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INFLUENCE OF STEEL STRUCTURE AND STRENGTH ON CORROSIVE-FATIGUE CRACK GROWTH IN THE THRESHOLD-CLOSE AREA

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The paper presents the results of research into fatigue cracking in the air and on fatigue-corrosive cracking in 3.5% NaCl distilled water solution. The samples of ferrito-perlite 15G2ANb and bainite and martensitic 14HNMBCu-special steels were tested. The tests were carried out in the threshold-close area at the two values of stress ratio $R = 0.2$ and $R = 0.7$. The research aimed at recognizing the boundary values of ranges of the stress intensity factors ΔK_{th} and ΔK_{thc} in the air and under the corrosive environmental conditions.

Key words: fatigue, cracking, corrosion

1. Introduction

The rate of fatigue cracking is usually described in terms of Paris' and Forman's equations, with the former being especially effective tool in analysis of the II phase of fatigue crack propagation. The Forman equation, which includes stress ratio, can be also used to broaden analysis of the III phase of fatigue cracking. A full diagram of the fatigue crack growth, as it is usually drawn, is shown in Fig.1.

Much of literature on the subject refers to the II phase of crack propagation curve, including its characteristics both in the air and in the corrosive environment. An thorough survey of these works can be found in the popular monograph (cf Kocańda (1985)).

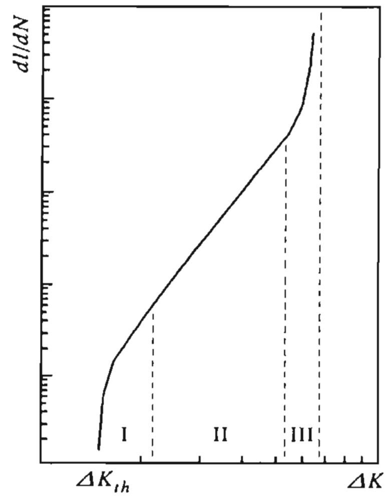

Fig. 1. Diagram of the fatigue crack growth rate

There are hardly any publications, on the I phase of propagation, in the threshold-close area. Over the last two years, however, a closer attention has been paid to this problem, and rightly so, as length of this phase determines the stability conditions of the constructional elements (cf Beevers (1980); Romaniv et al. (1983); Nikiforchin (1988); Steward (1980)) cracking in the air and in the corrosive environment. From few publications on this topic (cf Romaniv (1983); Nikiforchin (1988); Mayaki et al. (1990)), one may conclude that the structure and strength of sreel exert a greater influence on cracking in this area rathen than in the II phase represented by the Paris formula. In the I phase the crack growth is affected by the fatigue crack (cf Romaniv et al. (1983), (1985); Bordal et al. (1990)) tendency to close up. This phenomenon is especially effective at slow crack growth rates in the threshold-close area, where the crack is rather narrow, in comparison to the width of oxides layer appearing on tips of newly formed cracks.

The fatigue crack growth in the corrosive environment is much more complicated process. Besides the influence of mechanical factor discussed above there is also an influence of aggressive environment. In fact, there are two inverse processes that take place there. The aggressive corrosive environment brings about electro-chemicall failure of the crack tip, which diminishes the sharpness of the notch and relaxes tension at its top decreasing the stress intensity factor, on one hand, and increasing the space between the crack sides it weakens the closing-up effect and lowers the value of the opening factor K_{op}

(cf Nikiforchin (1988); Bignonent et al. (1990)).

Morphology of the crack surfaces is also different for cracks in the air and cracks in the corrosive environment. The crack edge in the air is smooth while it is more ragged in the corrosive environment, which is due to the presence of the multiple corrosive micro-centers and perpendicular secondary micro-cracks. This phenomenon slows down the of the fatigue growth in the threshold-close area (cf Bachmacz et al. (1994); Nikiforchin (1988); Mayaki et al. (1990)).

Hydriding of the metal in the corrosive environment can have dual effect on the crack growth depending on the steel structure and properties. The crack growth rate is higher in high-strength steels, and lower in plastic steels *having low yield value. This is due to a change of the cracking mechanism* from the fragile to the plastic one (cf Nikiforchin (1988)).

The stress ratio R can also influence the rate of fatigue cracking (cf Bignonet et al. (1990)). Its value depends also on the type of specimen material and loading conditions. The data qiven by Kocańda (1985) prove different influence of the stress ratio R. It can either increase or decrease the rate of cracking. This conclusion, however, should be considered in view of the fact that the quoted research concerned the II stage of the crack propagation.

