$\sqrt{\text{m}}$ at $v = 10^{-11}$ m/cycle (Fig. 9).

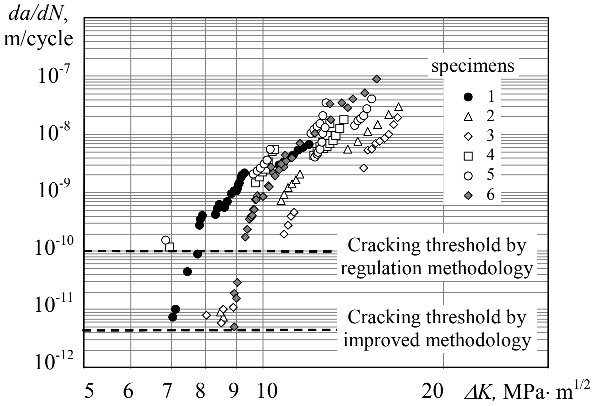


Fig. 8 Crack growth rate versus the range of stress intensity factor of basic metal in double welded plate

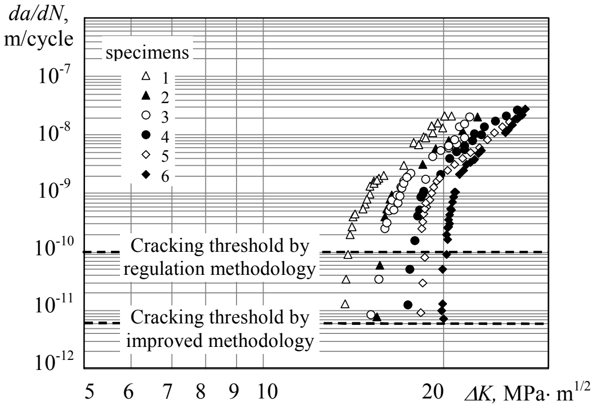


Fig. 9 Crack growth rate versus the range of stress intensity factor in the welded joints in double welded plate (crack is perpendicular to the weld); Light points denote the crack growth in the material of the pre-weld area. Dark points show the crack growth in the weld (or very close to it)

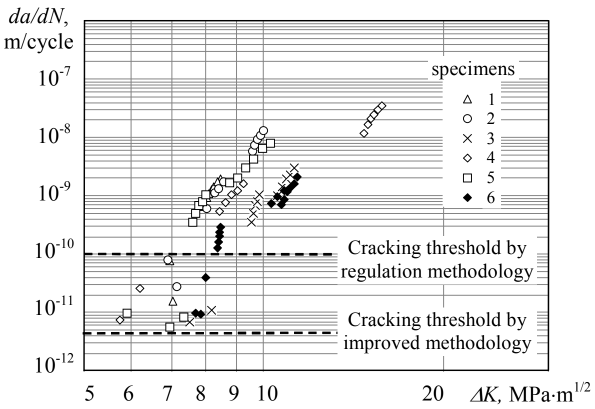


Fig. 10 Crack growth rate versus the range of stress intensity factor in the welded joints in double welded plate (crack is along or near the weld)

The dependences between the crack growth rate and stress intensity factor range for CT specimens of double welded joints, when crack growth is along the weld, are: $\Delta K_{th} = 6.9 - 8.3$ MPa $\sqrt{m}$ at $v = 10^{-10}$m/cycle, $\Delta K_{th} = 5.9 - 8.1$ MPa $\sqrt{m}$ at $v = 10^{-11}$ m/cycle (Fig. 10).

The dependences between the crack growth rate and stress intensity factor range for CT specimens of heat treatment joints are: $\Delta K_{th} = 7.6 - 8.2$ MPa $\sqrt{m}$ at

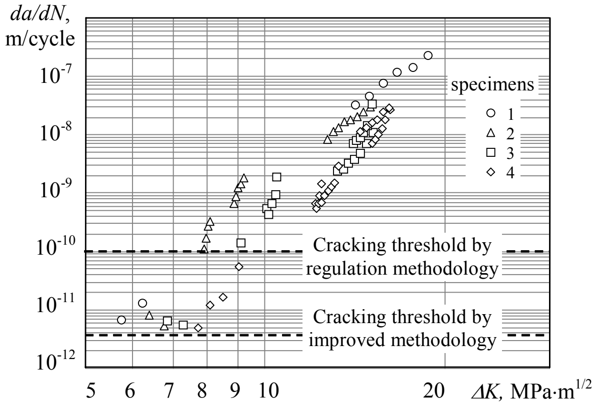


Fig. 11 Crack growth rate versus the range of stress intensity factor of basic metal in heat treated plate

