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EFFECT OF OVERLOADS ON THE FATIGUE CRACK GROWTH IN METALS

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Key words: fatigue crack growth, overloads, Wheeler's retardation model.

Abstract

The paper presents singularities of the fatigue crack growth for selected materials and different load conditions. The results of empirical tests in the form of $a = f(N)$ and $da/dN = f(\Delta K)$ curves were analyzed. Consequently, a modification of the Wheeler's retardation model of fatigue crack growth was proposed and the qualities of the modified model were presented. The modifications improve the description of the crack growth empirical data, in particular for higher overload values. The issues discussed in the paper give sufficient grounds for improving the accuracy of qualitative and quantitative analyses of the fatigue life of specimens and construction elements.

WPŁYW PRZECIĄŻEŃ NA ROZWÓJ PĘKNIĘĆ ZMĘCZENIOWYCH W METALACH I JEGO OPIS

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Słowa kluczowe: rozwój pęknięć zmęczeniowych, przeciążenia, model opóźnień Wheelera.

Streszczenie

Przedstawiono osobliwości rozwoju pęknięć zmęczeniowych w wybranych materiałach i różnych warunkach obciążenia. Analizie poddano wyniki badań doświadczalnych w postaci krzywych $a = f(N)$ i $da/dN = f(\Delta K)$. Zaproponowano modyfikację modelu opóźnień rozwoju pęknięć zmęczeniowych Wheelera i przedstawiono właściwości zmodyfikowanego modelu. Modyfikacje poprawiają opis danych doświadczalnych rozwoju pęknięć, szczególnie przy wyższych wartościach przeciążeń. Omawiane zagadnienia dają podstawy do poprawy dokładności analiz jakościowych i ilościowych trwałości zmęczeniowej próbek i elementów konstrukcji.

Introduction

It is commonly acknowledged that the fatigue tests under a constant amplitude load do not represent the service load sequence very well. In relation to the fatigue crack growth under variable load conditions, the term "load interaction effects" (also referred to as "load sequence effects" and "load history") is used for describing the phenomenon in which the crack growth in a given load cycle is different from the growth in a constant amplitude cycle at the same stress intensity range. The occurrence of a single overload cycle in a basic load spectrum generates the crack growth delay effect. The crack propagation rate da/dN induced by this overload cycle undergoes a change depending on the load parameters. Under special conditions the crack growth rate can decrease by a few orders of magnitude, or even can be stopped when the stresses differ significantly from the threshold ones.

From the engineering point of view, the problems encountered in the crack propagation rate analyses are related to, among other, with a selection of a proper calculation model which successfully represents geometric, load and material conditions of the question analyzed. Unfortunately, testing of such effects is difficult, time-consuming and expensive. The fatigue crack growth delay models result from a compromise in this field.

The fatigue crack growth delay models can be grouped according to different criteria. An obvious requirement for such models is their ability to estimate the variable amplitude test results with a satisfactory accuracy. Preferably, the influence of the change of load, material or geometric parameters on the fatigue behavior of a propagating crack should be estimated quantitatively. Different properties of the relationships $a = f(N)$ and $da/dN = f(\Delta K)$ make their homogenous, theoretical description difficult and sometimes they even prevent the application of the available, simple mathematical models.

Singularities of fatigue crack growth

Below there are results of the fatigue crack propagation tests conducted on specimens of *(Compact Tension)* type, made of PA7 duralumin, and of *SEN* (*Single Edge Notch*) type, made of 18G2A steel, under constant amplitude load conditions (of the $F_{min} - F_{max}$ range) with cyclic (every DN cycles) overloads characterized by a constant overload coefficient $k_{ov} = F_{ov}/F_{max}$, and examples of their model description (KŁYSZ 1998, KŁYSZ 2000, KŁYSZ 2001).

During the tests, the number of the given load cycles N as well as the size of the crack opening displacement (*COD*) were recorded. The size of *COD* was than converted into the propagating crack length a according to the compliance method.

The crack growth rate was described using the Paris relationship (*Paris, Erdogan* 1963):

$$\frac{da}{dN} = C \cdot (\Delta K)^m .$$

Stress intensity factor range ΔK, which includes load, material and geometric factors, determines the relationship (*Stress Intensity Factors Handbook* 1987):

– for specimen $CC(T)$:

$$\Delta K = \frac{\Delta F}{B \cdot \sqrt{W}} \cdot \frac{2+\alpha}{(1-\alpha)^{1.5}} \cdot \left(0.886 + 4.64 \cdot \alpha - 13.32 \cdot \alpha^2 + 14.72 \cdot \alpha^3 - 5.6 \cdot \alpha^4\right)$$

or

$$\Delta K = \frac{\Delta F}{B\sqrt{W}} \sqrt{\sec\left(\frac{\pi a}{2W}\right)}$$

