THE INFLUENCE OF EMBRITTLING ADDITIVES AND RESIDUAL STRESSES ON FATIGUE CRACK GROWTH RATE IN WELDED TITANIUM JOINTS

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ABSTRACT: *The authors studied mechanical properties, fracture toughness, and fatigue crack growth rate in titanium alloy 2V (material of the welded joint) contaminated by oxygen and nitrogen and in titanium alloy VT6C (base metal). The regularities in fatigue crack propagation in a welded joint are studied with allowance for residual welding stresses. It is shown that fatigue crack growth rate dependence on the effective stress intensity factor is invariant to the value of residual stresses.*

INTRODUCTION

Welded joints of titanium alloys have found a wide application in engineering. Fracture toughness and fatigue crack growth rate in welded joints are much influenced by the welding technology and, primarily, by the contamination of a welded joint with oxygen and nitrogen from the air, and by residual welding stresses. The paper presents the results of a comprehensive study into the influence of the above factors on fracture toughness and diagrams of fatigue crack growth (FCG) in a welded joint. An attempt has been made to explain the obtained relationships considering the effect of crack closure.

MATERIALS AND EXPERIMENTAL PROCEDURES

Titanium alloy VT6C (Ti – 6.0W – 4.0V) was chosen as the base metal for a welded joint. The alloy had the following characteristics of mechanical properties: yield stress $\sigma_{0.2}$ = 850 MPa, ultimate strength σ_u = 940 MPa, relative reduction in the cross–sectional area ψ = 50%. The welded joint was made by argon-arc welding with a nonconsumable electrode with an additive. The material of the weld corresponded to titanium alloy 2V (Ti – 2Al – 1.5V). The investigated additives of oxygen and nitrogen in this alloy and corresponding characteristics of mechanical properties are listed in Table 1 [1].

Investigations of static and cyclic crack growth resistance were performed on 25-mm thick standard compact-tension (CT) specimens using a servohydraulic machine "Hydropulse 400 kN". Crack growth resistance was studied both on specimens completely fabricated of alloys VT6C and 2V and on specimens of alloy VT6C with welded joints whose composition corresponded to that of alloy 2V.

TABLE 1: Additives and mechanical properties of alloy 2V

O_2 (%)	N_2 (%)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	ψ (%)	HV (MPa)
0.05	0.008	447	605	63	1813
0.11	0.008	622	740	43	2293
0.21	0.004	711	857	39	2246
0.27	0.010	822	966	37	2763
0.35	0.011	965	1085	-	2900
0.03	0.05	530	655	42	2078
0.04	0.09	647	761	41	2293
0.06	0.16	697	826	40	2322
0.05	0.35	940	1020	-	2862

Fracture toughness of the alloy was determined using force-based approaches according to known standards from the maximum load, K_Q^{max}, and the 5% secant, $K_Q^{5\%}$. Plane-strain conditions were determined by the formula

$$t \geq 2.5\ (K_Q^{5\%} / \sigma_{0.2})^2, \qquad (1)$$

where t is the specimen thickness.

In the cases where plane-strain conditions were not fulfilled, the fracture toughness, K_{IC},,was also determined from the critical J–integral value using known procedures [2].

Fatigue crack growth under cyclic loading was measured with an optical microscope in stroboscopic light. Measurements of the crack opening displacement in the course of cyclic loading were made using an extensometer of special design mounted at the crack tip.

The results of measurements were recorded with an *XY* recorder and on a magnetic disk of a computer. The values of the maximum stress intensity factor, K_{max}, crack opening stress intensity factor, K_{op}, and the effective stress intensity factor range, $\Delta K_{eff} = K_{max} - K_{op}$, were calculated on a computer using a specially developed program.

The calculation involved the use of the following formulas:

$$K = \frac{P\sqrt{\lambda}}{t\sqrt{b}}\,y \qquad (2)$$

and $y = \dfrac{2+\lambda}{\sqrt{\lambda(1-\lambda)}^{3}}\left(0{,}886 + 4{,}6\lambda - 13{,}32\lambda^2 + 14{,}72\lambda^3 - 5{,}6\lambda^4\right)$,

where P is the force, t and b are the specimen thickness and width, respectively, λ is the ratio of the crack length a to the specimen width b.

Cyclic tests were performed at the stress ratio in a cycle R = 0.1, the main frequency of cyclic loading was 25 Hz. A detailed description of the experimental procedure can be found elsewhere [3, 4].

