CORROSIVE-FATIGUE CRACK GROWTH RATE IN 15G2ANb STEEL

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The paper presents the results of research into fatigue and corrosive cracking in flat samples made of ferritic-perlitic 15G2ANb steel. The tests were performed under tensile fatigue loading at constant loading amplitude in two environments: in air and in 3.5% NaCl solution in distilled water. The crack growth across material (notch inside the sample) was also considered. The research was also aimed at a study on the second stage of crack development a threshold-close area at the value approaching K_{th}. The results show considerable influence of the corrosive environment on the fatigue crack growth rate, especially within the threshold close area. No influence of the samples thicknesses on the crack development was observed, however.

1. Introduction

Ferritic-perlitic steel of the 15G2ANb type is widely used in industry, especially in ship building. A description of its resistance, especially resistance to fatigue and to fatigue together with corrosion exposure, was possible due to the research conducted out in the 70-ties and 80-ties within the central programmes, e.g. in 02.1, 08.12, 6.6, the results of which were published (cf Kubera (1975), Jakubowski and Górski (1978), Bachmacz (1979) and (1985), Bachmacz et al. (1977), (1984) ÷ (1987), (1990) and (1992)).

The aim of this research is very detailed analysis of the fatigue – corrosive properties of this steel, especially:

– Influence of its thickness on the rate of steel cracking

- Cracking rate value within the threshold close area, for values of the stress intensity factor close to the K_{th} value.

This two problems have never been studied in regard to the 15G2ANb steel.

In view of the general principles of cracking mechanics, an increase in the thickness of the sample should result in faster fatigue cracking, due to a transition from the plane stress-state to the plane strain-state. There are however, numerous reports in literature, quoted also by Kocańda (1985), negating the presence of the above regularity. The author of the aforementioned monograph claims that the thickness influence depends not only on the stress state but also on the type of sample material as well as on its flexibility to plastic deformations. The 15G2ANb steel reveals very suitable plastic properties and for this reason it is difficult to estimate a priori a change in the crack growth rate brought about by a change in the sample thickness. An investigation into this subject is expected to have practical implications.

When conducting research into fatigue-corrosive crack growth rate in steels of higher strength (SHS), the authors of the present contribution have always obtained an intersection of graphs showing the crack growth rate in air and in the corrosive NaCl environment (cf Bachmacz et al. (1977), (1985), (1986), (1992) and (1993), Bachmacz (1985)). This meant that at low values of ΔK, crack growth in the corrosive environment is slower than in air. Jakubowski and Górski (1978), Bachmacz et al. (1993) showed that the diagrams of the second stage of fatigue crack growth rate in the air and in the corrosive environment here parallel lines. This observation has made the authors of this study undertake research into a crack growth rate within the threshold close area.

It is worth noticing that in majority of publications on the fatigue-corrosive crack growth rate study the second stage of crack development is studied and it is described by the Paris formula.

For constructional elements working at high-cycle fatigue it is more important to know the mechanism of fatigue cracking within the so-called threshold area, in the vicinity at the boundary value of the stress intensity factor ΔK_{th} (or the K_{th} value), below which the crack does not develop. And this conclusion holds true both for cracking in air as well as in a corrosive environment. It is the time of this I-stage, on which the resistance of the constructional elements mostly depends, which is why scientists have focused on this problem in recent years (cf Romaniv et al. (1983) and (1985), Mirakawa et al. (1983), Kawai (1982), Stewart (1980), Nikiforchin (1988), Mayaki and King (1990)).

2. Material and method of research

The samples were cut out from steel sheets 24 mm thick. All of them were cut along the rolling direction. According to the metallurgical attestation the mechanical properties and the chemical composition of sample steel are given in Table 1.

Table 1. Mechanical properties and chemical composition of the 15G2ANb steel (in %)

R_e [MPa]			R_m [MPa]				A_5 [%]		
375			510				30		
C	P	Mn	S	Cu	Si	Cr	Ni	Al	Nb
0.10	0.018	1.24	0.017	0.02	0.50	0.01	0.01	0.04	0.054

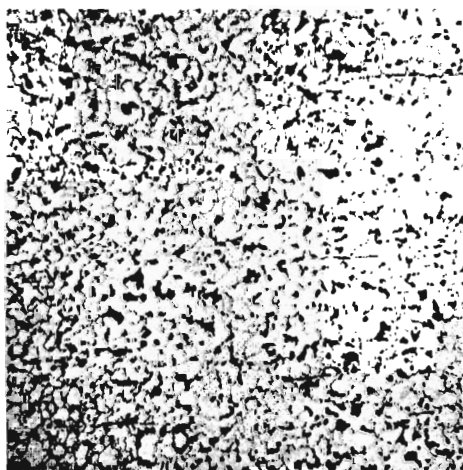Figure 1 is an illustration of the ferritic-perlitic structure of steel.