This study approaches also the problem of the load frequency effect. In the II phase of corrosive and fatigue cracking evens low frequency (~ 0.1 Hz) causes substantial increase in the crack growth rate in the corrosive environment. The tests, results of which are presented, were performed at the frequency of 4.17 Hz, the value determined the tester capabilities. This frequency can be also found in the machine building industry.

2. Materials and results

Two types of high strength steel were tested: the ferrito-perlitic steel 15G2ANb and two types of 14HNMBCu-special, bainitic and martensitic steels, respectively.

The structures of these steels are shown in Fig.2.

The chemical compositions of the steel were as follows:

- 15G2ANb-steel:

C=0.10%	P=0.018%	Mn=1.24%	S=0.01%	Cu=0.02%
Si=0.50%	Cr=0.01%	Ni=0.01%	Al=0.04%	Nb=0.05%

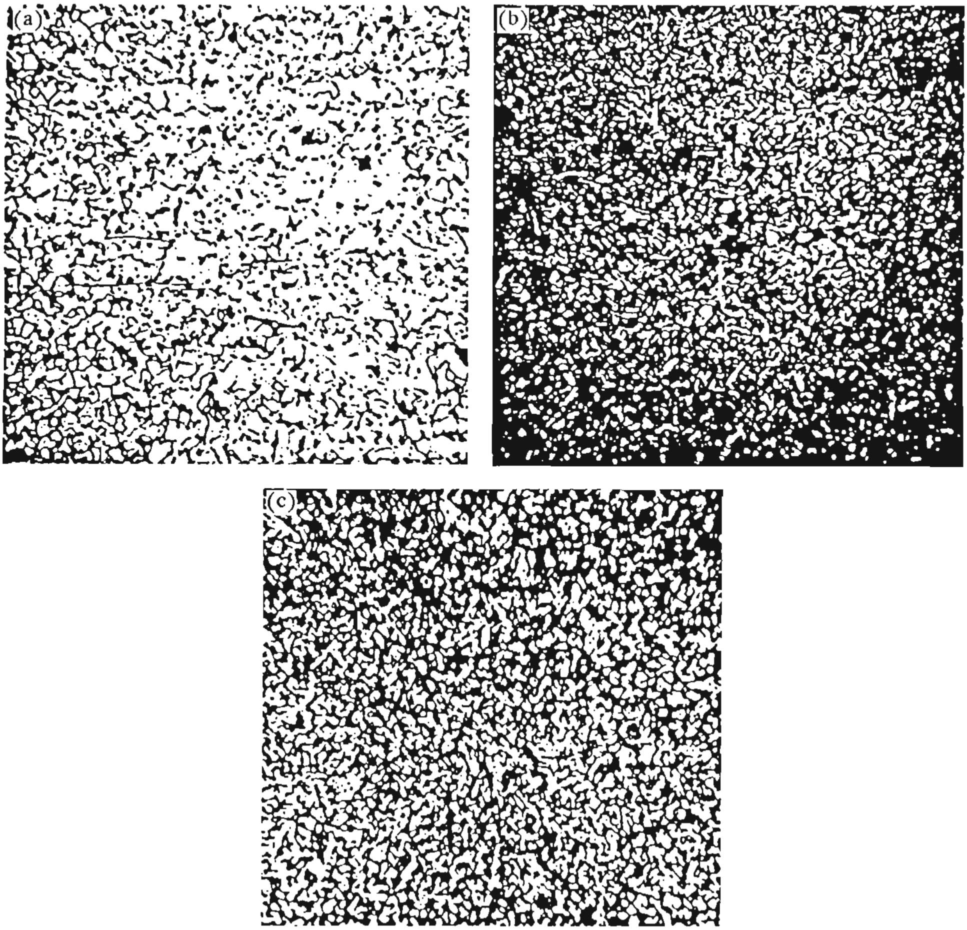

Fig. 2. Steel structure of high strength. Microsections were etched with nitale, magnification of 300×: (a) – 15G2ANb - ferrito-perlitic structure, (b) – 14HNMBCu-special – bainitic structure, (c) – 14HNMBCu-special – martensitic structure

- 14HNMBCu-special steel:

C=0.14%	P=0.018%	Mn=0.65%	S=0.005%	Cu=0.26%
Si=0.25%	Cr=0.052	Ni=0.71%	Al=0.031%	Mo=0.40%
Nb=0.008%	V=0.04%	B=0.003%		

Table 1 shows the strength and plastic properties of the steels.

