

## STUDY ON CORROSIVE-FATIGUE CRACK GROWTH IN STEELS OF HIGHER STRENGTH <sup>1</sup>

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The paper presents results of a study on a corrosive-fatigue crack growth across material and development of a semi-elliptical surface crack in weldable steels of higher strength and of a ferrite-perlitic structure 15G2ANb and 18G2AV-special. The tests were performed in two environments: in air and in 3.5% NaCl water solution. Changing tensile loadings at a constant amplitude and at cycle asymmetry coefficient  $R = 0.2$  were applied. The results showed a significant influence of the corrosive environment on a crack growth across material. Test performed on the samples with semi-elliptical crack confirmed the influence of the corrosive environment as well as of the loading frequencies and sample widths on the length development of the cracks on the sample surface.

### 1. Introduction

A fatigue crack growth in corrosive environment differs significantly from a similar process in air. In the aggressive environment the actions of mechanical fatigue and corrosion, respectively, though evoked by different conditions, have a joint influence on steel. Hence a combined effect of them is greater than the effect of their separate actions.

In the corrosive environment three main fracture mechanisms appear, which depend on the types of loading and corrosive environment, these being respectively: stress corrosion, fatigue corrosion and stress cracking at hydrogenizing influence of the environment (hydrogen brittleness). In the corrosive-fatigue processes all

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<sup>1</sup>The results of the study were partly presented at the XV-th Symposium on Experimental Engineering of Solid States in Jachranka 08-10 th of Oct., 1992. The title of the report was as follows: "Analysis of the results of research on fatigue crack growth in corrosive environment".

the above mentioned mechanisms may jointly affect the metal. For this reason beside the stress corrosion we should consider various other factors of mechanical fatigue such as cycle asymmetry, cycle shape and especially frequency of loading, which influence the metal fracture. The influence of these factors is limited by the properties of the material itself, the degree of environmental aggressiveness and the type of fatigue loading. The limitation is more significant at higher values of the range of the stress intensity factor  $\Delta K$ .

For  $\Delta K < K_{I_{sc}}$  (the border value of the stress intensity factor in conditions of stress corrosion) the dominant role in fatigue corrosion is played by the corrosive failure. There the environmental aggressiveness and the time of its activity on the material (frequency of loading, and the loading cycle shape) are of most significant influence. While for  $\Delta K > K_{I_{sc}}$  it is the fatigue phenomena that have the basic role to play in the process of fatigue-corrosive failure. Repassivation of the crack surface is the controlling factor in crack development at lower values of  $\Delta K_{sc}$ , an expression denoting the range of the stress intensity factor above which the repassivation does not prevent further fatigue cracking. Generally  $\Delta K_{sc}$  is lower than  $K_{I_{sc}}$ , and it is if it is so a cyclic deterioration of the passive layer progresses in front of the crack.

The value of  $\Delta K_{sc}$  coefficient depends on the chemical composition of the environment as well as on the loading frequency and the shape of the cycle. It was observed that the influence of the corrosive environment increased relative to length of the progressive, positive part of the cycle rather than on the interval of the maximum cycle stress (cf Francis et al., 1975; Vosikovsky, 1975; Salines and Pelloux, 1972). It is noteworthy, however, that speedy repassivation of the uncovered surface leads to immediate regeneration of the passive layer, while too slow repassivation may cause a solution of the lateral surfaces of the crack and the smoother action of the notch. With moderate passivation of the uncovered surface a plastic deformation at the top of the crack appears which hinders repassivation in that part while allowing it to take place on the lateral surfaces. The corrosive cell that results from this situation moves inwards the material.

The plastic deformation in front of the crack facilitates anodic solution of the material.

There are obviously different explanations and descriptions of the mechanism of the growth of corrosive-fatigue cracks. It was observed, for example, that a fatigue crack growth was accelerated under the conditions of cathode protection of the metal, in which the electrochemical corrosion does not occur and in which the determining role is played by hydrogen.

The hydrogen freed by dissociative chemisorption of the clean surface of the metal diffuses in depth and collects at the border of the plastic zone, leading to a concentration of dislocations there and a decrease in bonding energy, which favours the so-called hydrogen brittleness of the material (cf Achter, 1967; Wei,

1970; Salines and Pelloux, 1972; Coretti and Duquetti, 1974).

To the enormous complexity of the problems outlined above, which concern mainly the mechanisms of corrosive-fatigue cracking, we should add the problem of crack growth rate in a corrosive environment. The problem is most often described by the Paris formula, especially when it concerns conditions of laboratory air, and the middle phase of crack development

$$\frac{dl}{dN} = C(\Delta K)^m \quad (1.1)$$

where  $C$  and  $m$  are material constants to be established experimentally, and  $\Delta K$  is the range of stress intensity factor.

In literature there are different formulas that describe a crack growth rate of corrosive-fatigue type, in which the influence of the corrosion and the change of mechanical loading were taken into careful consideration. Among them we should mention the Wei's and Landes' equations, respectively, quoted by Kocańda (1985), Jakubowski and Górski (1978). The researchers formulated (Jakubowski and Górski, 1978) a linear hypothesis of summing crack growth rate of the corrosive-fatigue type

$$\left(\frac{dl}{dN}\right)_{kz} = \left(\frac{dl}{dN}\right)_k + \left(\frac{dl}{dN}\right)_z \quad (1.2)$$

where

- $(dl/dN)_{kz}$  - corrosive-fatigue crack growth rate
- $(dl/dN)_k$  - corrosive-stress crack growth rate component
- $(dl/dN)_z$  - fatigue crack growth rate component under normal condition in air.

Accepting that

$$\frac{dl}{dN} = \int_{\tau} \frac{dl}{dt} dt = \frac{1}{f} \frac{dl}{dt}$$

where the integral is calculated for one cycle, while subintegral function has the following shape

$$\frac{dl}{dt} = F[K(t)]$$

Considering the above the obtain

$$\left(\frac{dl}{dt}\right)_{kz} = \left(\frac{dl}{dt}\right)_k + \left(\frac{dl}{dt}\right)_z f \quad (1.3)$$

where  $f$  is the frequency of a fatigue loading.