– for specimen $SEN(T)$:

$$\Delta K = \frac{\Delta F}{B\sqrt{W}} \left(1.12 - 0.231\frac{a}{W} + 10.55\left(\frac{a}{W}\right)^2 - 21.72\left(\frac{a}{W}\right)^3 + 30.39\left(\frac{a}{W}\right)^4\right)$$

and the compliance function used for the crack length calculation has the form of (Polák 1991):

– for specimen $CC(T)$:

$$\frac{a}{W} = 1 - 4.0632u + 11.242u^2 - 106.04u^3 + 464.33u^4 - 1650.68u^5$$

– for specimen $SEN(T)$:

$$\frac{a}{W} = 1 - 4.0632u + 11.242u^2 - 106.04u^3 + 464.33u^4 - 1650.68u^5$$

where u denotes compliance, $u = \dfrac{1}{1 + \left(\dfrac{E \cdot B \cdot COD}{F}\right)^{0.5}}$,

B, W – thickness and width of the specimen,
$\alpha = a/W$ – dimensionless crack length,
ΔF – load range $F_{\max} - F_{\min}$,
E – Young's modulus,
COD – Crack Opening Displacement.

In the Wheeler's retardation model of fatigue crack growth, the retardation coefficient C_p was introduced into the propagation equation $da/dN = f(\Delta K)$. The coefficient has the following form (WHEELER 1970, WHEELER 1972):

$$C_p = \left(\frac{r_{p,i}}{a_{ov} + r_{p,ov} - a_i} \right)^n$$

where:

$r_{p,i}$, $r_{p,ov}$ – radiuses of plastic zones, for current cycle and overload cycle,
a_i, a_{ov} – crack length, in current and overload cycles, respectively,
n – exponent of the Wheeler's model.

The range of its application (i.e. the reduction of crack growth rate generated by an adequate change of load level) is defined with the following condition: $a_i + r_{p,i} <= a_{ov} + r_{p,ov}$. According to this model, the delay occurs as long as the plastic zone $r_{p,i}$ connected with a propagating crack (i.e. in a current load cycle) remains within the plastic zone $r_{p,ov}$ induced by the overload preceding a given cycle. With the constant amplitude cyclic load in the cycles after overloading, the retardation coefficient C_p changes in a monotonic way, rising to unity at the moment the current plastic zone reaches the front of the overload plastic zone (Fig. 1).

The Wheeler's model gives a good description of the fatigue crack propagation in these materials for which, after overloading, the change of crack length (or crack opening displacement COD) as a function of the number of load cycles, is of the nature shown in the following Figures, i.e.:

- initial reduction of the growth rate (in comparison with the rate before overloading), more or less intensive, then systematic (monotonic) increase - in an extreme case, up to the moment the growth rate equals the one before overloading (Fig. 2a). Before the specimen is damaged, there is a very rapid, critical increase in the quantity measured.
- significant growth rate reduction over a long period after overloading (or at least until the next overload occurs) – Fig. 2b. Before the specimen is damaged, there is no explicit indication that the quality measured had reached the critical value.

In the former case, corresponding (in the description made using the Wheeler's model) to a relatively low value of the exponent n, the propagating crack, partially or totally, goes through the overload plastic zone and emerges from the retardation generated by an overload before the next overload occurs.

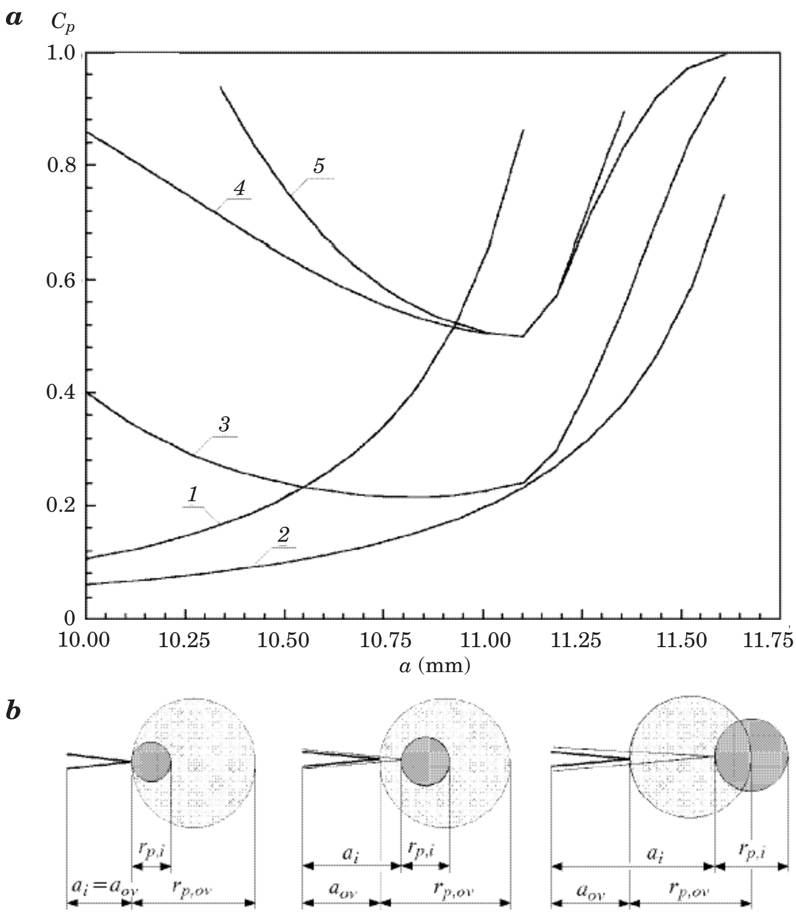
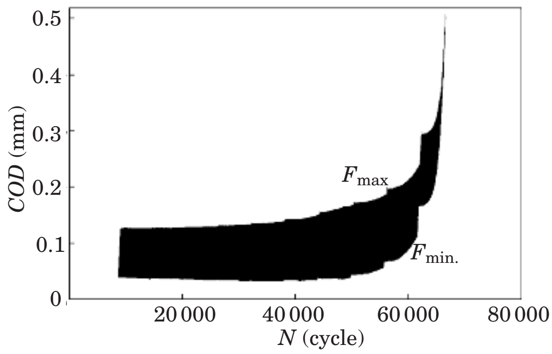