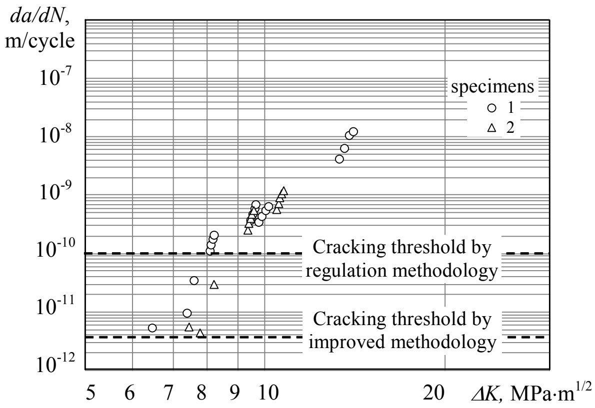


Fig. 12 Crack growth rate versus the range of stress intensity factor in the welded joints in heat treated plate (crack is along or near the weld)

$v = 10^{-10}$ m/cycle and $\Delta K_{th} = 6.4 - 8.0$ MPa $\sqrt{m}$ at $v = 10^{-11}$ m/cycle (Fig. 12).

The dependences between the crack growth rate and stress intensity factor range for CT specimens of rewelded joints, when fatigue crack growth is perpendicular to the weld, are: $\Delta K_{th} = 23 - 27$ MPa $\sqrt{m}$ at $v = 10^{-10}$ m/cycle and $\Delta K_{th} = 20 - 28$ MPa $\sqrt{m}$ at $v = 10^{-11}$ m/cycle (Fig. 14).

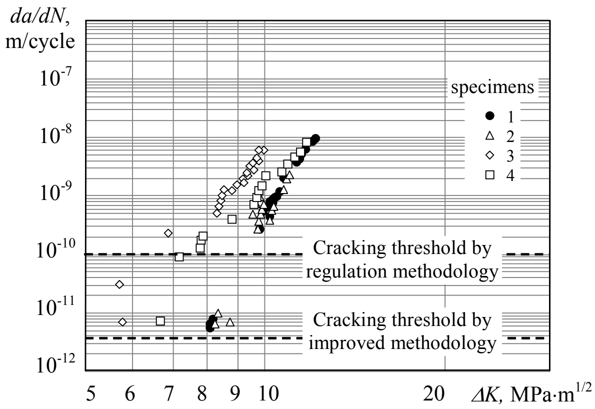


Fig. 13 Crack growth rate versus the range of stress intensity factor of basic metal in rewelded plate

The dependences between the crack growth rate and stress intensity factor range for CT specimens of rewelded joints, when crack growth is along the weld, are:

ΔK_{th} = 8.9 - 12.6 MPa $\sqrt{\text{m}}$ at $v = 10^{-10}$ m/cycle, ΔK_{th} = 7.6 - 12 MPa $\sqrt{\text{m}}$ at $v = 10^{-11}$ m/cycle (Fig. 15).

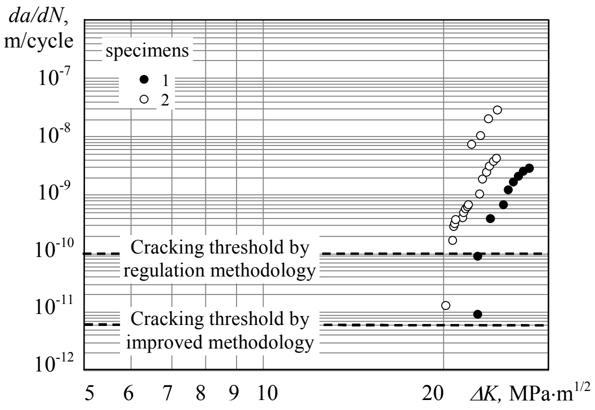


Fig. 14 Crack growth rate versus the range of stress intensity factor in the welded joints in rewelded plate (the crack is perpendicular to the weld); Light points denote the crack growth in the material before weld. Dark points show the crack growth in the weld (or very near the weld)