Eq (1.3) allows one to consider in calculations the influence of the component functions of time of stress corrosion and of the rate function of mechanical fatigue, respectively, on the corrosive-fatigue crack growth rate. Eq (1.3) describes well the fatigue crack rate of 4340 steel in peroxide water. In other research on the same

steel (see Gallagher and Sinclair, 1969) it was observed that for lower values of the stress intensity factor ( $\Delta K = 6.9 \text{ MN/m}^{3/2}$ ) the most influential role in crack growth was played by the processes included in stress corrosion. The speed  $dl/dt$  expressed as a function of mean stress intensity factor  $K_m$  did not differ much from the speeds of corrosive-stress cracking obtained under static loading expressible as a function of the static stress intensity factor  $K_s$  ( $dl/dt = f(K_s)$ ). It was also found that at higher frequencies,  $f > 1$  Hz, the differences in a crack growth rate in air and water diminish. At frequencies  $f < 1$  Hz the crack growth rate in sea water was almost constant, which means that the corrosive-fatigue processes in such a condition are exclusively dependent on the duration of the environmental action on metal (a condition close to that of stress corrosion). Crooker and Lang (1970) studying high strength steel, reached a conclusion that at frequencies of loading too high or at development of corrosive-fatigue cracking too slow, there are no essential differences between the processes of corrosive-fatigue cracking at higher or lower values of  $K_{Isc}$ , respectively.

As it has already been mentioned the process of corrosive fatigue takes place also at  $K_{max} < K_{Isc}$ . Only a few of materials are resistant to corrosive fatigue at low  $K_{Isc}$ . Most steels, including ship building steels undergo accelerated cracking when exposed to simultaneous action of the corrosive environment and the changing stress. Under such conditions (Barsom, 1971) the most decisive role is played by the frequency of loading change. This conclusion is supported by the parallel runs of  $dl/dN - \Delta K$  at varying frequencies and identical bending as for air.

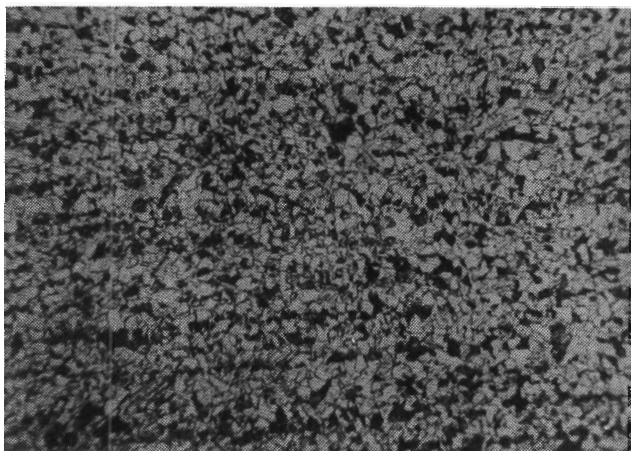
In most foreign and a few Polish publications the bulk of research has been concentrated on the speed of corrosive-fatigue cracking in steel at low frequencies – up to 1 Hz, where the influence of the corrosive environment is ostensibly visible. Ship and oil rig building industries and in general sea engineering are mostly interested in research at such low frequencies. There is less study made on steels used on nation-wide scale in civil engineering on cracking at higher frequencies, say up to 10 Hz. The present research concerns mainly the latter range of frequencies.

## 2. Methods, range and results of the study

This research was based on samples taken from two types of weldable steels of higher strength 15G2ANb and 18G2AV-special (ie. 18G2AV after a thermal improvement). These are fine-grained steels of ferrite-perlitic composition, the 18G2AV-special steel having sorbitic structure, resulting from the thermal improvement.

The structure of the steels are shown in Fig.1.

(a)



(b)

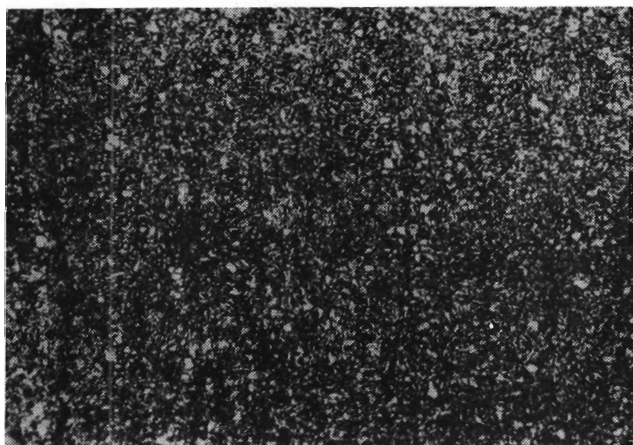


Fig. 1. Structure of steel sheets of samples of  $g = 12$  mm; (a) 15G2ANb steel sample with fine grained ferrite-perlitic composition of  $200 \times$  area; (b) 18G2AV-special steel sample with sorbitic composition of  $200 \times$  area

Table 1 shows the chemical composition of both types of steels and Table 2 shows their mechanical properties.

**Table 1.** Chemical composition in %

Steel	C	Si	Mn	P	S	Cr	Ni	Cu	Nb	V
15G2ANb	0.15	0.40	1.22	0.022	0.02	0.02	0.01	0.01	0.049	0.01
18G2AV-special	0.18	0.27	1.38	0.023	0.01	0.02	0.01	0.04	0.016	0.10

**Table 2.** Basic mechanical properties

Steel	$R_e$ [MPa]	$R_m$ [MPa]	$A_5$ %
15G2ANb	396	537	25.1
18G2AV-special	696	760	17.5

Our study focused on development of corrosive-fatigue across material cracks and semi-elliptic surface cracks.

For testing, samples 10 mm thick and 70 and 120 mm wide were chosen, all of them having been previously polished. The samples were taken from sheets 12 mm thick and cut along the rolling direction. In the samples the central stress concentrators were drilled in form of a whole  $\emptyset = 3$  mm with two notches of joined length  $l = 6$  mm (to test across material cracks) and a semielliptical fissure 0.4 mm long on the surface area  $2c = 15$  mm and 2 mm deep. The stress concentrators were carried out in the plane vertical to the main axis of the samples.