Fig. 1. Relationship between the retardation coefficient C_p and crack length (a) and plastic zones during crack propagation under overloads (b); curve no 1 – initial Wheeler's model, curves no 2–5 – Wheeler's model after modifications

In the latter case, corresponding (in the description made using the Wheeler's model) to a relatively high value of the exponent n (i.e. low value of C_p), the propagating crack does not goes through the overload plastic zone, developing under a considerable retardation generated by an overload, until the next overload occurs. The crack growths are more significant during an overload than between overloads.

Using the classic Wheeler's model, it is impossible to ensure at the same time a considerable reduction in the crack growth between overloads and a significant crack growth within an overload cycle (visible abrupt growths in Fig. 2). In order to make the growth within one overload cycle higher by one or two orders of magnitude than in a few thousand cycles



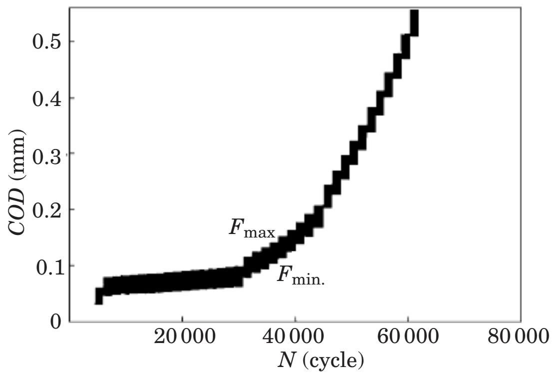


Fig. 2. Experimental records of crack opening displacement size *COD* of *CT* specimen made of PA7 alloy (a) and of specimen *SEN* made of 18G2A steel (b) during fatigue tests with cyclical overloads

between the overloads, the exponent n must assume a high value. As a consequence, the coefficient C_p will reach a small value (resulting in a significant crack growth delay). At the same time, the coefficients C and m should be big enough to ensure this significant crack length growth within a single overload cycle (then $C_p = 1$). However, in this situation the cracks in the specimens tested without overloads (at least in the range up to the first overload or in all adequate growth periods, when $C_p = 1$) would grow 10 to 100-fold faster when compared with the cracks in overloaded specimens (and, in consequence, the strength of these specimens would be lower by the same number of times) – yet in practice this is not possible on such a large scale.

Empirically determined propagation curves obtained on the specimens with a single edge crack made of 18G2A steel and tested under constant amplitude load conditions (characterized by the stress ratio $R = 0.3$) with cyclical (every DN cycles) overloads at a level of $k_{ov} = 1.2$, 1.4, 1.6, 1.75 are presented in Figures 3 – 6 (KŁYSZ 1999a, KŁYSZ 1999b, KŁYSZ 2002).