EXPERIMENTAL RESULTS

The Influence of Additives on Mechanical Properties and Fracture Toughness of Alloy 2V

The results of investigation of the dependence of the mechanical properties of alloy 2V on the content of oxygen and nitrogen are presented in Figure 1.

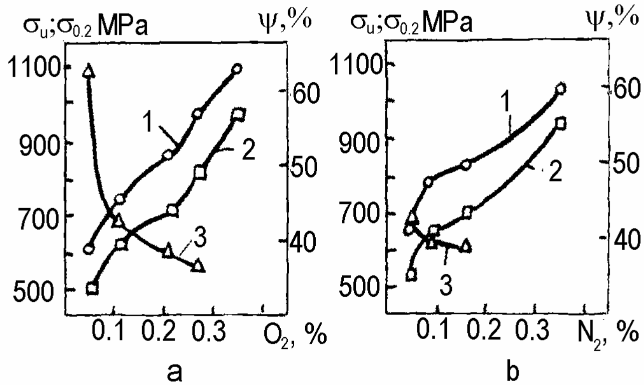

Figure 1: The influence of oxygen (*a*) and nitrogen (*b*) additives on characteristics of mechanical properties: σ_u (1), $\sigma_{0.2}$ (2), and ψ (3) of titanium alloy 2V

Their analysis shows that with increasing content of oxygen and nitrogen the magnitudes of $\sigma_{0.2}$ and σ_u increase and the ψ value, which characterizes plasticity, decreases appreciably. Figure 2 shows the dependence of K_Q^{max}, $K_Q^{5\%}$, *and* K_{IC} values for alloy 2V on the content of oxygen and nitrogen additives [1].

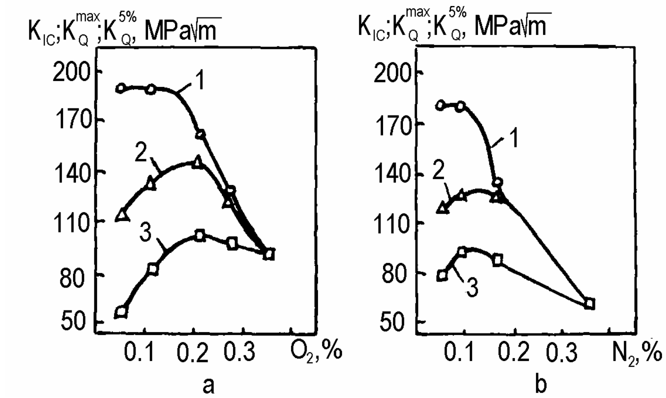

Figure 2: The influence of oxygen (*a*) and nitrogen (*b*) on fracture toughness K_{IC} (1), K_Q^{max} (2), and $K_Q^{5\%}$ (3) for alloy 2V.

Analysis of fulfillment of plane-strain conditions according to formula (1) revealed that for 25-mm thick specimens this criterion is fulfilled only when the content of nitrogen and oxygen is 0.35%. Comparison of the K_{IC} values with K_Q^{max} and $K_Q^{5\%}$ shows that with a small content of the additives the values of K_{IC} for alloys with nitrogen calculated using the J–integral are more than twice as large as those of $K_Q^{5\%}$ and, for alloy with oxygen, they exceed those of K_Q more than thee times.

Fatigue Crack Growth Rate in Alloy 2V

The results of investigation of the influence of oxygen and nitrogen (within 0.05…0.35%) on the fatigue crack growth rate in alloy 2V are shown in Figure 3 as FCG diagrams in the coordinates "$da/dN - K_{max}$".

From the results presented it follows that increasing the content of oxygen and nitrogen in the alloy affects the FCG diagrams in a different way. With an increase in the content of oxygen from 0.05% to 0.27%, the rate of FCG at the onset of Paris's region increases eight-to ten-fold. The further increase in the oxygen content to 0.35% leads to some decrease in the FCG rate. The effect of the content of oxygen and nitrogen on the value of the threshold stress intensity factor, K_{th}, is also ambiguous.

As revealed by the analysis performed, representation of the FCG diagrams for alloy 2V with various contents of oxygen and nitrogen in the coordinates "*da/dN* - ΔK_{eff}" does not lead to their invariance to the content of the additives.

