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RESEARCH OF SURFACE CRACKS PROPAGATION WITH A COMPLEX GEOMETRIC CONTOUR AFTER THE INFLUENCE OF TENSILE OVERLOADS

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Summary. *In the paper, the authors experimentally investigated the growth of low-alloy steel surface cracks under constant amplitude loading and under single overloads. Surface semi-elliptical cracks of canonical shape, as well as cracks with a contour of complex geometry were considered. Each overload increased the number of cycles of crack growth retardation, with higher significance in non-canonical surface cracks. The contour of surface cracks also changed in single-overload condition.*

Key words: *constant amplitude loading, single overloading, surface crack, non-canonical contour, crack growth rate.*

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Statement of the problem. The machines and structures in operation are subjected to loads, which often lead to an instantaneous or monotonous change in stresses. The simplest manifestations of such changes are peak one-time overloads, cyclic overloads or underloads of a certain duration, software load, etc. Numerous studies [1–3] indicate significant transient effects of changes in the rate of growth of fatigue cracks making it difficult to estimate the durability of structures with cracks. This question is especially relevant in the presence of structural cracks in structural elements.

Analysis of the available investigations. The simplest case of a single overload is the most thoroughly studied for through-thickness cracks and gives an idea of the probable tendencies and mechanisms inherent in more complex transient processes in fatigue of materials. It is found that intense tensile overload of an element with crack significantly slows its growth if the subsequent cyclic loading is at least 1,3 times (for aluminum alloys) and ≥1,4 times (for steels) is lower than the level of overload. It is also obvious that as the level of overload goes up, the number of delayed cycles N_D increases, and that for many aluminum alloys at an overload coefficient $Q_{OL} = K_{OL}/K_{BL}$ (or $Q_{OL} = \Delta K_{OL}/\Delta K_{BL}$) = 2,3…3,0 (Figure 1) crack growth stops completely, while for structural steels this threshold rises to 3,2…4,0 [4]. The described phenomenon is of great practical importance for the development of methods to assess the durability of irregular loading, in particular when justifying the testing modes during testing or installation in order to increase the reliability of the machines and structures elements. The number of cycles of crack growth retardation N_D for the through-thickness cracks depends on the parameters of the overloading cycle K_{OL} and the main (base) loading level K_{BL}; initial mechanical characteristics of the material; its structural condition; properties of hardening and softening of metal during plastic deformation; degree of compression of deformations; and environment [4, 5].

The effect of overload on the retardation of surface cracks growth is similar to the through-thickness cracks [6], but consideration of this process is complicated with additional factors typical for surface cracks. One factor is the variability of the shape of the surface cracks, which are characterized by the axes ratio *a/c* [7].

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The distinction is made between the energy-stable contour [6, 8], when the SIF along the front of the fatigue crack during its development acquire almost identical values (at a/c ≈ 0,8), and the energy-unstable contour with significantly different values of the SIF along the front.

Surface cracks with their complex geometry contour belong to the energy-unstable contour category [9]. The contour can be formed by coalescence of smaller macrocracks, for example in areas of welds [10]. The effect of overload on the growth retardation of such cracks has not been studied.

Another factor typical for the surface crack is the presence of variable stiffness of the stress-strain state along the crack, when the growth of surface and near-surface points under cyclic loading is realized under conditions of plane stress state, and for points in the deepest part of the contour in the state of plane deformation.

The influence of the above factors on the magnitude of the fatigue crack growth retardation N_D after overload is ambiguous. Let us consider, for example, the influence of the thickness of the samples of aluminum alloys and low-alloy steel on the retardation value N_D after overloading. For aluminum alloy 2024-T3 (analog of D16) [11] with mechanical characteristics $\sigma_{0,2}$ = 362 MPa; σ_u = 495 MPa increase in plate thickness from 1,6 mm to 3,2 mm and further up to 26,0 mm leads to a significant (3–5 times) decrease in the retardation period N_D of fatigue crack growth after Q_{OL} = 1,5; 1,8; 2,0 tensile overload and for four levels of basic cyclic loading ΔK_{BL} = 9,0; 15,0; 20,0; 23,0 MPa $\cdot \sqrt{m}$. Also in all cases there is an increase in N_D with an increase in ΔK_{BL}.