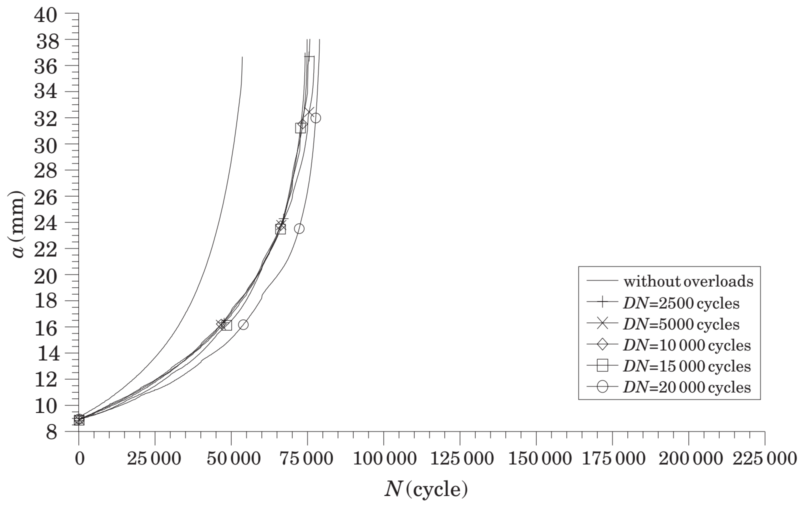


Fig. 3. Relationship $a = f(N)$ for the specimen tested under overload k_{ov} =1.2

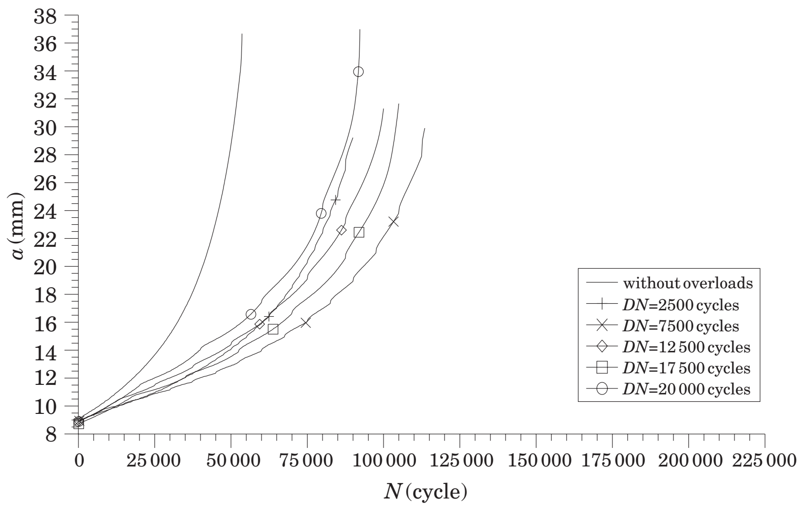


Fig. 4. Relationship $a = f(N)$ for the specimen tested under overload k_{ov} =1.4

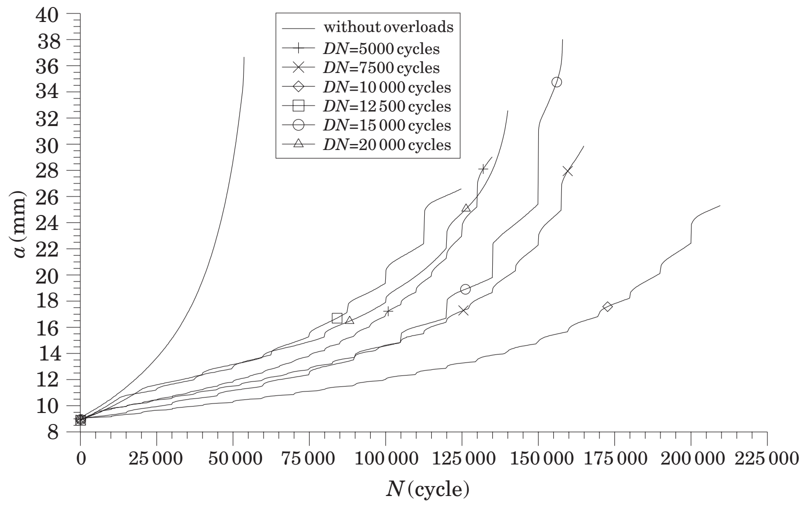


Fig. 5. Relationship $a = f(N)$ for the specimen tested under overload k_{ov} =1.6

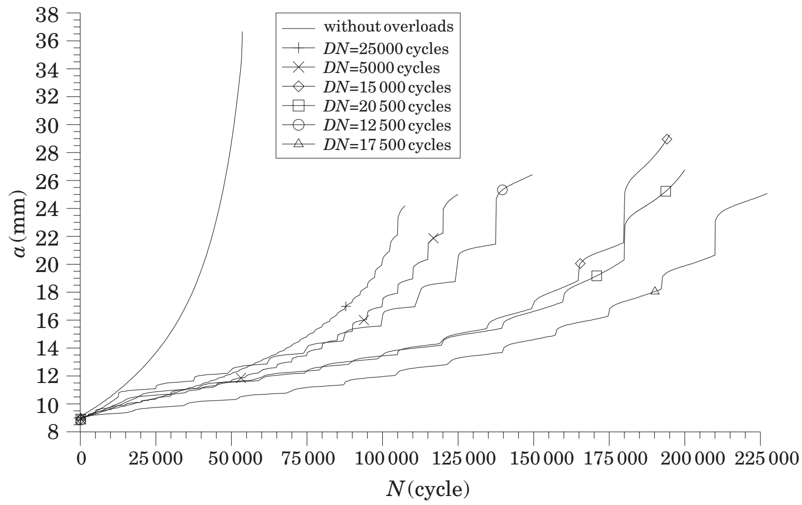


Fig. 6. Relationship $a = f(N)$ for the specimen tested under overload k_{ov}=1.75