The authors also studied on a limited scale the influence of the loading frequency on the FCG rate in alloy 2V with various content of oxygen. The results of this study revealed that the reduction of the loading frequency from 25 Hz to 0.5 Hz leads to a slight increase in the FCG rate within Paris's region for small content of oxygen. With the content of oxygen close to 0.35%, the effect of the loading frequency becomes insignificant.

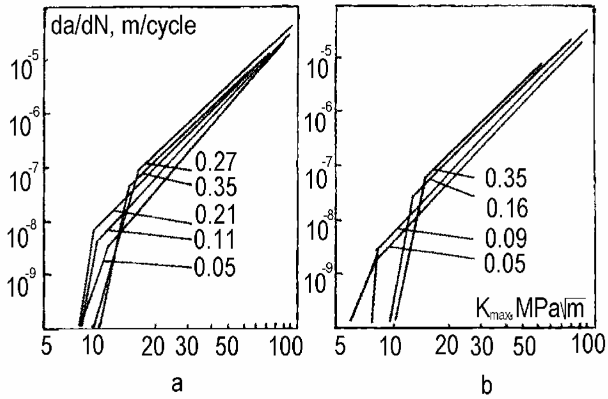

Figure 3: Fatigue crack growth (FCG) diagrams for alloy 2V with various contents of oxygen (*a*) and nitrogen (*b*).

FCG Rate in Alloy VT6C

We studied the crack growth resistance of alloy VT6C in the initial state and after plastic prestraining of billets to 10%. From the results of the investigation, FCG diagrams were plotted on the coordinates "*da/dN* – K_{max}" and "*da/dN* - ΔK_{eff}". Analysis of the results obtained revealed an ambiguous influence of plastic prestraining on the FCG rate and threshold stress intensity factor. It can be only noted that plastic prestraining from 0 to 10% leads to a 1.4- to 4-fold increase in the FCG rate on the linear portion of the diagram and to some increase in the threshold stress intensity factor after 10% deformation. It was found that the FCG diagrams in the coordinates "*da/dN* - ΔK_{eff}" are invariant to the magnitude of plastic prestraining.

FCG Rate in a Welded Joint

One of the main factors that define FCG rate in a welded joint along with embrittling additives is residual stresses.

Figure 4 shows the orientation of welded joints with respect to the crack growth direction and the pattern of residual welding stress distribution σ_r [4]

In specimens presented in Figure 4a, a fatigue crack propagates mainly in the base-metal VT6C perpendicularly to the weld, i.e., perpendicularly to residual compressive stresses whose magnitude increases as the crack extends along the specimen.

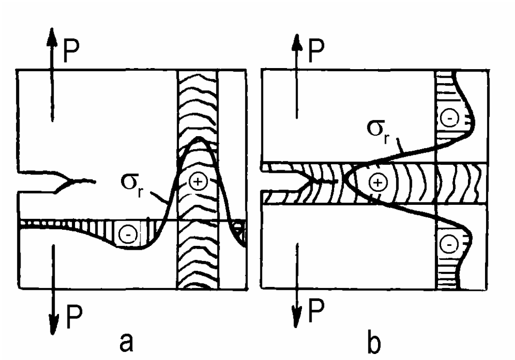

Figure 4: Specimens with a welded joint

The main difficulty in the investigation of crack propagation in this case consists in that, at a given level of the stresses induced by the load as the crack approaches the weld, the FCG rate decreases to the point of complete arrest. The further propagation of the crack is possible only after a discrete increase in K_{max}. Results of the investigation of such specimens with a weld containing 0.11% of oxygen and 0.08% of nitrogen are given in Figure 5.

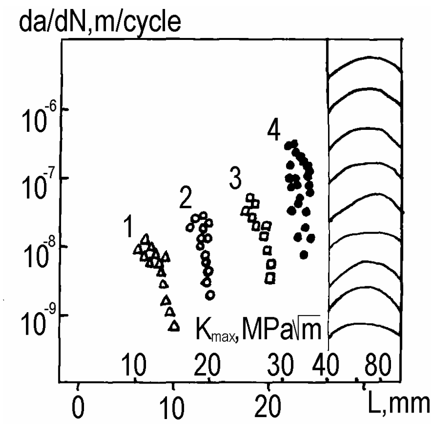

Figure 5: FCG diagrams for a welded joint: $1 - K_{max} = 12 MPa\sqrt{m}$; $2 - 20 MPa\sqrt{m}$; $3 - 38 MPa\sqrt{m}$; $4 - 50 MPa\sqrt{m}$

Fatigue crack growth rates in specimens of alloy VT6C with and without a weld were compared by plotting FCG diagrams in the coordinates "*da/dN* - ΔK_{eff}". The diagrams in these coordinates were practically identical.