Fig. 1. Structure of 15G2ANb steel (microsection etched with nitale), magnification ×350

The samples used to test the effect of their thickness were taken from a sheet of $g = 24$ mm thicknessand the desired thicknesses were obtained by planing and grinding off a layer of 1 mm from one side of the samples and by planing and grinding the other side to achieve 21 mm, 12 mm, 6.5 mm in thickness, respectively. A symmetric notch was made in the middle of each sample, 3 mm in diameter, together with two lateral incisions. Samples of various thicknesses were obtained from one iron sheet 24 mm thick, which

guaranteed a uniform structure of the short series. At the final stage a thin layer of metal was planed off while the samples were being cooled down with a liquid. This procedure decreased residual stresses to a minimum and secured their uniform value and distribution in all sample series.

The crack growth rate across the metal within the threshold area was tested on samples 21 mm thick and 100 mm wide. The fatigue crack growth rate was examined both in the air and in the 3.5% NaCl distilled water solution.

The NaCl solution was flowing through out a chamber mounted on the sample which was to undergo the fatigue loading. The flow input of the fluid was 10^{-2} dcm^3/s and its acidity varied from $pH = 6.85 \div 6.94$. The tests were carried out at changing tensile loading, the amplitude of which was constant and the cycle asymmetry coefficient $R = 0.2$ and frequencies $f = 4.17$ Hz.

The fatigue crack growth was measured on the surface of the samples by means of a microscope of magnification ×25 with a reading precision of up to 0.02 mm.

3.   Discussion

Tests on the corrosive-fatigue crack growth across the metal carried out on flat samples showed that an increase of the fatigue cracking in the 3.5% NaCl water solution at its initial stage was lower than in air. It was higher, however, at the final stage of crack growth. This observation was supported by tests conducted on the samples of all thicknesses under study (see Fig.2), respectively and at all levels of the fatigue loading applied.

The growth rate of cracking across the metal in 3.5% water solution was lower at its initial stage than the corresponding process in the air. At the final stage, however, the rate was apparently higher (see Fig.3) in the corrosive environment.

The crack growth rate dl/dN in the basic II phase ($dl/dN = 5 \cdot 10^{-5} \div 2 \cdot 10^{-3}$ mm/c) was described by the Paris formula for both environments

$$\frac{dl}{dN} = C(\Delta K)^m \tag{3.1}$$

where
  C, m –   constants established experimentally
  ΔK –   range of stress intensity factor.
The intersection points of the Paris runs for tests in the air and in the NaCl solution existed despite the changed thicknesses of samples. The samples
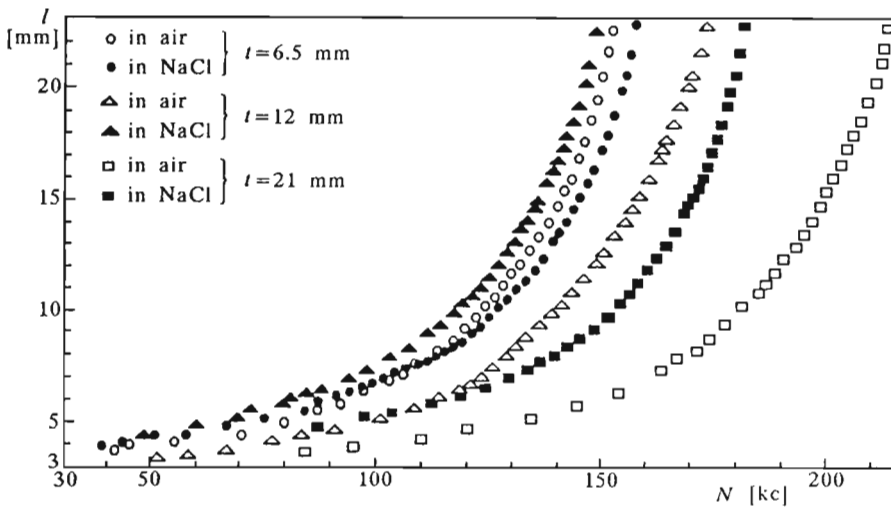
Fig. 2. Increase of fatigue cracking in 15G2ANb steel: the results of measurements;
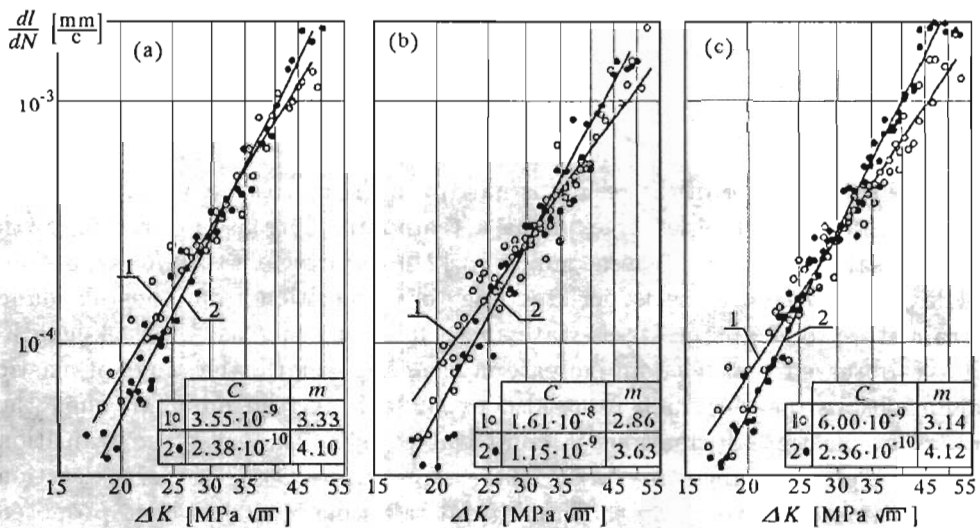$\sigma = 112 \pm 75$ MPa, $R = 0.2$, $f = 4.17$ Hz