The range of the stress intensity factor for across material cracking was established from the formula

$$\Delta K = \Delta \sigma \sqrt{\pi l M} \quad (2.1)$$

where

$\Delta \sigma = 2\sigma_a$  – stress amplitude

$l$  – half length of crack

$M$  – correction coefficient relative to finite width values of samples.

The coefficient  $M$  was calculated for samples  $w$  – wide according to formula

$$M = 1 - 0.1 \frac{2l}{w} + \left(\frac{2l}{w}\right)^2 \quad (2.2)$$

In the case of semi-elliptical cracks the stress intensity factor  $K$  was calculated for any given direction of semi-elliptical fissure development as reported by Irwin (1962) and Broek (1974)

$$K = \frac{\sigma \sqrt{\pi a}}{I_e} \sqrt{\sin^2 \varphi + \frac{a^2}{c^2} \cos^2 \varphi} M_f M_k \quad (2.3)$$

- where
- $a$  – depth of semi-elliptical crack
  - $c$  – length of semi-elliptical crack on the sample surface
  - $\varphi$  – angle establishing the direction of semi-elliptical crack development ( $\varphi = 0$  on the sample surface)
  - $M_f$  – coefficient of influence of overall stress concentrations in the cracking area and the influence of free surfaces in front of the crack
  - $M$  – correction coefficient of the sample finite dimensions.

For the direction of the semi-elliptical crack growth inwards the sample the coefficients take the values

$$M_f = 1 + 0.12 \left(1 - \frac{a}{c}\right) \quad (2.4)$$

$$M_k = \sqrt{\frac{2g}{\pi a} \tan \frac{\pi a}{2g}}$$

where  $I_e$  is an elliptical integral of II kind dependent exclusively on the crack parameters  $a$  and  $c$

$$I_e = \int_0^{\frac{\pi}{2}} \sqrt{1 - \frac{c^2 - a^2}{c^2} \sin^2 \varphi} d\varphi \quad (2.5)$$

Eq (2.3) shows a noticeable match of the calculated values of the stress intensity factor with data obtained experimentally for the direction of crack growth inwards the sample ( $\varphi = \pi/2$ ). The values, however, may differ for the direction along the sample surface ( $\varphi = 0$ ) from the results obtained in experiments, cf Aboutarbi and Colwing (1968). In the experimental research on semi-elliptical cracks, the range of the factor  $\Delta K$  was calculated for direction  $\varphi = \pi/2$  (inwards the sample) in agreement with Eq (2.3) and considering Eqs (2.4). In Eq (2.3) stress  $\sigma$  has been replaced by expression  $\Delta\sigma = 2\sigma_a$ .

The values  $\Delta K$  for direction  $\varphi = 0$  along the sample surface was calculated on the basis of the crack growth rate  $dc/dN$  describable by the Paris formula

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

where constants  $C$  and  $m$  were experimentally established on the cracks development across of samples the material. The Paris formula was used to describe direction  $\varphi = 0$ , as, in agreement with the data presented by Aboutarbi and Colwing (1968), the equation allows one to establish the real values of the factor  $\Delta K$ . Eq (2.3) used for this purposes gave higher values of this parameter.

The study on the fatigue crack growth was carried out in air and in a corrosive environment of 3.5% solution of NaCl. Various levels of changing tensile stress

loading at constant amplitude were applied as well as various levels of stress, of asymmetry coefficient  $R = 0.2$  and frequencies  $f = 8.33$  Hz and  $f = 4.17$  Hz.

The length of crack was measured on the surface of the sample by means of an optical method, microscopes magnifying  $25\times$  (with precision of up to  $0.05$  mm). The measurement was taken during fatigue loading. In the samples with semi-elliptical cracks, the length,  $2c$  of the cracks was additionally measured on the surface of the sample as well as its depth  $a$  on blown up photographs of the cross section of the samples. For this purpose the trace obtained on the surface of the fracture by a short-lived lowering of the amplitude of the stress, at various stages of the crack development was used for further measurements. Fig.2 shows random photos of fractures of samples of 18G2AV-spec. steel.

(a)



(b)



Fig. 2. Traces of crack front on the surface of the sample fracture of 18G2AV-special steel;  $\sigma = 150 \pm 100$  MPa: (a) test in air, (b) test in 3.5% NaCl water solution

To calculate the curves of cracking increase for both types of steel studied in air and in 3.5% NaCl solution a polynomial of 5th grade was suggested

$$l = \sum_{i=0}^5 A_i N^i \quad (2.6)$$

where

$l$  – half length of crack

$N$  – number of fatigue loading cycles

$A_i$  – constants established experimentally ( $i = 0 \div 5$ ).

On the basis of the obtained experimental values of the crack growth, the rate of fatigue cracking  $dl/dN$  was calculated from the Paris formula. The results of the calculations were presented graphically in Fig.3 through Fig.13.



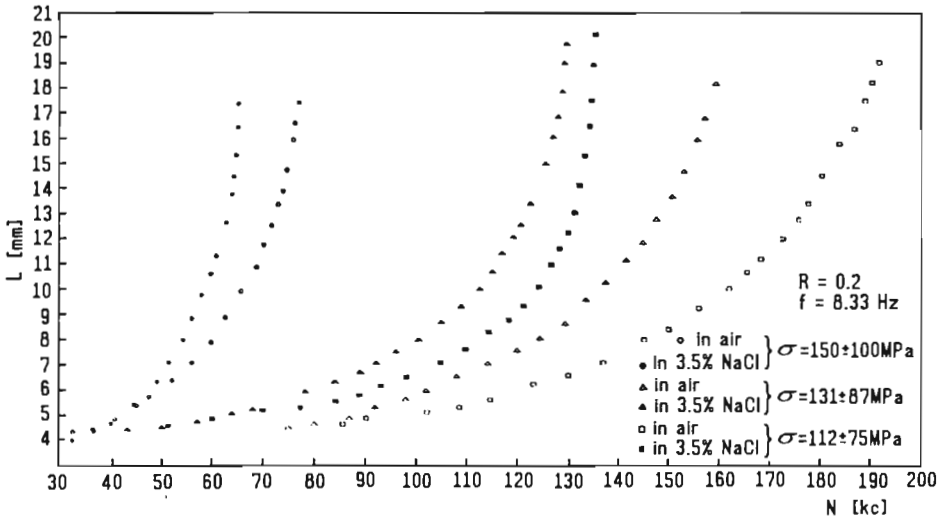


Fig. 3. Crack growth in 15G2ANb steel at  $R = 0.2$ ,  $f = 8.33$  Hz (research data)