The graphs prove the generally known fatigue crack propagation characteristics under overload conditions:

– single as well as cyclical overloads increase fatigue life in comparison with the life without overloads,
– in general, together with the increase in an overload level, the fatigue life is prolonged (at least in the case of the range of overload levels analyzed in the study),

– however, there is an optimum distance between overloads, for which fatigue life is maximal (i.e. too frequent or too rare overloads (in relation to this optimal distance) result in a smaller crack growth retardation effect).

Analyzing the Figures, there are clear-cut differences in the courses of individual crack propagation curves – the crack length increment dynamics, convex of curves in the sections between overloads, are different in particular graphs (and also when compared with the graphs presented earlier). For the overloads at a level of $k_{ov} = 1.2$ and 1.4, the crack length increments are almost monotonic (only in the final sections bends are visible in the moments of overloads). In the case of greater overloads, the curves $a = f(N)$ very clearly represent (by their bends) almost every overload. Moreover, the crack length increments are also more considerable within the overload cycles.

Additionally, the courses of relevant relationships of the propagation rate da/dN as a function of the stress intensity factor range ΔK are also characteristic. In the case of crack propagation tests conducted without overloads, a typical graphic representation of this relationship (determined with the use of a secant method, at successive measurement points (a_i,N_i) – shown in Fig. 7) – demonstrates general features of a systematic growth (preserving the characteristic dispersion of propagation rate values).

During the specimen tests including cyclical overloads, the empirically recorded relationships $da/dN = f(\Delta K)$ progressed as shown in Fig. 8. Between successive overloads, with a systematically increasing ΔK (together with a growing crack length), the crack growth rate decreases – the course characterized by a negative slope towards the X-axis, which seems to contradict the Paris relationship. The presented graph corresponds to the overload of

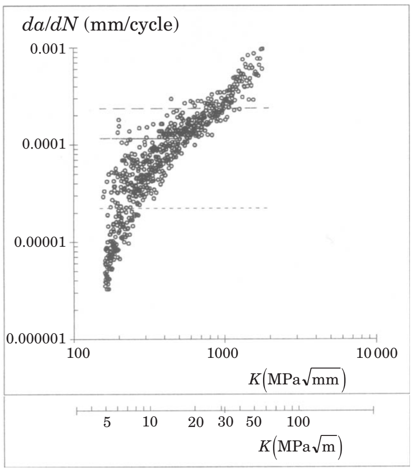


Fig. 7. Relationship $da/dN = f(\Delta K)$ for the specimen tested without overloads

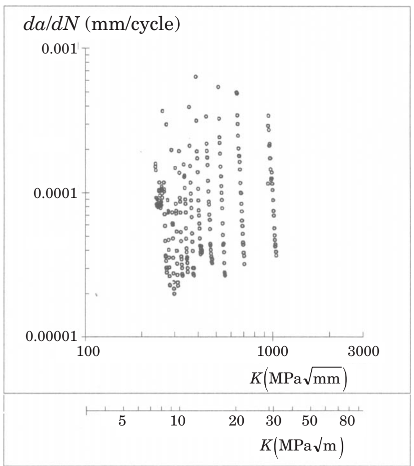


Fig. 8. Relationship $da/dN = f(\Delta K)$ for the specimen tested under overload k_{ov}=1.75

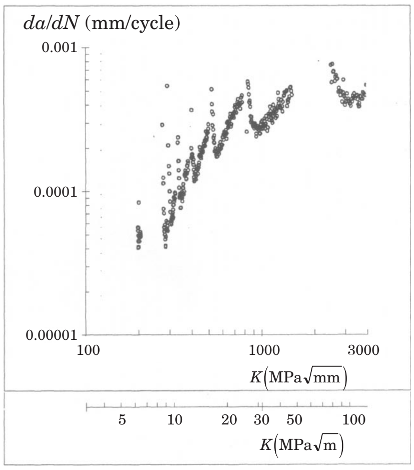


Fig. 9. Relationship $da/dN = f(\Delta K)$ for the specimen tested under overload k_{ov}=1.6