Fig. 3. Growth rate of fatigue cracking in 15G2ANb steel in samples with the
following cross-section: (a) – 6.5 mm, (b) – 12 mm, (c) – 21 mm;
$\sigma = 112 \pm 75$ MPa, $R = 0.2$, $f = 4.17$ Hz; 1 – in air, 2 – in NaCl

thicknesses did not also influence essentially the growth rate of fatigue cracking
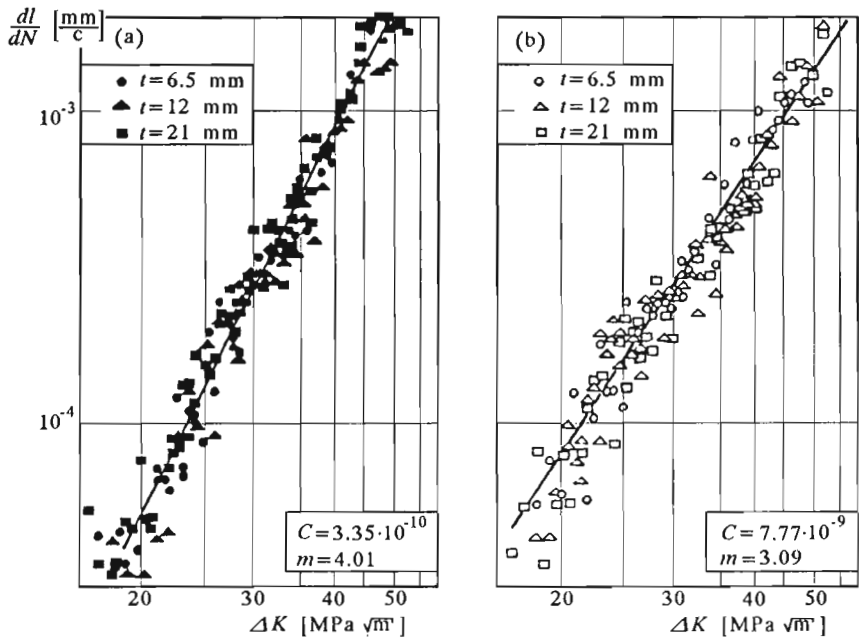in 15G2ANb steel in tests done either in the air or in the NaCl solution (Fig.4).

Fig. 4. Distribution of results of research into crack growth rate in 15G2ANb
samples of varying thickness in 3.5% NaCl water solution (a) and in air (b);
$\sigma = 112 \pm 75$ MPa, $R = 0.2$, $f = 4.17$ Hz

The scatter band of the results is narrow in the corrosive environment and
wider in the air. The latter explains a temporary decrease in crack growth
in thin samples, $t = 6.5$ mm and $t = 12$ mm, present at $\Delta K \sim 25 \div 30$
MPa$\sqrt{m}$. This decrease is perhaps due to a transition from the the plane
strain-state to the plane stress-state and a following increase of crack length.
It was observed that with an increase in the crack length, the range of plastic
deformations on the crack front also expanded. At the moment when the
range of plastic deformations is comparable to its thickness the transition
from the plane strain-state to the plane stress-state (along the crack section
of the samples in front) on the crack front takes place. It has been proposed
in the present study that the range of plastic deformation on the crack front
can be calculated upon measurements of the deformed area on the fatigue
fracture front. The deformation (caving) area on the sample surface is the
area of plastic deformations on the crack front. Measurements of this area
were taken by means of a profilographer. Fig.5 shows the measurement results