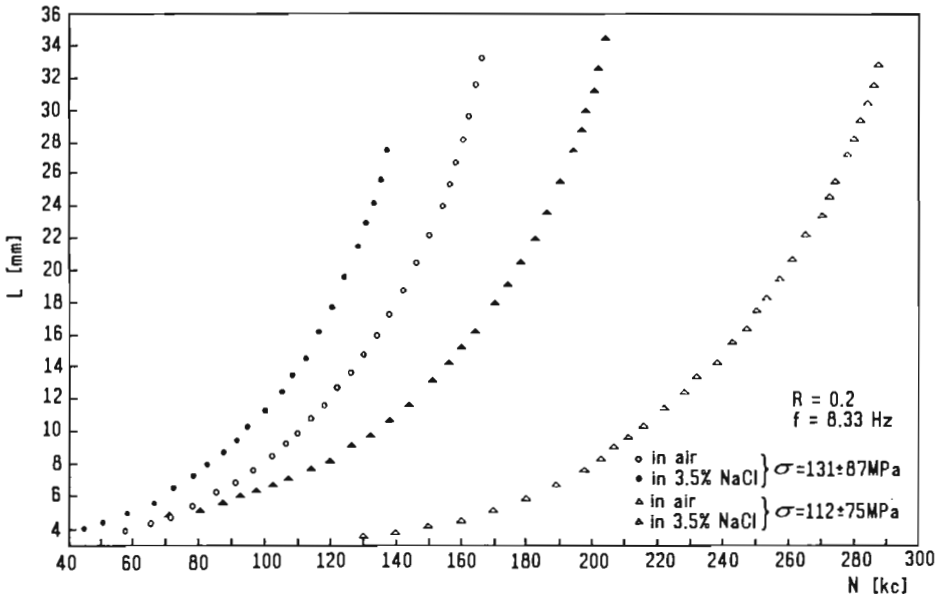


Fig. 4. Crack growth in 18G2AV-special steel at  $R = 0.2$ ,  $f = 8.33$  Hz (research data)

### 3. Discussion on results and conclusions

The results of measurements of the across material cracks in the samples showed that their development in 3.5% solution of NaCl is different that in air (Fig.3 and 4).

The polynomial of 5th degree used in describing the curves of crack growth (formula (2.6)) showed a great degree of compatibility with the values calculated for any of the tested sample.

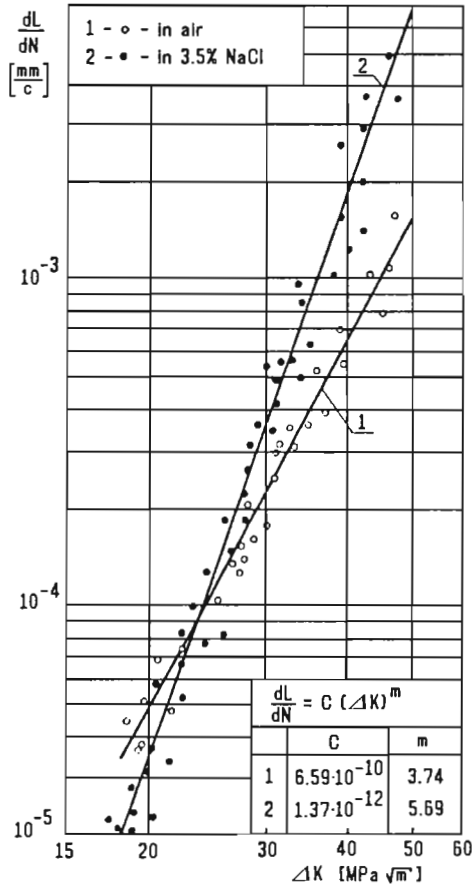


Fig. 5. Crack growth rate in 15G2ANb steel at  $\sigma = 112 \pm 75$  MPa ( $R = 0.2$ ),  
 $f = 8.33$  Hz

The corrosive environment showed a significant influence on the crack growth rate. The fatigue crack growth rate of the 15G2ANb steel in 3.5% solution of NaCl at stress  $\sigma = 112 \pm 75$  MPa ( $R = 0.2$ ) at the initial stage of crack development (at low values of  $\Delta K < 24$  MPa/m) was lower than in air (Fig.5).