Effect of tensile overload Q_{OL} = 2,0 on the retardation of fatigue crack growth in steel samples of different thickness t = 2,0; 4,0; 9,0 and 18,0 mm in HT-80 steel ($\sigma_{0,2}$ = 665 MPa; σ_u = 811 MPa) [11] is not as straightforward as in aluminum alloys. At ΔK_{BL} = 20,0 MPa $\cdot \sqrt{m}$ the rolled thickness practically does not affect the fatigue crack growth retardation, and at larger ΔK_{BL} (up to ΔK_{BL} = 50,0 MPa $\cdot \sqrt{m}$), the increase of the thickness of the samples from 2 to 18 mm reduces the retardation N_D by 5 times. In addition, at a small thickness t = 2 mm, when a plane stress state is being implemented, the fatigue crack growth retardation increases with the increase of ΔK_{BL}. At the same time, when the through crack propagates under conditions close to plane deformation (t = 18 mm), N_D decreases as the basic cyclic load level ΔK_{BL} increases. There is also some range of thicknesses $t = 4 \div 8$ mm for the tested steel NT-80, for which the retardation N_D after overload Q_{OL} is practically independent of the thickness of the rolled metal. This uncertainty of the influence of various factors on the rate of fatigue crack growth necessitates the development of a design and experimental technique for predicting the durability of structural elements in the presence of loading cycles.

Purpose of research. The aim of the research is to establish the influence patterns of tensile overloads on the transient processes of the growth rate of surface fatigue cracks with a complex geometry contour.

Main thesis. In order to study the kinetics of the growth of the non-canonical shape surface crack under the tensile overload and subsequent cyclic loading, experimental studies of 09G2S steel plates with a cross section of 80x20 mm under the action of cyclic tensile loading on the hydro-pulsator ZDM-100 were carried out. In the plates using a thin disk cutter with thickness of 0,13 mm coplanar cuts of different depth which overlapped each other were initiated (Figure 2). Under cyclic loading, an asymmetrical surface fatigue crack was initiated, simulating the process of coalescence of the cracks. For the purpose of this research, let us identify a larger crack as crack I with a length on the sample surface c_1 = 12,0 mm and a smaller crack as crack II with a length on the sample surface c_2 = 10,0 mm. The total length of the macro-crack is equal $2c = c_1 + c_2$ = 22 mm. It was at a total length of $2c$ = 22,0 mm that an overload of Q_{OL} = 1,67 was applied to; basic cyclic load parameters K_{BL}^{max} = 187,5 MPa; cycle stress ratio R = 0,25. Subsequent overload Q_{OL} = 1,5 was applied with the same basic cyclic loading parameters and at crack length $2c$ = 33,2 mm.

For comparison, the development of semielliptical surface cracks with a standard contour at similar overloads as well as at constant amplitude loading were also investigated (Figure 1). Fractures of samples and schemes of contours of surface cracks are presented in Figure 2.