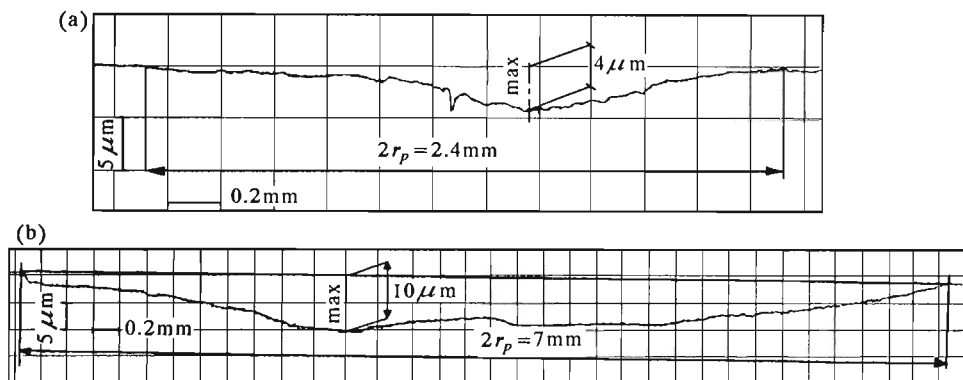of the deformation area on the crack front in the direction vertical to the crack growth rate direction.

Fig. 5. Area of plastic deformations on the crack front in a 15G2ANb sample of $t = 12$ mm in air at $R = 0.2$, $\sigma_{max} = 187$ MPa; (a) – $l = 7.5$ mm, (b) – $l = 15$ mm

The measurement of the caving area on the sample surface, resulting from the test, should be interpreted as a two-fold value of the radius of the area along the direction normal to the direction of fatigue fracture propagation. It is worth noting that the zone of plastic deformations established experimentally was larger than the one established theoretically by Irwin cited by Kocańda (1985). Below there is a comparsion of the radius of experimental plastic deformations and the one calculated theoretically for given thicknesses:

$l = 7.5$ mm $r_p = 1.2$ mm (experiment) $r_p = 0.68$ mm (calculation)
$l = 15$ mm $r_p = 3.5$ mm (experiment) $r_p = 2.21$ mm (calculation)

A long term study on the fatigue crack growth rate at low levels of stress within the threshold areas allowed to determine the threshold stress intensity factor K_{th} for the 15G2ANb steel. The values were reached by a step by step lowering the stress level till the rates of approx 10^{-8} mm/c were obtained. This rate is generally accepted in literature, also by Kocańda (1985), as the one corresponding to the K_{th} value. The cycle asymetry coefficient was $R = 0.2$.

The rebuts of these tests are shown in Table 2.

Table 2

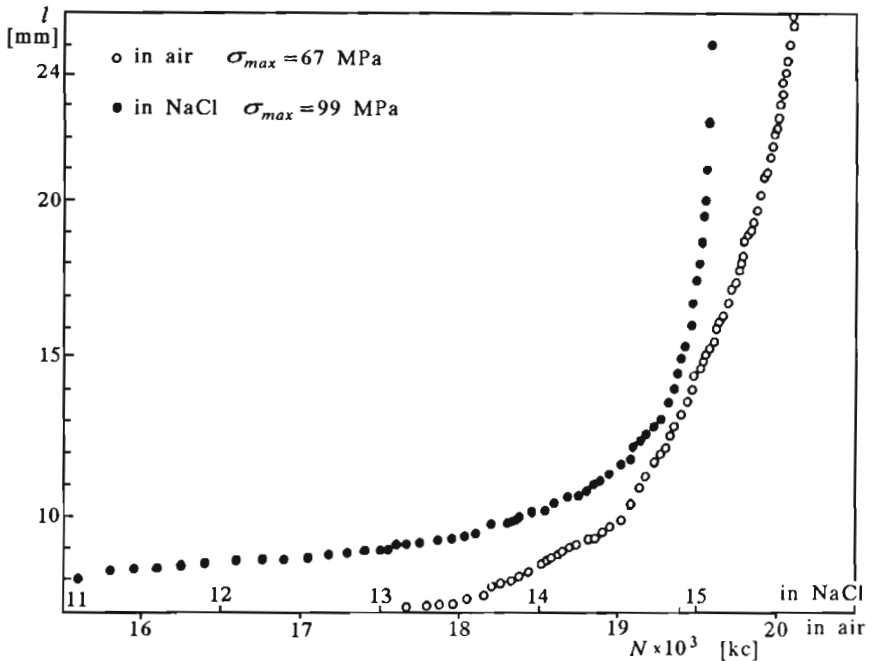| Test	$\sigma_{\max}$ [MPa]	ΔN [kc]	l [mm]	K_{th} MPa$\sqrt{m}$	ΔK_{th} MPa$\sqrt{m}$
in air	66	10400	7.10 7.18	9.91	7.93
in NaCl	95	11100	7.92 8.02	15.10	12.08

Fig. 6. Threshold values of stress intensity factor and crack growth rate within the threshold close areas (at low stress level); in 15G2ANb steel, $R = 0.2$, $f = 4.17$ Hz

It is possible to draw the following conclusion from the above results. The value of K_{th} in the corrosive environment, that is, in 3.5% NaCl solution is higher 1.5 times that the one in the air.