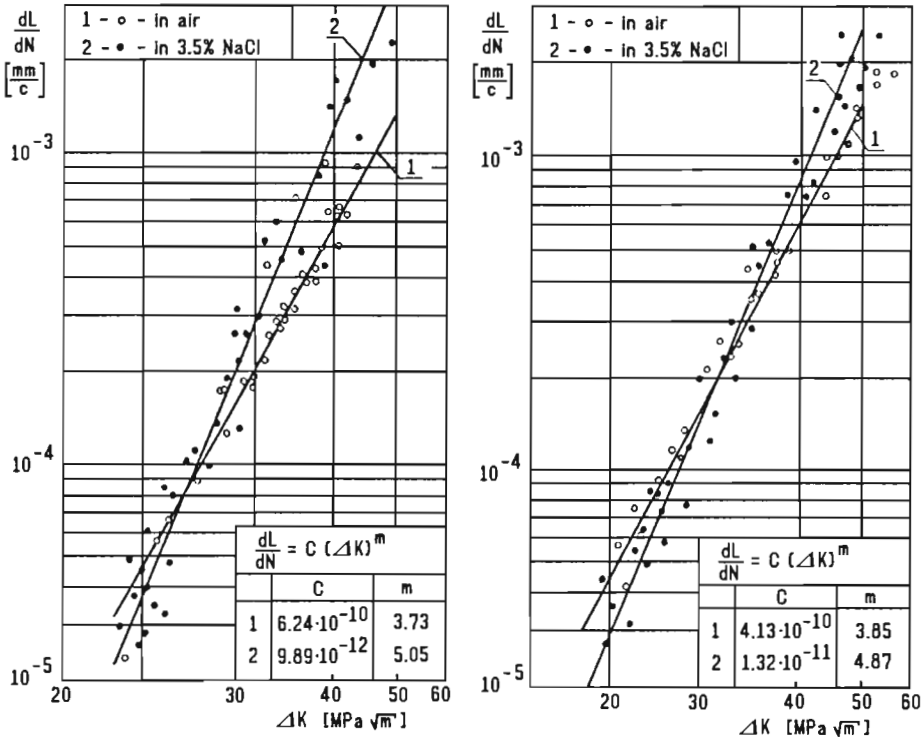


Fig. 6. Crack growth rate in 15G2ANb steel at  $R = 0.2$ ,  $f = 8.33$  Hz:  
 (a)  $\sigma = 131 \pm 87$  MPa, (b)  $\sigma = 150 \pm 100$  MPa

Later, however, at higher values of  $\Delta K$ , the crack growth rate was higher. The regularity was verified at various levels of fatigue stress both for steel 15G2ANb (Fig.6) and 18G2AV-special (Fig.7).

The crack growth rate in 18G2AV-special steel is slower than in 15G2ANb steel (the lesser angle of Paris line) and this was observed both in air and in NaCl solution. This fact is definitely due to the sorbitic structure of that type of steel, which is more resistant to cracking, especially in the corrosive environment, than the ferrite-perlite structure of 15G2ANb steel. Hence the influence of the corrosive environment on the crack growth rate of 18G2AV-special is much lower than in 15G2ANb. The obtained experimental results are in good agreement with those presented by Romaniv (1986) and Nikiforchin (1988). Table 3 shows a comparison of the crack growth rate and the crack growth rate increases of the respective steels in 3.5% solution of NaCl.

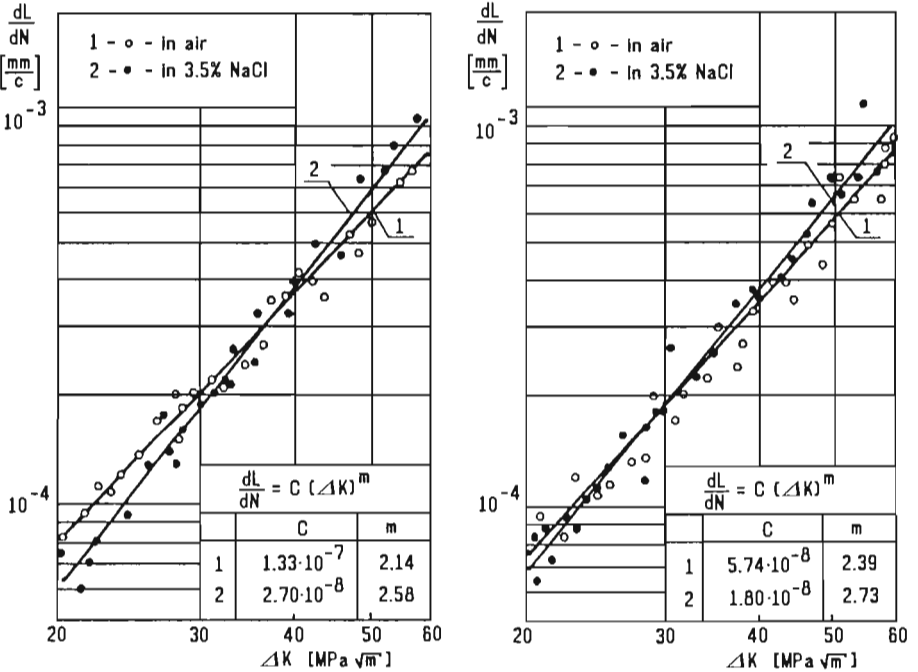


Fig. 7. Crack growth rate in 18G2AV-special steel at  $f = 8.33$  Hz: (a)  $\sigma = 112 \pm 75$  MPa ( $R = 0.2$ ), (b)  $\sigma = 131 \pm 87$  MPa ( $R = 0.2$ )

**Table 3.** Crack growth rate calculated from Paris formula and crack growth rate increase in the corrosive environment (in  $mm/c \cdot 10^{-4}$ ) at  $\sigma = 112 \pm 75$  MPa ( $R = 0.2$ ),  $f = 8.33$  Hz

Steel	$\Delta K$ [ $MPa\sqrt{m}$ ]	20	30	40	50	60
15G2ANb	in 3.5% NaCl	0.346	3.48	17.90	63.7	-
	in air	0.484	2.20	6.47	14.9	-
	$\Delta$	-0.138	+1.28	+11.43	+48.8	-
	$\Delta$ [%]	-28.5	+58.2	+176.7	+327.5	-
18G2AV-special	in 3.5% NaCl	0.614	1.75	3.67	6.53	10.45
	in air	0.809	1.93	3.57	5.57	8.49
	$\Delta$	-0.195	-0.18	+0.10	+0.78	+1.96
	$\Delta$ [%]	-24.1	-9.3	+2.8	+13.6	+22.5

The results of a study on larger samples at frequencies 4.17 and 8.33 Hz presented by the authors of this paper as well as of earlier studies (cf Bachmacz et al., 1986, 1991 and 1992) show that the speed of corrosive fatigue crack growth rate is significantly dependent on the value of  $\Delta K$ . With lower values of  $\Delta K$ , the fatigue crack growth rate is slower than in air. The angle of Paris line  $(dl/dN)_{kor}$

is greater than  $(dl/dN)_{pow}$ . In view of these factors a modification two-member formula of Wei and Lasndes was proposed

$$\left(\frac{dl}{dN}\right)_{kor} = C(\Delta K)^m + \sum_{i=0}^4 D_i(\Delta K)^i \quad (3.1)$$

In the formula two expressions were identified: the expression describing the crack growth rate in air and the expression describing the crack growth rate increase caused by the corrosive environment. The formula describes the crack growth rate in the corrosive environment  $(dl/dN)_{kor}$  as a sum of the crack growth rate in air (described by the Paris formula) and the crack growth rate increase in the corrosive environment (described by the polynomial of 4th degree). Constants  $C$  and  $m$  in the test in air as well as constants  $D_i$  ( $i = 0 \div 4$ ) for the crack growth rate increase in the corrosive environment were established experimentally.