Table 1. Strength and plastic properties of steels

Steel	R_e [MPa]	R_m [MPa]	A_5 [%]
15G2ANb	375	510	30
14HNMBCu-s bainitic str.	776	825	15.5
14HNMBCu-s martenstic str.	1300	1190	10

The samples were made from steel sheets 24 mm thick, cut along the rolling direction, i.e., their axes coincided with the rolling direction. Samples were planed on both surfaces to obtain the thickness of 21 mm. The samples were intensively cooled with a liquid to avoid appearance of the residual stresses after grinding. The samples were ~ 420 mm long and 100 mm wide. A symmetric centric notch was made in each sample, 3 mm in diameter, together with two later incisions of 1.5 mm each (6 mm totaly). The fatigue crack growth rate was examined in the air and in the 3.5% NaCl solution in distilled water.

NaCl solution flowed throughout a chamber mounted on the sample when it underwent fatigue loading. The afflux rate of the fluid was $10^{-2}\,\mathrm{dcm^3/s}$ and its acidity varied from $pH = 6.85 \div 6.94$. The experiments were carried out under varying tensile loading, the amplitude of which was constant and at two stress ratios $R = 0.2$ and $R = 0.7$ and frequencies $f = 4.17$ Hz in the corrosive environment and $f = 8.33$ Hz in the air. The fatigue crack growth was measured on the samples surfaces by means of an optical method using a microscope of magnification 25× with a reading accuracy up to 0.02 mm.

The range of stress intensity factor at the threshold-close are was measured in the way complying with the American Standard E-647-88a (cf [12]) by a step-wise decreasing the stress down to the crack growth rate of 10^{-8} mm/cycle. This rate was assumed in literature to be the value corresponding to the threshold value of the factor ΔK_{th}. The stress σ_{max} was reduced by 10% relative to the initial value, while the stress level at the cracking rate of $5 \cdot 10^{-7}$ mm/cycle was reduced, by $5 \div 2\%$ relative to the initial value.

The rate of fatigue crack growth dl/dN in the I phase was described by a modified form of the Paris formula (cf Kocańda (1985))

$$\frac{dl}{dN} = \frac{4A}{\pi R_e E}(\Delta K^2 - \Delta K_{th}^2) \tag{2.1}$$

where

R_e – yield stress

E – modulus of elasticity

ΔK – range of stress intensity factor
ΔK_{th} – threshold value of the stress intensity factor range
A – constant parameter evaluated experimentally.

Table 2 gives the values of the stress intensity factors K_{th} and K_{thc} and their ranges ΔK_{th} and ΔK_{thc} corresponding to $\Delta\sigma = \sigma_{max} - \sigma_{min}$.

Table 2. Values of the stress intensity factors K_{th} and K_{thc} and their ranges ΔK_{th} and ΔK_{thc} for high-strength steels

Steel	R	σ_{max} [MPa]	Crack length l [mm]	Environ-ment	K_{th}, K_{thc} [MPa$\sqrt{\text{m}}$]	$\Delta K_{th}, \Delta K_{thc}$ [MPa$\sqrt{\text{m}}$]
15G2ANb	0.2	65	7.18	air	9.8	7.93
		95	8.04	NaCl	15.2	12.08
14HNMBCu-s bainitic str.		61	4.72	air	7.5	6.0
		59	7.22	NaCl	8.89	7.1
14HNMBCu-s martenstic str.		42	6.13	air	5.83	4.67
		36	4.95	NaCl	4.49	3.59
15G2ANb	0.7	66	9.48	air	11.5	3.7
		93	11.48	NaCl	17.9	5.4
14HNMBCu-s bainitic str.		68	6.20	air	9.5	2.9
		67	7.60	NaCl	10.4	3.1
14HNMBCu-s martenstic str.		55	5.68	air	7.35	2.20
		43	5.63	NaCl	5.72	1.72

3. Discussion

The tests have proved that the threshold-close values of the stress intensity factor K_{thc} and its range ΔK_{thc} in the 15G2ANb and bainitic 14HNMBCu-special steels, respectively, are higher in the environment of 3.5% NaCl water solution than the values of K_{th} and its range ΔK_{th} in the air. The K_{thc} and the ΔK_{thc} values are lower for martensitic steel 14HNMBCu-special. The same influence of the corrosive environment on the threshold values of K_{thc} and ΔK_{thc} was observed two values of the stress ratio $R = 0.2$ and $R = 0.7$.