This means that steel resistance to the fatigue cracking in the 15G2ANb steel at low values of K at the I stage of crack development is higher in the corrosive environment than in the air.

The fatigue crack growth within the threshold close zones is a very complicated process, indeed. The literature points to a important role played by the material structure (cf Mayaki and King (1990)), even more important at

in the II stage of cracking than described by the Paris formula.

One of the major factors infuencing the growth rate at the I stage of cracking is a process of fatigue fracture closing (cf Elber (1970), Romaniv et al. (1983), Mirakawa et al. (1983)). The fracture sides (surfaces) come close to each other at certain moments of the positive periods of a fatigue cycle. At further deloading compressing stresses appear which change the stress distribution in the vivinity of the fracture front. The closing mechanism may be also evoked by plastic deformations of the fracture sides or by the presence of oxides on their surfaces. Surface roughness may also play a certain role, especially when analysing sides deformations the II model of growth rate.

The closing mechanism, in which the presence of oxides is considered is extremely effective in explaining small crack growths within the near-threshold areas, especially when their openings are insignificant and the thickness of the oxide layer is comparable to the openings width. Cracking will start growing only when a stress is applied sufficient to cause openinig. Crack closing lowers the range of stress intensity factor ΔK to the effective value of ΔK_{eff}. The closing effect is usually referred to as the fracture opening coefficient.

$$U = \frac{K_{max} - K_{op}}{K_{max} - K_{min}} = \frac{\Delta K_{eff}}{\Delta K} \qquad (3.2)$$

where

K_{max}, K_{min} — maximum and minimum values of stress intensity factor, respectively

K_{op} — level of K coefficient at which the crack stays open.

Measuring the opening coefficient U is a task both complicated and energy consuming. Some methods have been reported by Romaniv et al. (1983), Kawai (1982). The closing phenomenon depends, among other factors, also on the cycle asymmetry coefficient R, and it diminishes with the latter increase. It should be noted, however, that crack closing lowering ΔK_{eff} (at unchanged value of ΔK_{max}) results in an increase in the effective cycle asymmetry coefficient R_{eff}. Crack closing is a property characteristic of plastic steels, in which the yield strength R_e is rather low, though it may also be present in high-strength steels.

Fatigue crack growth in the near-threshold zones is even more complicated in the corrosive environment. An extensive survey of literature on this topic can be found in the works by Romaniv et al. (1985) and Nikiforchin (1988). Also there are the reports about the process of crack closing. The corrosive environment regulary increases ΔK_{op}, compared with the air environment, due to the intensive formation of corrosive products, which close the crack. The closing effect is greatest at low values of ΔK, which is due to its small

opening, as well as to slow rate of it growth, which favours formation of a
thick layer of oxides (cf Stewart (1980)). The frequency of load changing as
well as the structure of material play an essential role in the whole mechanism
as well. The corrosive environment causes anodic dissolution of the crack tip,
which enlarges the radius notch curvature at its top and relaxes the stress.
Diminishing the stress intensity factor on one hand and increasing the distance
between the fracture sides, in weakens the closing effect and lowers ΔK_{op} on
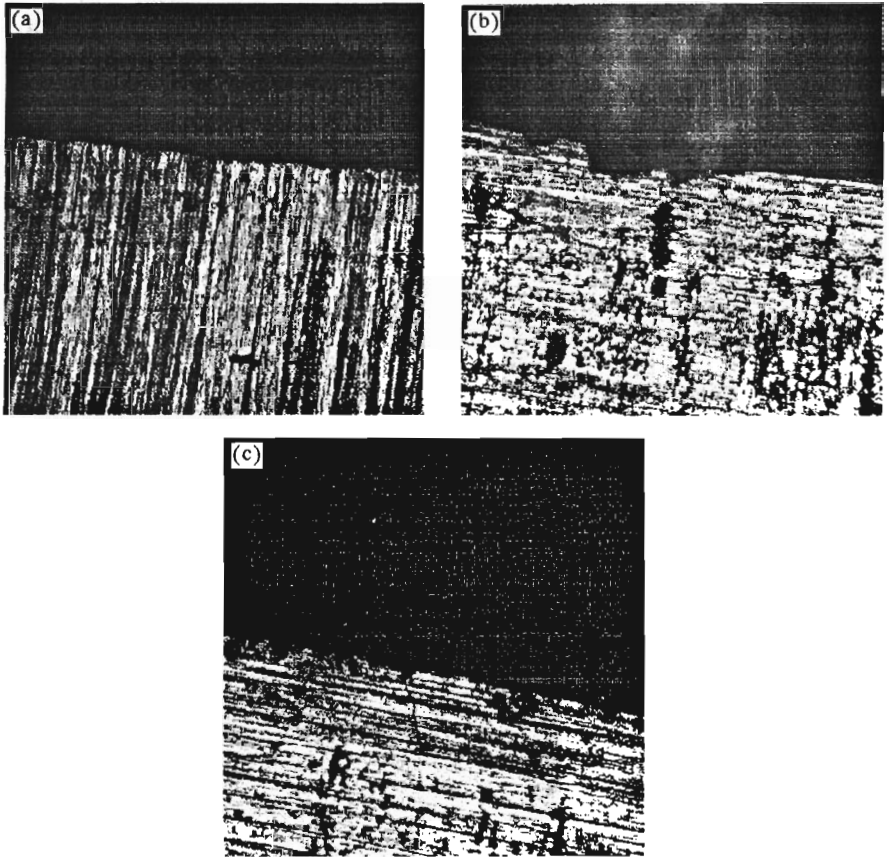the other.