Table 4 gives an instantiation of the constants  $C$ ,  $m$  and  $D_i$  for both steels under study at stress  $\sigma = 112 \pm 75$  MPa ( $R = 0.2$ ) and  $f = 8.33$  Hz.

**Table 4.** Values of constants  $C$ ,  $m$  and  $D_i$  in formula (3.1) for steel 18G2AV-special and 15G2ANb studied in air and in 3.5% NaCl water solution at  $\sigma = 112 + 75$  MPa ( $R = 0.2$ ) and  $f = 8.33$  Hz

	15G2ANb	18G2AV-special
$C$	$6.6 \cdot 10^{-10}$	$1.3 \cdot 10^{-7}$
$m$	3.74	2.14
$D_0$	$4.1 \cdot 10^{-3}$	$-1.5 \cdot 10^{-5}$
$A_1$	$-5.8 \cdot 10^{-4}$	$1.6 \cdot 10^{-6}$
$A_2$	$3.1 \cdot 10^{-5}$	$-1.7 \cdot 10^{-7}$
$A_3$	$-7.6 \cdot 10^{-7}$	$4.3 \cdot 10^{-9}$
$A_4$	$7.6 \cdot 10^{-9}$	$-1.5 \cdot 10^{-11}$

Crack growth rates calculated from Eq (3.1) show a very good compatibility with experimental data at a specified level of the fatigue stress.

After the correction coefficient  $B$  had been introduced into the formula (3.1), just before the expression describing the crack growth rate increase in the corrosive environment, the equation could be used to calculate the crack growth rate in the corrosive environment at different levels of stress that the one at which the constants  $C$ ,  $m$  and  $D_i$  were determined. The following form of the coefficient  $B$  was proposed

$$B = \frac{\sigma_{maxe}}{\sigma_{max}} \frac{\sigma_{ae}}{\sigma_a} \left(\frac{\sigma_{me}}{\sigma_m}\right)^2$$

where

$\sigma_{maxe}$  - maximum stress

$\sigma_{me}$  - average (mean) stress

$\sigma_{ae}$  - stress amplitude at which the constants  $C$ ,  $m$  and  $D_i$  were established.

Considering above the formula takes the following shape

$$\left(\frac{dl}{dN}\right)_{kor} = C(\Delta K)^m + B \sum_{i=0}^4 D_i(\Delta K)^i \quad (3.2)$$

The basis for calculations of Eq (3.2) for a given level of stress  $\sigma = \sigma_m \pm \sigma_a$  are the constants  $C$ ,  $m$ ,  $D_i$ , established at another level of the fatigue stress  $\sigma_e = \sigma_{me} \pm \sigma_{ae}$ . The crack growth rate of the tested steels in 3.5% NaCl solution at  $\sigma = 131 \pm 87$  MPa ( $R = 0.2$ ) and  $f = 8.33$  Hz calculated from Eq (3.2) are shown in Table 5.

**Table 5.** Crack growth rate of 18G2AV-special and 15G2ANb steels in 3.5% NaCl solution at  $\sigma = 131 \pm 87$  MPa ( $R = 0.2$ ),  $f = 8.33$  Hz (in mm/c  $\cdot 10^{-4}$ ). The constants  $C$ ,  $m$  and  $D_i$  are established at  $\sigma = 112 \pm 75$  MPa ( $R = 0.2$ ),  $f = 8.33$  Hz. (See Table 4.)

Steel	$\Delta K$ [MPa $\sqrt{m}$ ]	20	30	40	50
15G2ANb	from Eq (3.2)	0.398	2.88	12.60	41.21
	research data	0.386	2.85	12.18	37.58
18G2AV-special	from Eq (3.2)	0.707	1.83	3.62	6.17
	research data	0.691	1.85	3.75	6.46

The crack growth rates of the steels under study in the corrosive environment calculated after the formula (3.2) agree with the experimental results.

A study on development of surface semi-elliptical cracks showed that the increase of the cracks on the sample's surface is greater in the corrosive environment NaCl than in air. This is true about both types of steel 18G2AV-special and 15G2ANb (Fig.8).

The curves of length increase of the cracks on the surface of the sample were expressed as a function of the relative depth of the crack  $2c = f(a/g)$  and they were approximated to the exponential function as in Fig.9

$$2c = \alpha \left(\frac{a}{g}\right)^\beta + \eta \quad (3.3)$$

where  $\alpha$ ,  $\beta$ ,  $\eta$  - constants established experimentally.

The cracking length increase on the sample surface  $2c$  was dependent to a significant degree on the frequency of fatigue loading (Fig.10).

An decrease of frequency from 8.33 Hz to 4.17 Hz in the case of 15G2ANb steel tested in 3.5% NaCl solution caused almost a double increase in the crack length  $2c$ . This fact was obviously due to the longer period of corrosive influence and an easier access of the corrosive environment to the sample surface.