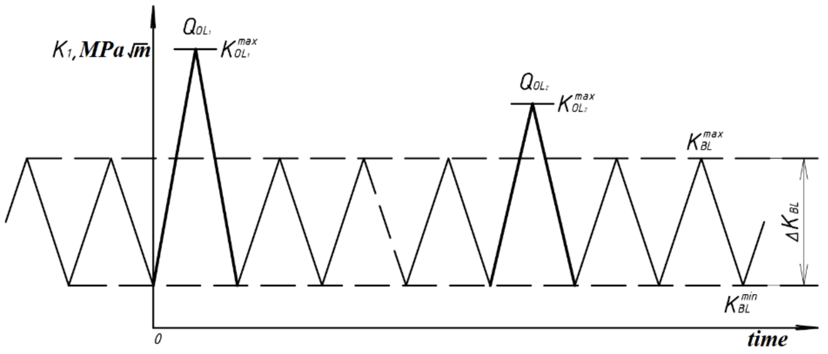
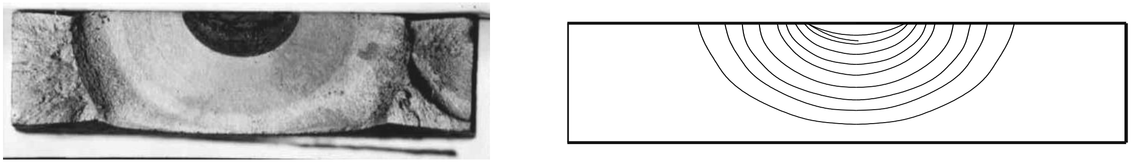
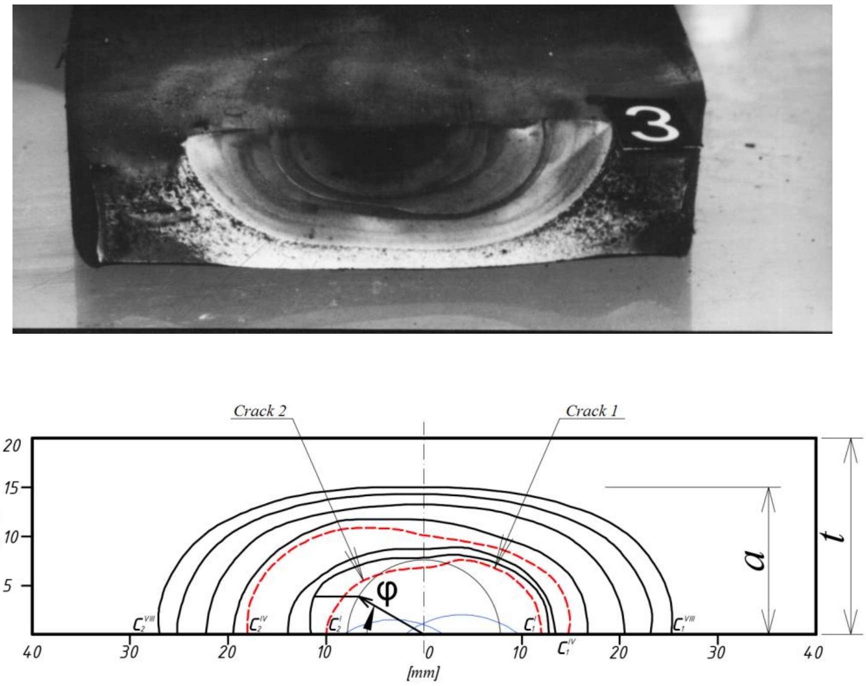


Figure 1. Scheme of the studied load spectrum



a)



b)

Figure 2. Fractures of samples and schemes of contours of surface cracks:
a) semielliptical crack under constant amplitude loading; b) crack with initially complex geometric contour after overloads and subsequent constant amplitude cyclic loading

Consider the qualitative results of the development of surface non-canonical crack under tensile overload. After the action of a single overload Q_{OL} = 1,67 on the macrocrack, formed during the coalescence of different cracks, the development of the surface crack along its contour was slowed down. Further cyclic loading initially triggered the development of the smaller crack (II) contour, while the contour of the larger of the cracks (I) was still in a state of slow development (Figure 3). Obviously, depending on the magnitude of the overload, the smaller crack can exceed the size of the adjacent crack, which happened in our case. With the application of the subsequent overload Q_{OL} = 1,5 the tendency for surface crack propagation remained the same: after a period of slow development, the smaller of the cracks (in this case I) began to develop more actively, followed by the larger one. It should be noted that the intensity of the retardation of the fatigue crack growth after overloading Q_{OL} = 1,5 was less than after overloading Q_{OL} = 1,67.

The analysis of the change in the shape of the non-canonical surface crack after the effect of the overload and the subsequent cyclic loading differs significantly from the change in the shape of the symmetrical surface crack under the same loading conditions. Symmetrical surface crack retains the semielliptical shape at constant amplitude loading, and after tensile overload. Whereas, the non-canonical crack shape at overloads is close to rectangular, since the crack develops rapidly in directions corresponding to the parametric angle $\varphi = 30 \div 35^{\circ}$. The greatest retardation of the crack development is observed in the zone of crack coalescence.

Therefore, the overload in the cracks of non-canonical shape leads to an intense retardation in the fatigue crack growth, as well as to a significant change in the shape of the crack contour. Almost the same shape becomes a single surface crack under the influence of surface hardening [191], which is widespread in mechanical engineering, or surface cracks filling [191], although in these cases, completely different mechanisms affect the contour. Also it becomes possible to control the change in the surface crack front in some cases of crack geometry and overload parameters.