Fig. 7. Side of fatigue fracture in 15G2ANb steel 21 mm thick tested at $R = 0.2$ in
the near-threshold value of ΔK factor; (a) – in air, (b) and (c) – in 3.5% NaCl
solution; magnification $\times 100$ (noticeable surface roughness, corrosive cells and the
microcrack developed from the direction of the main crack)

In the air environment the fracture side is smooth, while in the corrosive
environment it is rough, which is due to the presence of multiple corrosive cells

on the sample surface and multiple branching of the main crack (see Fig.7). This also explains the lower fatigue crack growth rate within the near-threshold areas.

Hydriding of the steel just in front of the fracture head speeds up its propagation in high-strength material. The process is slowed down in plastic steels of low yield strength, which is explained by the change of the cracking mechanism from brittle to plastic one.

The total influence of all factors causes an the corrosive-fatigue crack growth rate increase within the near-threshold areas in steel of high strength and a decrease of the respective process in plastic steels, relative to the air environment, as reported by Nikiforchin (1988).

If we accept, as reported by Nikiforchin (1988) and Romaniv et al. (1984) that for a steel, carbon content and yield strength R_e of why is close to that of the 15G2ANb, a linear change of the value $U = 0.8 \div 1.0$ in the air and $0.6 \div 1.0$ in the corrosive environment (3.5% NaCl solution) for $\Delta K = 5 \div 25$ MPa$\sqrt{m}$ appears. Fig.8 shows graphs of the fatigue speed growth rates in the 15G2ANb steel in $(\Delta K_{eff}, dl/dN)$ unit of axes with the change of U value included.

The results show that diagrams of growth rate versus ΔK_{eff} are shifted towards smaller values of ΔK and tend approaching the respective threshold values.

The results of the fatigue crack growth rate measured at varying levels of stress create one stream. This holds true for the tests in the air and in the 3.5% NaCl solution (see Fig.9).

The curvelinear part of the graphs showing the crack growth was described by means of the equation quoted by Kocańda (1985)

$$\frac{dl}{dN} = \frac{4A}{\pi R_e E}(\Delta K^2 - \Delta K_{th}^2) \qquad (3.3)$$

where

R_e —   yield strength of the material
E —   elastic modulus of the material
A —   constant determined experimentally.