The increase in the value of R from $R = 0.2$ to $R = 0.7$ results in an increase in the threshold value of the stress intensity factor K_{th} and a decrease in its range ΔK_{th} for all types and structures of the tested steels both in the air and in the NaCl solution. The results shown in Table 2 prove on

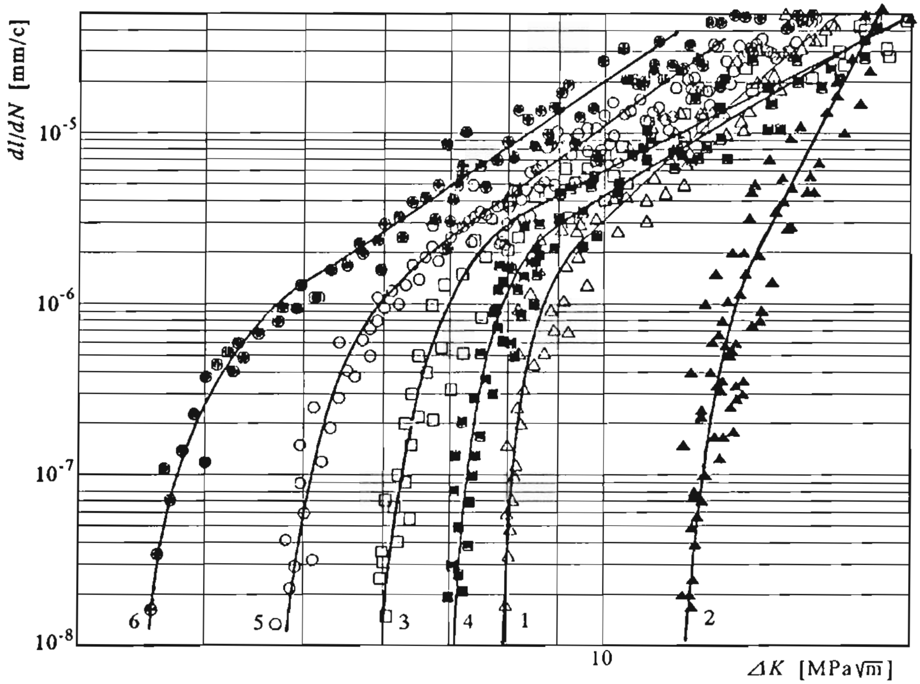

Fig. 3. Fatigue crack growth rate in high-strength steels at $R = 0.2$: 1,3,5 – in the air; 2,4,6 – in the NaCl solution; 1,2 – 15G2ANb; 3,4 – 14HNMBCu-s bainitic structure; 5,6 – 14HNMBCu-s martensitic structure

the greatest influence the corrosive environment exerts on the steel 15G2ANb. The increase in the ΔK_{thc} relative to ΔK_{th} in the corrosive environment was 52% at $R = 0.2$ and 46% at $R = 0.7$, respectively. The percentage change of the ΔK_{thc} value in the steel 14HNMBCu-special in the 3.5% NaCl solution at $R = 0.2$ and $R = 0.7$ was significantly lower depended the steel structure.

The 15G2ANb steel has a ferrito-perlite structure and very good plastic properties. This favors intensification of the closing-up process of the fatigue cracking, especially at low values of the stress ratio R. The closing-up mechanism is especially effective in the corrosive environment where, besides plastic deformations at the crack edges, it is reinforced by corrosive growths developing on the crack surfaces. A relatively high value of $\Delta K_{thc} = 5.4\,\mathrm{MPa}\sqrt{\mathrm{m}}$ in steel 15G2ANb measured in the NaCl solution at $R = 0.7$ allows for assuming that the closing-up process can take place even at so high R coefficient at the threshold-close area.