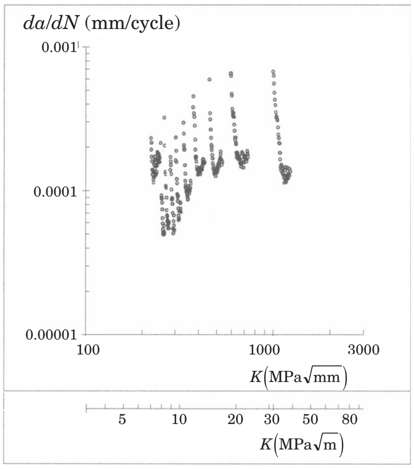


Fig. 10. Relationship $da/dN = f(\Delta K)$ for the specimen tested under overload k_{ov}=1.4

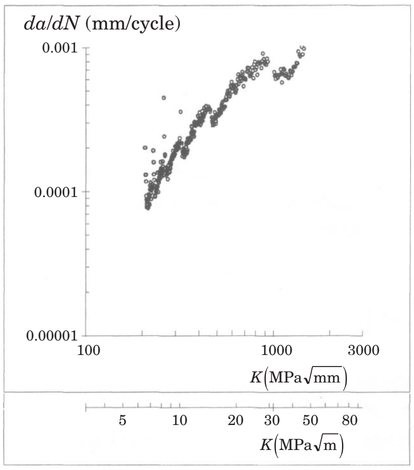


Fig. 11. Relationship $da/dN = f(\Delta K)$ for the specimen tested under overload k_{ov}=1.2

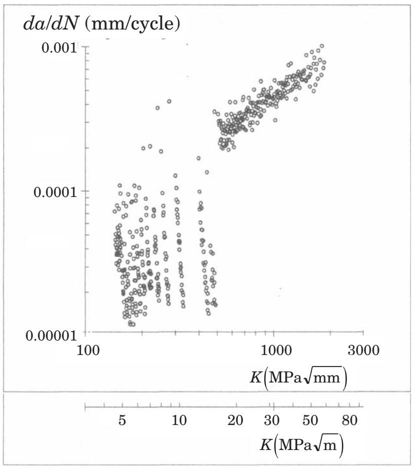


Fig. 12. Relationship $da/dN = f(\Delta K)$ for the specimen tested under overloads and without overloads

k_{ov} = 1.75, applied every DN = 12 500 cycles. The propagation rate between particular overloads decreases in a range of 2–3 orders of magnitude. The decrease in the crack growth rate (its level and range of occurrence) generally depends on the overload magnitude.

Successive figures show relationships equivalent to those presented in Fig. 8, but these were obtained for the specimens tested under lower overloads – k_{ov} = 1.6, 1.4, 1.2 respectively. It is evident that with the decrease in the overload level, the growth delay level also decreases (the propagation rate does not drop so considerably), the crack begins to come out from the delayed growth:

– for the overload $k_{ov} = 1.6$ – for bigger crack length values and only in the final growth phase between overloads,
– for the overloads $k_{ov} = 1.4$ and 1.2 – almost over the entire range of crack length considered in the study,
– for the overload $k_{ov} = 1.2$ – with an explicit dominance of a non-delayed growth between overloads.

Certainly, the delay level and the range of its occurrence fundamentally influence the final fatigue life of the specimens tested – in this case, with the same intervals between overloads *DN*, the fatigue life would change for individual overload levels like 150 000 : 125 000 : 100 000 : 71 560 cycles.

When the delay effect is over and another overload is not expected, the crack grows in the same way as in the specimens without overloads – the left-hand side of Fig. 12 corresponds to the crack growth during 12 successive (every *DN*) overloads, and the right-hand side corresponds to the further growth under the constant amplitude load conditions.

Modifications of the theoretical description of the fatigue crack growth

The papers (KŁYSZ 1999a, KŁYSZ 1999b, KŁYSZ 2002) present the modification of the fatigue crack propagation retardation model as for the consideration of the above-mentioned singularities. It has been assumed that the crack growth delay generated by an overload exists as long as the crack tip (and not the plastic zone spreading in front of it) reaches the front of the plastic zone induced by this very overload. It seems to be more justified (in relation to the initial model) that the front of the overload plastic zone is treated as a physical barrier to be overcome by the front of a propagating crack. Only when the crack is through this plastic zone (and not by the crack plastic zone), does the retardation coefficient reach the value of 1 – and the crack grows again with the rate corresponding to that observed when there is no overload. Moreover, the author has introduced the correlation of the exponent n of the Wheeler's model upon the location of the crack and the current plastic zone in front of it – in relation to the plastic zone generated by an overload cycle (like in the case of the retardation coefficient C_p alone, in the initial model). For the range when the plastic zone of the propagating crack is completely included in the plastic zone induced by an overload cycle ($a + r_{p,i} <= a_{ov} + r_{p,ov}$), the exponent n is determined by the following formula:

$$C_p = \left(\frac{r_{p,i}}{a_{ov} + r_{p,ov} + r_{p,i} - a_i} \right)^{n'} = \left(\frac{r_{p,i}}{a_{ov} + r_{p,ov} + r_{p,i} - a_i} \right)^{1 - \left(\frac{a_{ov} + r_{p,ov} - a_i - r_{p,i}}{r_{p,ov}} \right) \cdot n}$$