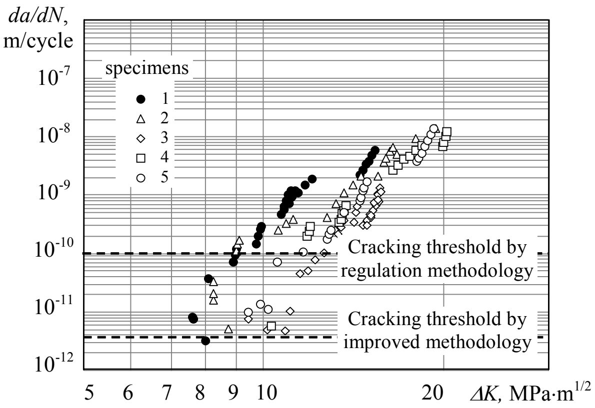


Fig. 15 Crack growth rate versus the range of stress intensity factor in the welded joints in rewelded plate (crack is along the weld)

Fig. 16 presents boundaries of the crack resistance of differently obtained welds, when crack growths are along or near the weld.

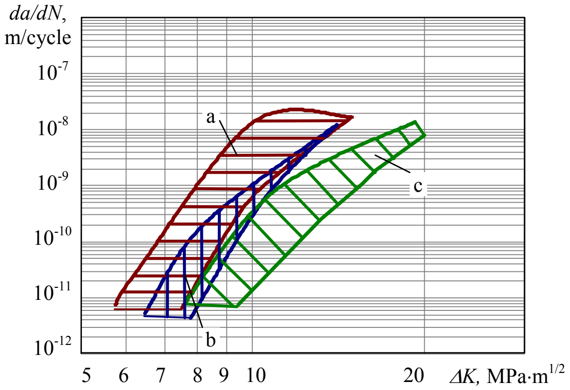


Fig. 16 Boundaries of the crack resistance of differently obtained welds: a – double welded plate; b – heat treated plate; c – rewelded plate

Fracture surface of CT specimens is shown in Fig. 17. It depends on the structure of the material and discontinuation of cracking. The mechanism of decomposition changes at the top of the crack. The crack front of the CT samples follows the main patterns of the fatigue crack. Fragile and tough zones are found in the static fracture area.

Since specimens are ductile ($Z \approx 70\%$), then, given the static loading (when specimens break) the stress state is two-dimensional. The fracture develops according to the plastic shear mechanism. Surfaces of fractures are oblique; however, some transitional process zone exists.

It is difficult for the crack to propagate in the CT samples with a slot made at the junction of the weld and the basic metal as the front of the crack runs into various structures. The crack passes through the joints and the basic metal, crossing their junction, i.e. the area of incomplete welding.

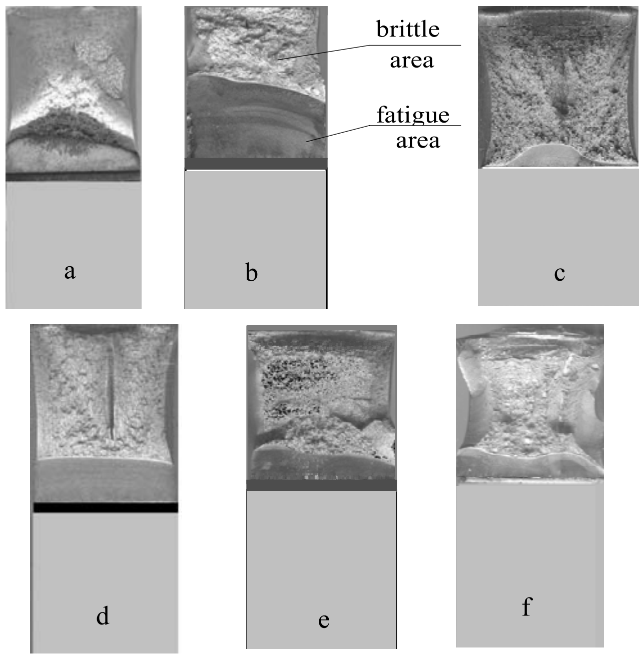


Fig. 17 Fracture surface of CT specimens. Double welded plate: a – basic metal; b – crack growth is perpendicular to the weld; c – crack - near the weld. Heat treated plate: d – basic metal; e – crack growth is near the weld. Rewelded plate: f – crack growth is near the weld

Each area has a different structure even after heat-treatment. The portion of the crack passing through the joint falls behind the crack portion passing through the basic metal, with the front of the crack acquiring the shape of a curve. Therefore, a conclusion can be drawn that both the joint and the area of the incomplete welding can withstand the cyclic load. A portion of the static fracture area has fragile and tough zones, and the impact is also made by the metal of the plate and joint.