It was observed that 14HNMBCu-special steel of higher fragility can exert

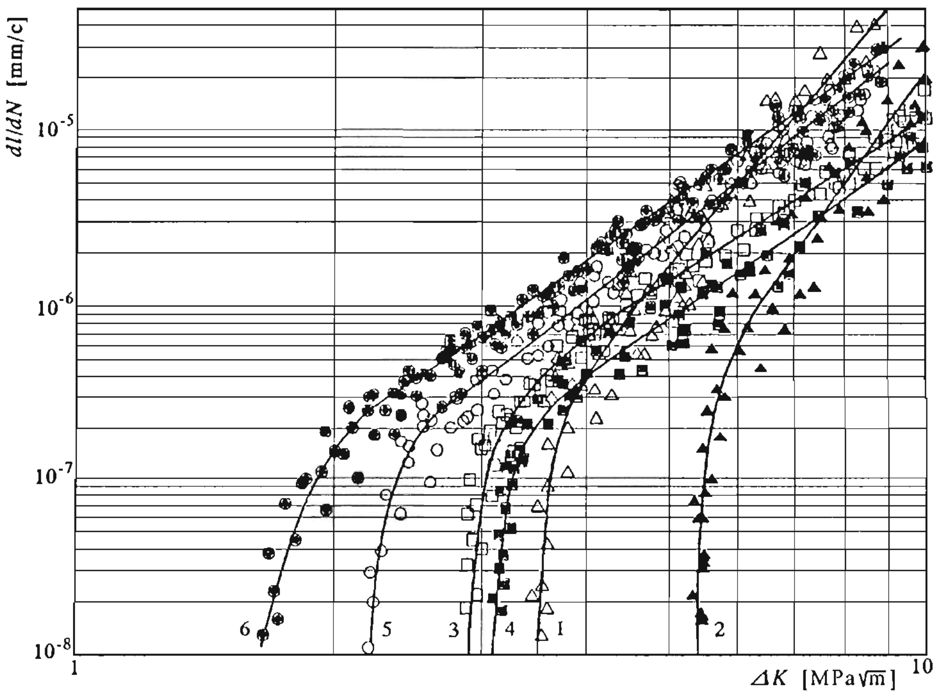

Fig. 4. Fatigue crack growth rate in high-strength steels at $R = 0.7$: 1,3,5 – in the air; 2,4,6 – in the NaCl solution; 1,2 – 15G2ANb; 3,4 – 14HNMBCu-s bainitic structure; 5,6 – 14HNMBCu-s martensitic structure

some influence on the crack growth rate. That is why the values of stress intensity factor K_{th} and its range ΔK_{th} are lower both in the air and in the NaCl solution, which is clearly visible in the martensitic steel. Hence this steel is less sensitive to the influence of corrosive environment.

The tests on the fatigue crack growth rate in the I phase showed that the corrosive environment caused noticeable shifts of the fatigue rate curves:

- in the steel 15G2ANb and the bainitic steel 14HNMBCu-special towards higher values of ΔK
- in the martensitic steel 14HNMBCu-special towards lower values of ΔK.

The shifts are clearly visible at $R = 0.2$ (Fig.3) and less noticeable at $R = 0.7$ (Fig.4). As a result, there was lower crack growth rate observed in the corrosive environment rather than in the air in the I phase of crack growth even by one value order in steel 15G2ANb. The influence of corrosive environment on the steel 14HNMBCu-special depends on its structure and differences between crack growth rates in the air and in the corrosive environment are much smaller, especially at $R = 0.7$.

The rate graphs characterizing the I phase of crack growth show that the curves in the air tend to intersect with the curves in the NaCl solution for both types of steels, especially for the steel 15G2ANb.