For the range when the plastic zone before a propagating crack intersects the plastic zone induced by an overload cycle ($a + r_{p,i} > a_{ov} + r_{p,ov}$), it has been suggested that the exponent n is determined with the following formula:

$$C_p = \left(\frac{r_{p,i}}{a_{ov} + r_{p,ov} + r_{p,i} - a_i} \right)^{n'} = \left(\frac{r_{p,i}}{a_{ov} + r_{p,ov} + r_{p,i} - a_i} \right)^{1 - \left(\frac{a_{ov} + r_{p,ov} - a_i}{r_{p,i,\max}} \right)^n}$$

where $r_{p,i,\max}$ denotes the size of the largest current plastic zone created in successive cycles after overloading, which got through the overload zone during a delay generated by this overload.

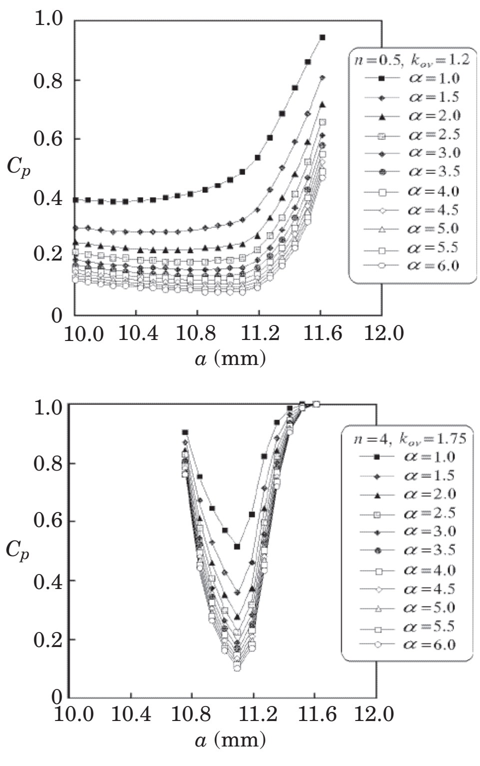


Fig. 13. Variability of the modified retardation coefficient of the Wheeler's model

The delay exponent n' can be thus described by the following equation:

$$n' = \operatorname{sgn}\left(a_i \le a_{ov} + r_{p,ov} - r_{p,i}\right) \cdot \left[1 - \left(\frac{a_{ov} + r_{p,ov} - a_i - r_{p,i}}{r_{p,i,\max}}\right) \cdot n\right] +$$
$$+ \operatorname{sgn}\left(a_i > a_{ov} + r_{p,ov} - r_{p,i}\right) \cdot \left[\left(\frac{a_{ov} + r_{p,ov} - a_i}{r_{p,i,\max}}\right)^{n}\right]$$

Ultimately, for the retardation coefficient C_p in the from:

$$C_p = \left(\frac{1}{\alpha \cdot k_{ov}} \cdot \frac{r_{p,i}}{a_{ov} + r_{p,ov} + r_{p,i} - a_i}\right)^{n'}$$