The experimental results showed a noticeable influence of the width of the sample on the length increase of semi-elliptical cracks  $2c$ . The change in widths of the samples made of 18G2AV-special steel from 120 mm into 70 mm induced a

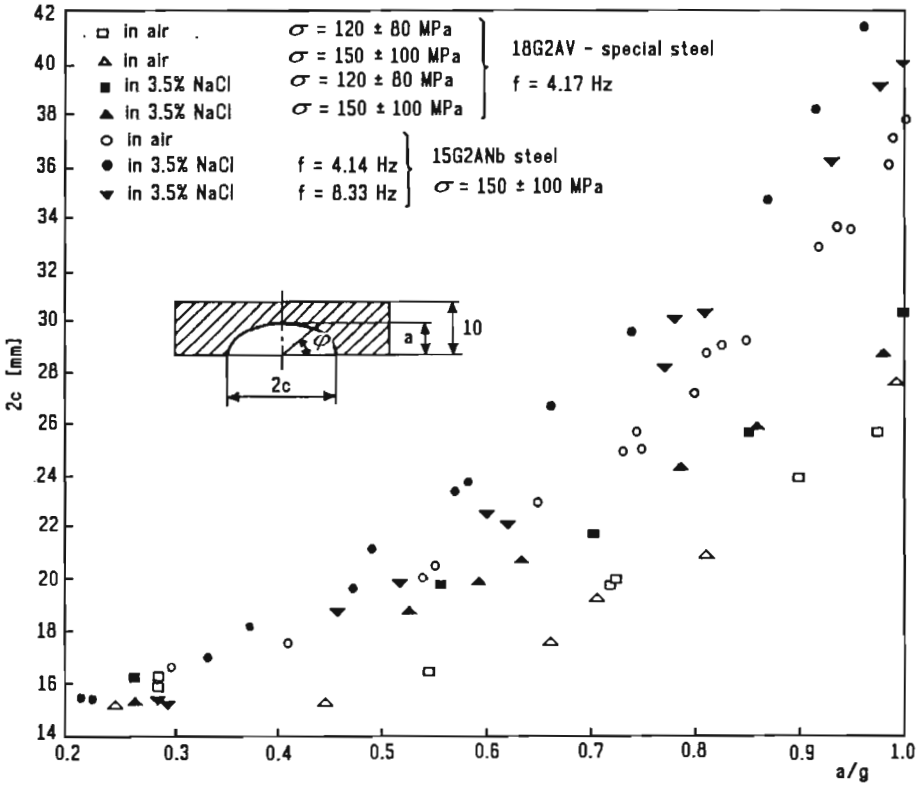


Fig. 8. Crack growth on the surface of semi-elliptical cracks (research data)

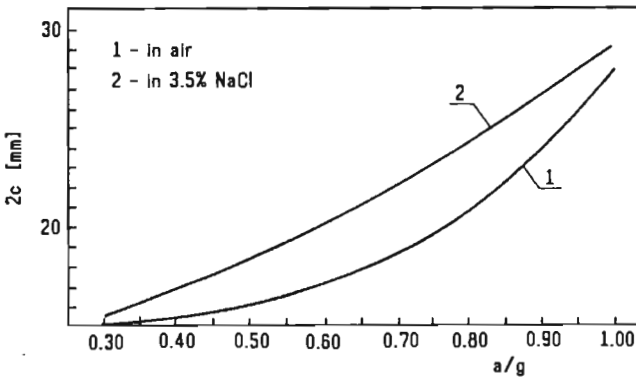


Fig. 9. Crack growth on the surface (semi-elliptical cracks); 18G2AV-special steel,  $\sigma = 150 \pm 100$  MPa,  $f = 4.17$  Hz

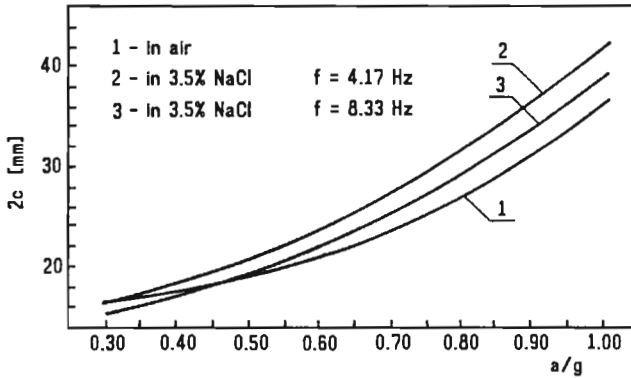


Fig. 10. Crack growth on the surface (semi-elliptical cracks) at  $\sigma = 150 \pm 100$  MPa ( $R = 0.2$ )

significant increase in the length of the crack on the surface of the sample. There is almost no observable influence of the corrosive environment on the development of the crack (Fig.11).

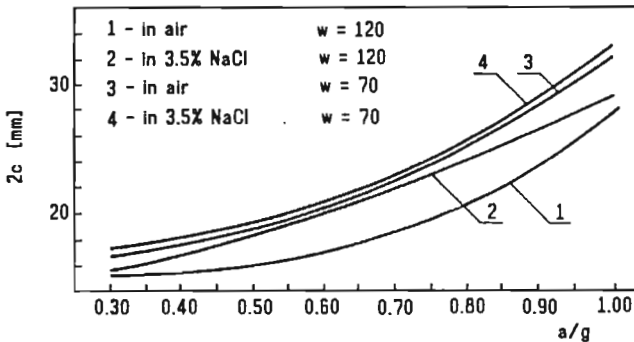


Fig. 11. Crack growth on the surface (semi-elliptical cracks); 18G2AV-special steel,  $\sigma = 150 \pm 100$  MPa,  $f = 4.17$  Hz, specimen widths: 120 mm and 70 mm

The cause is a strong action of the sides of the cracks in the narrow samples on the stress fields nearby the fatigue fissure. As the result the role of the mechanical factors begins to grow in explanation of the development of corrosive-fatigue cracks.

The development speed of semi-elliptical cracks expressed as a function of relative depth of the crack (Fig.12) seems to become pronouncably higher in the corrosive environment and develops both in the direction along the surface of the sample ( $\varphi = 0$ ) and in the direction inwards the sample ( $\varphi = \pi/2$ ).