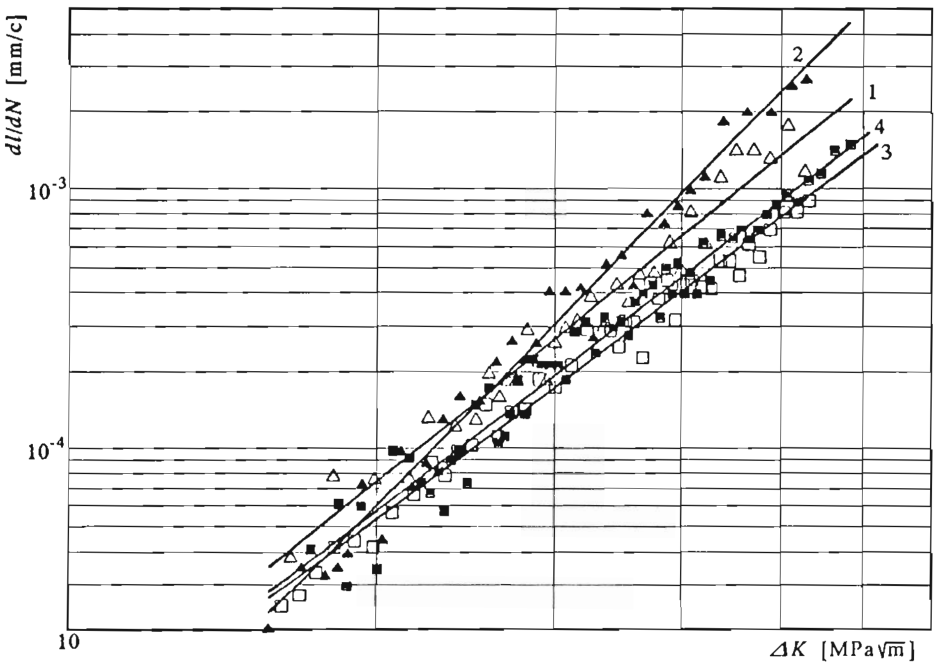

Fig. 5. Fatigue cracking rate at $R = 0.2$ in the II phase of crack growth in steel of high-strength; 15G2ANb steel: 1 – in the air, 2 – in the NaCl solution; 14HNMBCu-special steel with bainitic structure: 3 – in the air, 4 – in the NaCl solution

The conclusions are supported by the rate curves in the II crack growth phase for both steel types, where the intersection of the Paris lines in the air and in the NaCl solution (Fig.5) are easy to see.

When comparing the rate curves in the I phase of crack growth in samples tested in the air (Fig.6) one can note that the increase in the value of R from $R = 0.2 \div 0.7$ shifts the curves towards lower values of ΔK. A similar shift can be observed in 3.5% NaCl solution, as shown in Fig.7.

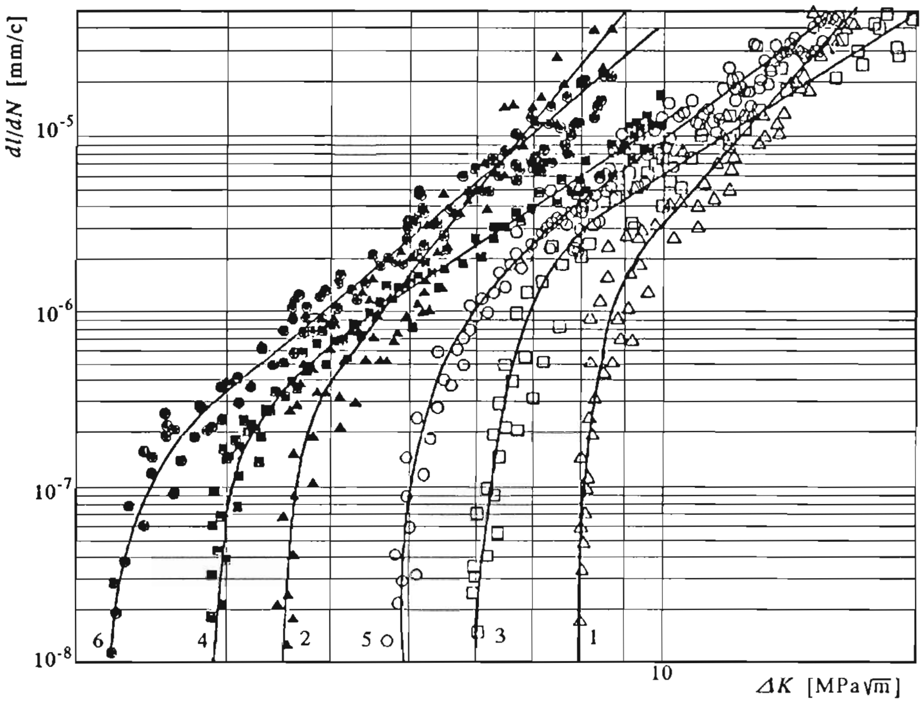

Fig. 6. Fatigue crack growth rate in high-strength steels tested in the air: 1,3,5 – at $R = 0.2$; 2,4,6 – at $R = 0.7$; 1,2 – 15G2ANb; 3,4 – 14HNMBCu-s bainitic structure; 5,6 – 14HNMBCu-s martensitic structure

The shift of rate curves towards smaller values of ΔK in the I phase of crack growth depend also on the steel structure and its plastic properties. Structures more fragile in steels of high strength and low plasticity have lower threshold values ΔK_{th} in the air and ΔK_{thc} in the corrosive environment, respectively.