where α is determined empirically,

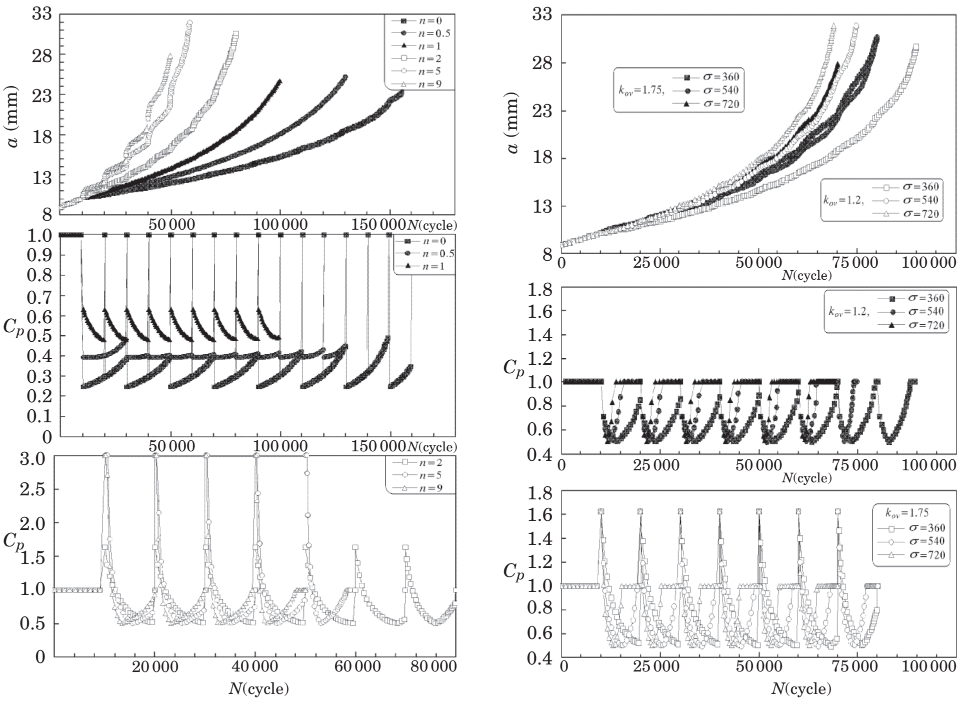


Fig. 14. Examples of crack propagation curves and changes in the retardation coefficient C_p for the modified Wheeler's model

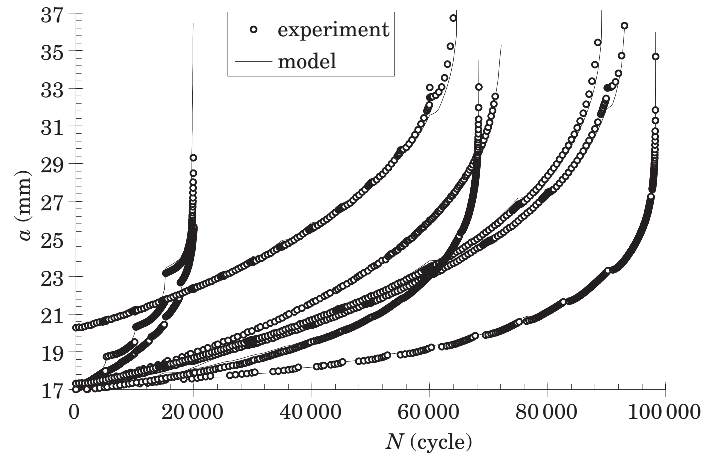


Fig. 15. Examples of descriptions of empirical data with the use of the modified retardation model

a wide range of variation was obtained (Fig. 13). This enables a large-scale adjustment of a theoretical description to experimental data (Fig. 14). The proposed modification ensures a satisfactory representation of complex and diversified empirical courses $a = f(N)$ (Fig. 15) – frequently found in research practice. Yet, the most important thing is that the precision of the estimation of the propagation equation coefficients and final fatigue life is satisfactory. With such an exact representation of experimental data, the model allows to estimate the dispersion of these parameters (e.g. during the analysis of a specific type of a test carried out on an adequate number of specimens). The problems presented above provide the basis for a correct fatigue life analysis of specimens and construction elements, which indicates the usefulness of the model discussed in the paper for practical applications.

References

KŁYSZ S. 1998. *Modyfikacja modelu opóźnień Wheelera rozwoju pęknięć zmęczeniowych.* XVII Sympozjum nt. *Zmęczenie Materiałów i Konstrukcji.* Pieczyska pod Bydgoszczą, ss.153-158.

KŁYSZ S. 1999a. *Analiza rozwoju pęknięć zmęczeniowych w stali 18G2A i jego opis modelowy.* Zagadnienia Eksploatacji Maszyn, 2 (118): 223-234.

KŁYSZ S. 1999b. *Szacowanie trwałości wybranych materiałów i elementów konstrukcji lotniczych w zakresie rozwoju pęknięć zmęczeniowych*. Prace Naukowe ITWL, 5: 1-180.

KŁYSZ S. 2000. *Wpływ przeciążeń i sekwencji obciążeń na `własności niskocyklowe stali 18G2A i St3SY*. Zagadnienia Eksploatacji Maszyn, 4(124): 139-154.

KŁYSZ S. 2001. *Rozwój pęknięć zmęczeniowych w materiałach lotniczych i stali konstrukcyjnej z uwzględnieniem przeciążeń.* Prace Naukowe ITWL, 12: 1-151.

KŁYSZ S. 2002. *Wpływ przeciążeń na rozwój pęknięć zmęczeniowych w wybranych materiałach lotniczych*. Prace Naukowe ITWL, 15: 1-147.

PARIS P.C., ERDOGAN A. 1963. *A critical analysis of crack propagation laws.* J. Bas. Engng, 85: 528-534.

POLÁK, J. 1991. *Cyclic Plasticity and Low Cycle Fatigue Life of Metals.* Materials Science Monographs, 63. Elsevier, Amsterdam.

Stress Intensity Factors Handbook: The Society of Materials Science, Japan, Editor-in-chief: Murakami Y., Pergamon Press, 1987.

WHEELER O.E. 1970. *Crack growth under spectrum loading*. General Dynamics, Rep. F2M 5602.

WHEELER O.E. 1972. *Spectrum loading and crack growth.* J. Basic Engng Trans., ASME.

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