The data obtained in the present work were used in the calculation of strength and durability of the welds, when the number of loading cycles exceeded 10^8.

4. Conclusions

1. The dependences between the crack growth rate and limit stress intensity factor range for double-welded joints are as follows: fatigue crack grows perpen-

dicular to the weld - ΔK_{th} = 13.6 - 20.2 MPa$\sqrt{m}$ at v = = 10^{-11} m/cycle; fatigue crack grows along or near the weld - ΔK_{th} = 5.9 - 8.1 MPa$\sqrt{m}$ at $v = 10^{-11}$ m/cycle; for heat-treated welded joints (crack is along - near to the weld) are as follows - ΔK_{th} = 6.4 - 8.0 MPa$\sqrt{m}$ at $v = 10^{-11}$ m/cycle; for rewelded joints (crack is along – near to the weld) are as follows - ΔK_{th} = 7.6 - 12 MPa$\sqrt{m}$ at $v = 10^{-11}$ m/cycle; crack is perpendicular to the weld - ΔK_{th} = 20 - 23 MPa$\sqrt{m}$ at $v = 10^{-11}$ m/cycle. The obtained results show that qualitatively rewelded seam is resistant enough.

2. The results show that cracking threshold perpendicular to the weld is 2-3 times as high as the cracking threshold along the weld. If the crack grows perpendicular to the welded joint, it impedes crack opening, thereby increasing stress intensity factor.

3. The obtained results are necessary to improve the welding technology to base calculation methods and insure strength of constructive elements.

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SUVIRINTŲJŲ JUNGČIŲ PLEIŠĖJIMAS VEIKIANT DAUGIACIKLIAM APKROVIMUI

R e z i u m ė

Straipsnyje pateikiami duomenys apie suvirintų plieno plokščių, dvigubo virinimo jungties, termiškai apdorotos jungties ir pervirintos (remontuotos) jungties atsparumą cikliniam apkrovimui. Nustatyta medžiagos ir siūlės mikrostruktūra ir mechaninių savybių rodikliai, pateikiami daugiaciklio nuovargio eksperimentinio ir analitinio tyrimo rezultatai. Išbandžius kompaktinius necentrinio tempimo CT bandinius, gautos pleišėjimo slenksčio ΔK_{th} vertės, kai plyšio plitimo greitis artimas $v = 10^{-12}$ m/ciklą. Nustatyta, kad priklausomai nuo plyšio plitimo plokštumos padėties skirtingai paruoštų virintųjų jungčių siūlėje pleišėjimo slenkstis kinta nuo 5.7 MPa$\sqrt{m}$ iki 23 MPa$\sqrt{m}$.

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CRACKING THRESHOLD OF THE WELDED JOINTS SUBJECTED TO HIGH-CYCLIC LOADING

S u m m a r y

The paper presents the data on the resistance to cycle loads of welded steel plates of double-welded, heat-treated and rewelded (repaired) joints. The microstructure and mechanical properties of the basic metal and the weld have been estimated and the results of high-cycle fatigue experimental and analytical research have been presented. By testing compact tensile specimens CT, threshold values are obtained when the crack growth rate is near $v = 10^{-12}$ m/cycle. It has been found that, depending on the location of the plane of crack propagation in the joint, the threshold varies from 5.7 MPa$\sqrt{m}$ till 23 MPa$\sqrt{m}$ in differently obtained welds.

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ТРЕЩИНОСТОЙКОСТЬ СВАРНЫХ СОЕДИНЕНИЙ ПРИ МНОГОЦИКЛОВОМ НАГРУЖЕНИИ

Р е з ю м е

В настоящей работе приведены данные о сопротивлении циклическому нагружению сварных соединений выполненных двойной сваркой, повторной сваркой и термически обработанных. Представлена структура и механические свойства основного металла и сварного шва. Проведено экспериментальное исследование компактных образцов внецентренным растяжением и установлена трещиностойкость ΔK_{th} при скоростях распространения трещины, близких к v = = 10^{-12} м/цикл. Установлено, что трещиностойкость изменяется от 5.7 MPa$\sqrt{m}$ до 23 MPa$\sqrt{m}$ в зависимости от плоскости распространения трещины.

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