When fatigue crack propagates in a weld (see Figure 4*b*) and when the stresses induced by external load are perpendicular to residual tensile stresses, its velocity is appreciably lower (Figure 6) than the crack propagation rate in alloy 2V of similar chemical composition. This is explained by the biaxiality of the stress state within the crack propagation zone. Similar results were obtained by Adams in [5], where he studied the influence of biaxiality on fatigue crack growth rate under similar loading conditions.

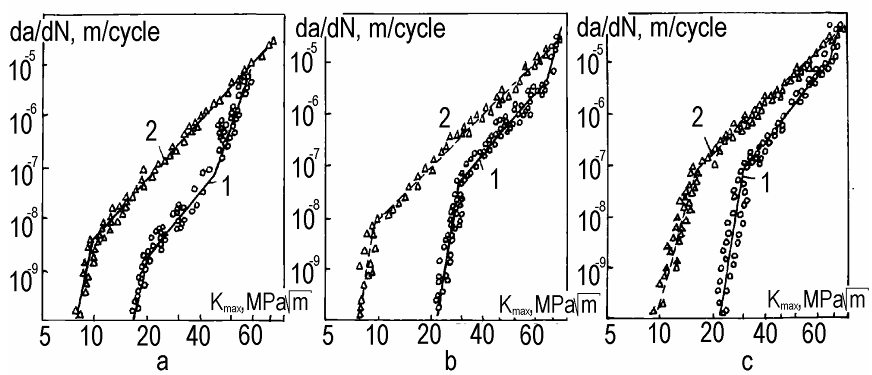

Figure 6: FCG diagrams in a weld (1) and in alloy 2V (2) with various content of oxygen in the coordinates "*da/dN* – K_{max}": *a* – 0.11%O_2; *b* – 0.21% O_2; *c* – 0.27% O_2..

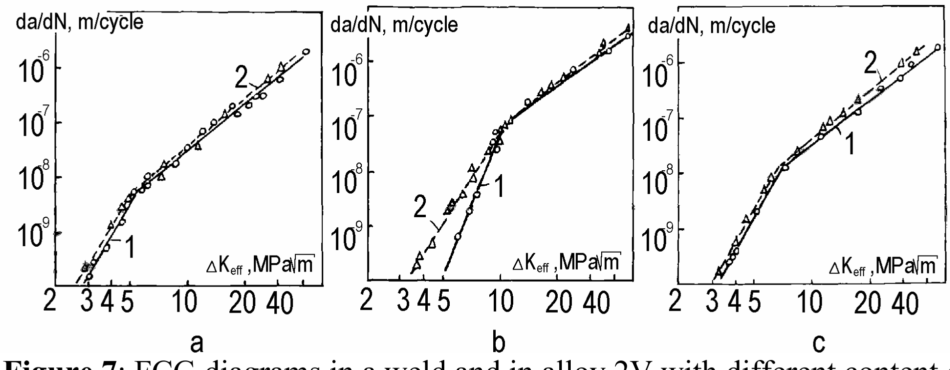

Figure 7: FCG diagrams in a weld and in alloy 2V with different content of oxygen in the coordinates "da_a/dN - ΔK_{eff}". Notations are similar to those in Figure 6

Comparison of the FCG diagrams for a weld and alloy 2V with a similar content of oxygen plotted on the coordinates "da/dN - ΔK_{eff}" is presented in Figure 7. One can see a fairly good agreement between the FCG diagrams obtained for the cases of the presence and absence of residual stresses.

CONCLUSION

The investigations performed revealed an appreciable influence of the oxygen and nitrogen additives on mechanical properties, fracture toughness, and fatigue crack growth rate in titanium alloy 2V, whose composition is similar to that of the weld material. The effect of residual welding stresses on the FCG rate has been studied in a titanium welded joint with various directions of fatigue crack growth with respect to the direction of the weld. It is shown that the influence of residual stresses on the FCG rate can be taken into account by the use of effective stress intensity factors.

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