The influence of the corrosive environment on the crack growth rate is linked with the stage of the crack development. It increases progressively with  $a/g$ . Noticeably a greater increase in the cracks development was observed on the surface



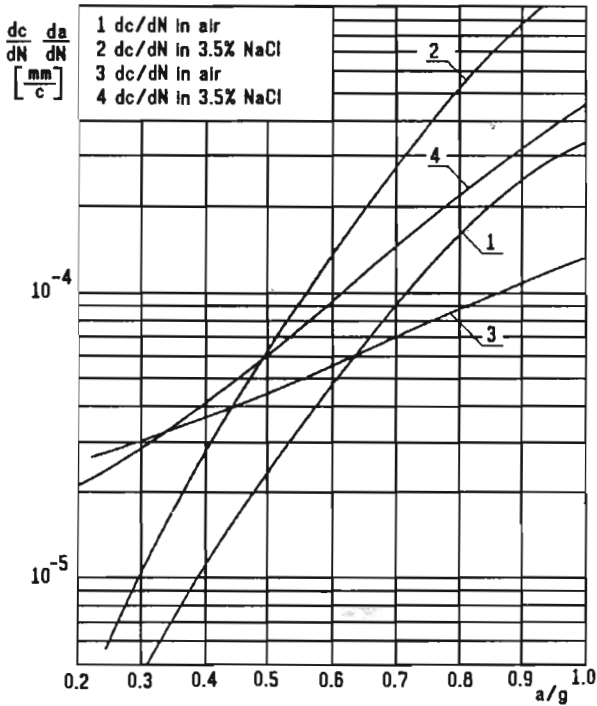


Fig. 12. Crack growth rate in the directions  $\varphi = 0$  and  $\varphi = \pi/2$  (semi-elliptical cracks) as a function  $a/g$ ; 15G2ANb steel,  $\sigma = 150 \pm 100$  MPa,  $f = 8.33$  Hz

of the sample rather than in its inside and this holds true both for a study in air and in the NaCl solution. It could be explained by a strong action of the back surface to the front of the crack head and its influence on the propagation of the fatigue fissure inside the material. Significant concentration of stresses (very high values of  $K$ ) at the crack front in the direction ( $\varphi = \pi/2$ ) causes a pronounceable growth of the zone of plastic deformation, which hinders the development of the crack.

The crack growth rate along the surface of the sample and into the material expressed as a function of  $\Delta K$  (Fig.13) shows the same regularity as the cracking rates across the sample, i.e. those taking place at applied values of  $\Delta K$ : they are lower in 3.5% NaCl solutions than in air and they are higher at higher values of  $\Delta K$ , Fig.13. The crack growth rates for direction  $\varphi = 0$  as well as for direction  $\varphi = \pi/2$  can be described by the same two-member equation (3.1).

On the basis of the foregoing analysis one can reach conclusions given below.

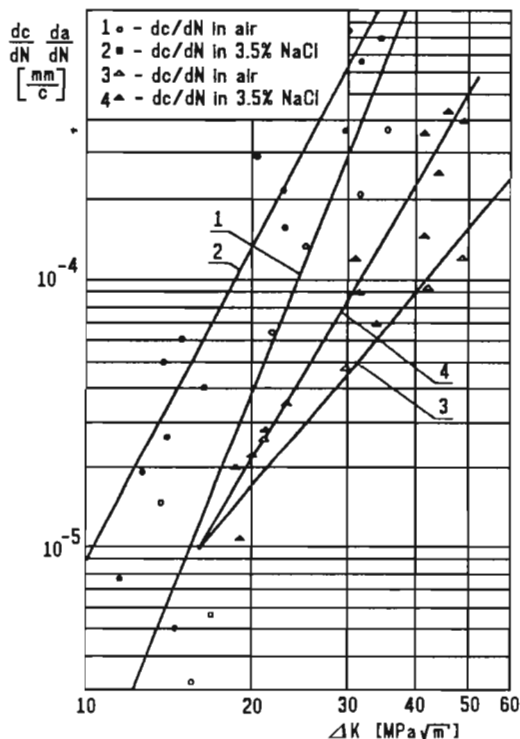


Fig. 13. Crack growth rate in the directions  $\varphi = 0$  and  $\varphi = \pi/2$  (semi-elliptical cracks) as a function of  $\Delta K$ ; 15G2ANb steel,  $\sigma = 150 \pm 100$  MPa,  $f = 8.33$  Hz

- The rate of fatigue crack growth across the samples tested in 3.5% NaCl water solution is lesser than in air at the initial stage of crack growth development (at low values of  $\Delta K$ ) and greater in further phases of crack development (at higher values of  $\Delta K$ ).
- The fatigue crack growth rate of tested steels in the corrosive environment can be described in terms of two-member equation, in which the former expression describes the crack growth rate for the natural environment (air) by means of the Paris formula and the latter describes the crack growth rate increase in the corrosive environment calculable by means of the polynomial of 4th degree.
- The length increase of semi-elliptical surface cracks in the steels tested for the direction along the surface of the sample is greater in the corrosive environment than in air.

- The influence of the corrosive environment on semi-elliptical crack growth decreases with increase of the loading frequencies and decrease of the samples widths.

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### **Badania korozyjno-zmęczeniowego pęknięcia w stalach o podwyższonej wytrzymałości**

#### **Streszczenie**

W pracy przedstawiono wyniki badań rozwoju zmęczeniowych pęknięć na wskroś i powierzchniowych półeliptycznych w próbkach ze stali o podwyższonej wytrzymałości o strukturze ferrytyczno-perlitycznej: 15G2ANb i 18G2AV-specjal. Badania przeprowadzono w środowisku powietrza i w 3.5% roztworze wodnym NaCl. Zastosowano zmienne obciążenia rozciągające o stałej amplitudzie i współczynniku asymetrii cyklu  $R = 0.2$ . Wyniki badań wykazały istotny wpływ środowiska korozyjnego na rozwój pęknięć. Do opisu prędkości pęknięcia w środowisku korozyjnym zaproponowano dwuczłonowy wzór, w którym pierwszy człon opisuje prędkość w środowisku obojętnym (wg wzoru Parisa), a drugi – przyrost prędkości pęknięcia w środowisku korozyjnym (wielomian 4-go stopnia). Zależność ta wykazała dobrą zgodność z wynikami doświadczenia dla obu gatunków stali przy różnych poziomach naprężenia zmęczeniowego. Badania pęknięć półeliptycznych potwierdziły wpływ środowiska korozyjnego, częstotliwości i szerokości próbek na rozwój pęknięć półeliptycznych na powierzchni próbki.

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