4. Conclusions

- The steel structure and strength exert an essential influence on the fatigue and corrosive-fatigue crack growth rate in the I phase of crack development.
- In steel of low yield strength with ferrito-perlitic structure, the threshold value of the stress intensity factor K_{thc} is essentially greater in the

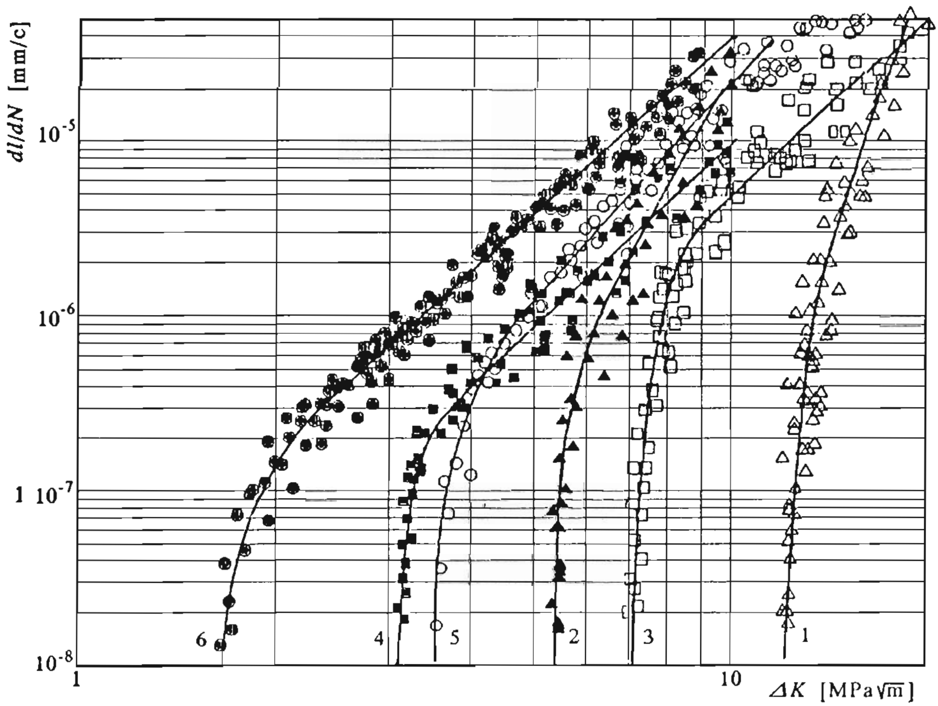

Fig. 7. Fatigue crack growth rate in high-strength steels tested in the NaCl solution: 1,3,5 – at $R = 0.2$; 2,4,6 – at $R = 0.7$; 1,2 – 15G2ANb; 3,4 – 14HNMBCu-s bainitic structure; 5,6 – 14HNMBCu-s martensitic structure

corrosive environment than that observed in the air. In a high-strength martensitic steel an inverse process takes place: the values of K_{thc} and ΔK_{thc} are lower in the 3.5% NaCl solution than the values of K_{th} and ΔK_{th} in the air. In the bainitic steels the corrosive environment affects the threshold values growth only to a slightly higher degree than in air.

- Cracking rate curves in the I phase of fatigue crack growth in steels of low yield strength in the corrosive environment tend to shift towards higher values of the ΔK factor. The cracking rates in NaCl solution are lower by one order of magnitude. In fragile steels the influence of the corrosive environment in the I phase of crack development the process is inverse.

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Wpływ struktury i własności wytrzymałościowych stali na rozwój pęknięć korozyjno-zmęczeniowych w obszarze przyprogowym

Streszczenie

W artykule przedstawiono wyniki badań rozwoju pęknięc zmęczeniowych w powietrzu i korozyjno-zmęczeniowych w 3.5% roztworze NaCl w wodzie destylowanej. Badano stale 15G2ANb o strukturze ferrytyczno-perlitycznej i 14HNMBCu-specjal w dwóch odmianach: o strukturze bainitycznej i martenzytycznej. Badania prowadzono w obszrze przyprogowym przy dwóch współczynnikach asymetrii cyklu $R = 0.2$ i $R = 0.7$. Wyznaczono również wartości graniczne zakresu współczynnika intensywności naprężeń w powietrzu ΔK_{th} i w środowisku korozyjnym ΔK_{thc}.

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