The linear line part of the graph (the one for higher values of fatigue growth) was described by the Paris formula.
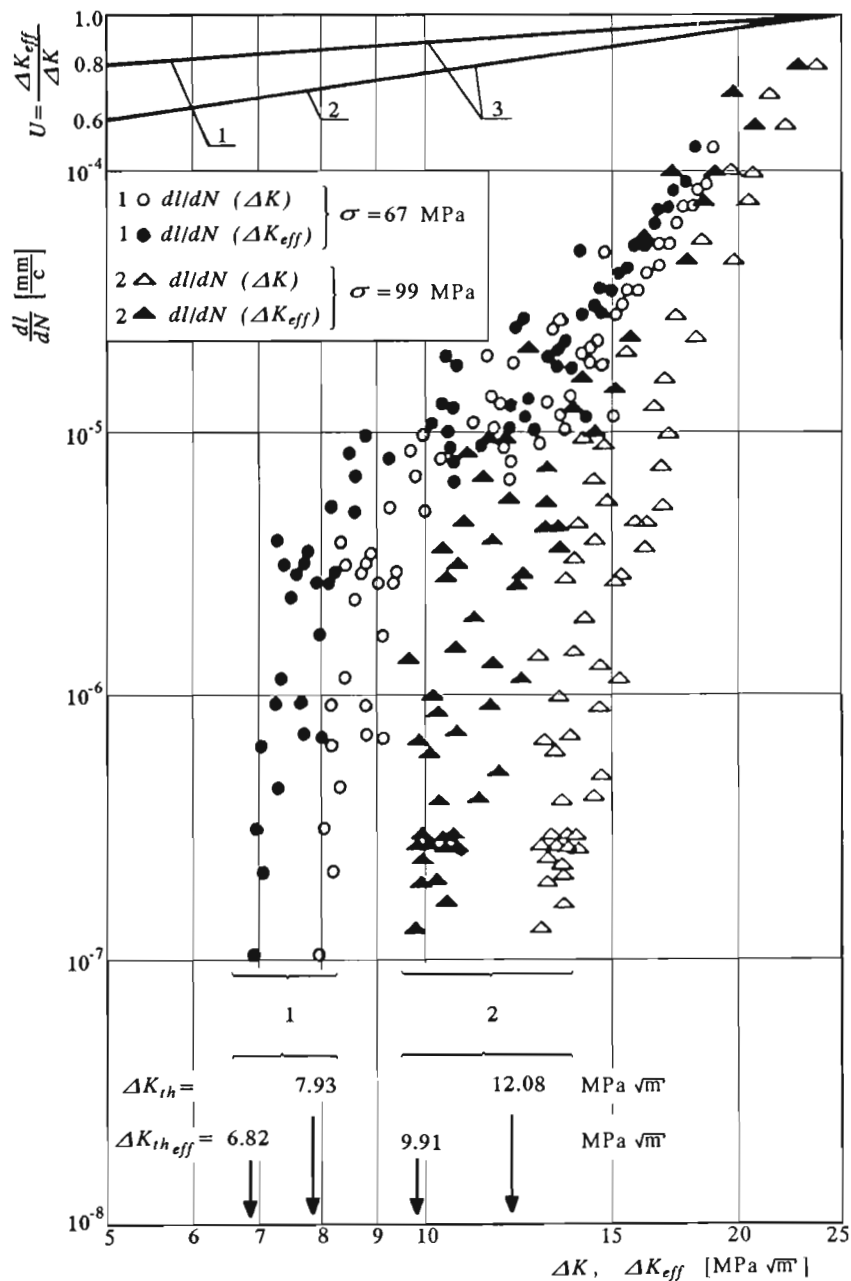
Fig. 8. Fatigue crack growth rate in 15G2ANb steel within the near-threshold area;
$R = 0.2$, $f = 4.17$ Hz; 1 – in air, 2 – in NaCl, 3 – according to Mirakawa
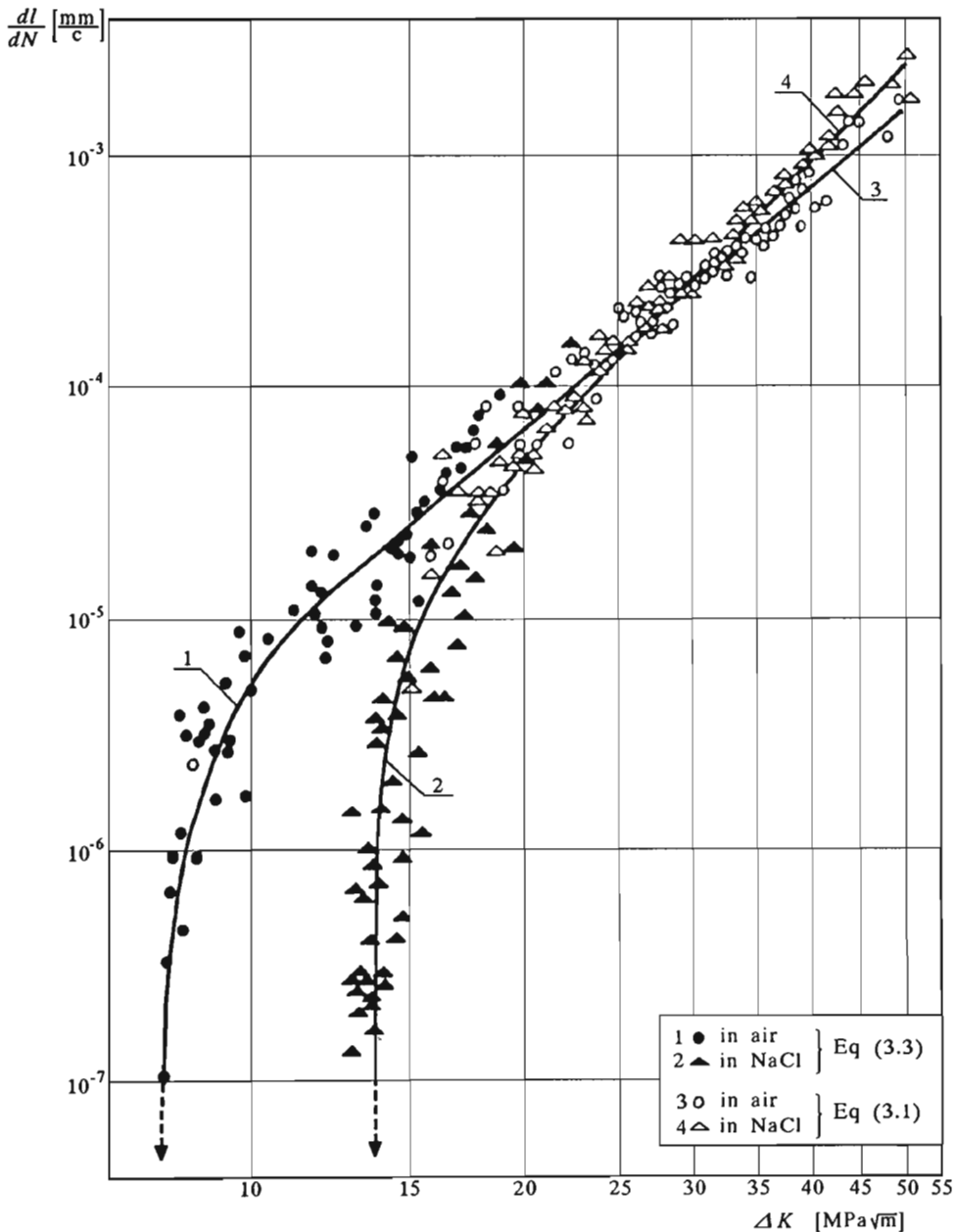et al. (1983), Kawai (1982)

Fig. 9. Fatigue crack growth rate in 15G2ANb steel measured at varying stress
levels at cycle asymmetry coefficient $R = 0.2$, $f = 4.17$ Hz;
$1 - \sigma_{max} = 67$ MPa, $A = 9.274$, $\Delta K_{th} = 7.93$ MPa, $R_e = 375$ MPa,
$E = 2.1 \cdot 10^5$ MPa; $2 - \sigma_{max} = 99$ MPa, $A = 15.512$, $\Delta K_{th_c} = 13.88$ MPa,
$R_e = 375$ MPa, $E = 2.1 \cdot 10^5$ MPa; $3 - \sigma_{max} = 187$ MPa, $C = 2.119 \cdot 10^{-9}$,
$m = 3.423$, $4 - \sigma_{max} = 187$ MPa, $C = 2.303 \cdot 10^{-10}$, $m = 4.113$

4. Conclusions

1. Corrosive-fatigue crack growth rate in the 15G2ANb steel within the threshold close area is higher in the 3.5 % NaCl solution than in the air. This is due to decrease of stress level at the fracture head by the corrosive environment and intensive closing action in the crack resulting in formation of corrosive cells in the fatigue fractures.

2. The threshold value of the stress intensity factor ΔK_{th} is higher in NaCl solution than the ΔK_{th} in the air approx 1.5 times.

3. Crack closing causes a shift of the fatigue crack growth curve within the threshold close area towards lower values of ΔK_{eff} in the $(\Delta K_{eff}, dl/dN)$ unit of axes both in the corrosive NaCl environment and in the air.

4. In the II stage of fatigue crack growth starting with the value of ΔK equal approx 30 MPa$\sqrt{m}$ described by the Paris formula, the NaCl environment fatigue crack growth rate increases in the 15G2ANb steel relative to the air environment.

5. A change in thickness of the 15G2ANb sheet within $6.5 \div 21$ mm made no difference in changing the fatigue crack growth rating both in the air and in the 3.5% NaCl water solution.

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Prędkość rozwoju pęknięć korozyjno-zmęczeniowych w stali 15G2ANb

Streszczenie

W pracy przedstawiono wyniki badań korozyjno-zmęczeniowych w próbkach płaskich wykonanych ze stali ferrytyczno-perlitycznej gatunku 15G2ANb. Badania przeprowadzono przy obciążeniu zmęczeniowym rozciągającym o stałej amplitudzie obciążenia w dwóch środowiskach: w powietrzu i w 3.5% roztworze NaCl w wodzie destylowanej. Zbadano rozwój pęknięć przechodzących na wskroś (karb w środku próbki). Badania wykonano dla drugiego etapu wzrostu pęknięcia oraz w obszarze przyprogowym, bliskim wartości K_{th}. Wyniki badań wykazały zauważalny wpływ środowiska korozyjnego na prędkość zmęczeniowego pękania, zwłaszcza w obszarze przyprogowym. Nie stwierdzono natomiast wpływu grubości próbek na rozwój pęknięć zmęczeniowych.