Consider the quantitative results of the effect of the overload Q_{OL} = 1,67 and Q_{OL} = 1,5 on the development of a surface crack with complex geometry. In Figure 3 fatigue cracks along the surface axis are presented. The moment of application of the overload Q_{OL} = 1,67 corresponds to the contour I of the surface crack with fixed points C_1^{I} and C_2^{I} on the surface of the sample (and with the corresponding semi-diagonals c_1^{I} and c_2^{I}). The moment of application of the overload Q_{OL} = 1,5 corresponds to contour IV, with fixed points on the surface C_1^{IV} and C_2^{IV}, corresponding to the ends of semi-diagonals c_1^{IV} = 15,2 mm and c_2^{IV} = 18 mm. Other curves represent the running contours of the crack, which are fixed in the process of plate with the crack testing by constant amplitude loading. In Figure 3 the kinetics curves of fatigue crack growth that are identical to the canonical semielliptical crack with averaged semi-axes of contour I and the ratio of axes $a/c \approx 0{,}78$ at constant amplitude loading (curve A) and after overload Q_{OL} = 1,67 (curve B) are presented for comparative analysis (Figure 3).

Comparison of curves growth of semielliptical surface cracks with parameters $2c$ = 22,0 mm, a/c = 0,78 at constant amplitude tensile loading σ_{max} = 187,5 MPa; R = 0,25 (curve A) and with an overload Q_{OL} = 1,67 under the same conditions of the basic cyclic loading (curve B) showed retardation in crack growth after the action of overload: N_D = 21690 cycles.

In the study of the effect of overload of the same Q_{OL} = 1,67 level on the surface crack of non-canonical shape under similar conditions of the basic cyclic load, a much larger crack growth retardation was found both along the $c_1 - N_D$ = 138000 cycles and along the $c_2 - N_D$ = 67000 cycles. This retardation led to a general change in the contour of the surface crack relative to the vertical axis: contour IV became asymmetric to contour I (Figure 2, b). Subsequent overload Q_{OL} = 1,5 at the length of semi-axes c_1^{IV} = 15,2 mm and c_2^{IV} = 18 mm led to an additional retardation of crack growth, but with less intensity (retardation along the c_2 axis was N_D = 33700). The intensity of the overload effect is also characterized by the change in the crack growth rate after the overload (Figure 4). For semielliptical canonical surface crack of similar size N_D equals 5600 cycles, which is significantly smaller.

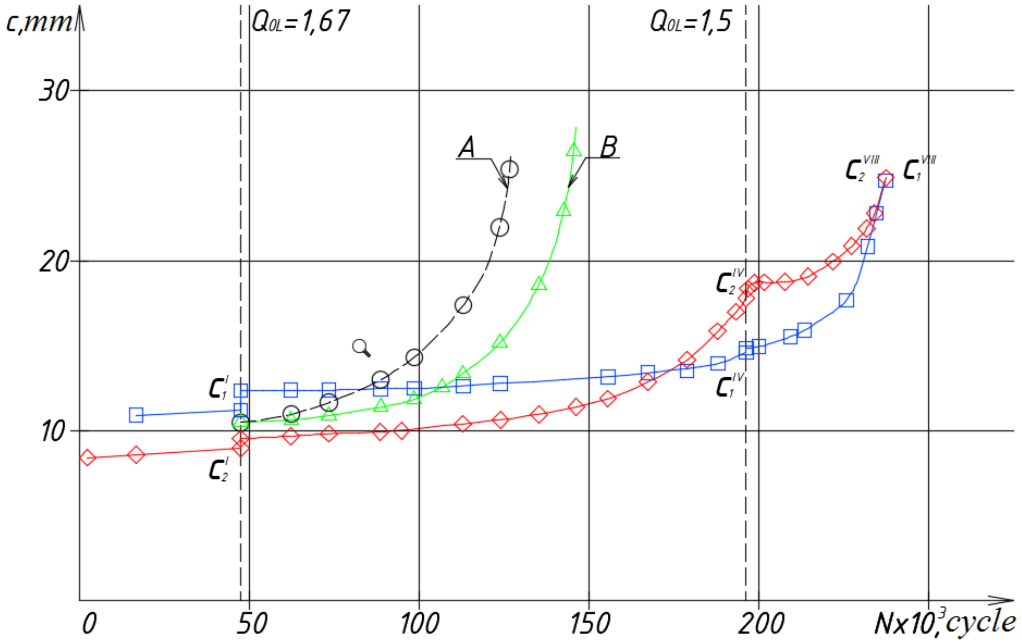


Figure 3. Regularities of the influence of overloads on the propagation of surface cracks in low-alloy steel 09G2S: A – growth of semielliptical crack under cyclic loading; B – growth of a semielliptical crack after an overload; □ – propagation of crack I after overloads; ◊ – propagation of crack II after overloads

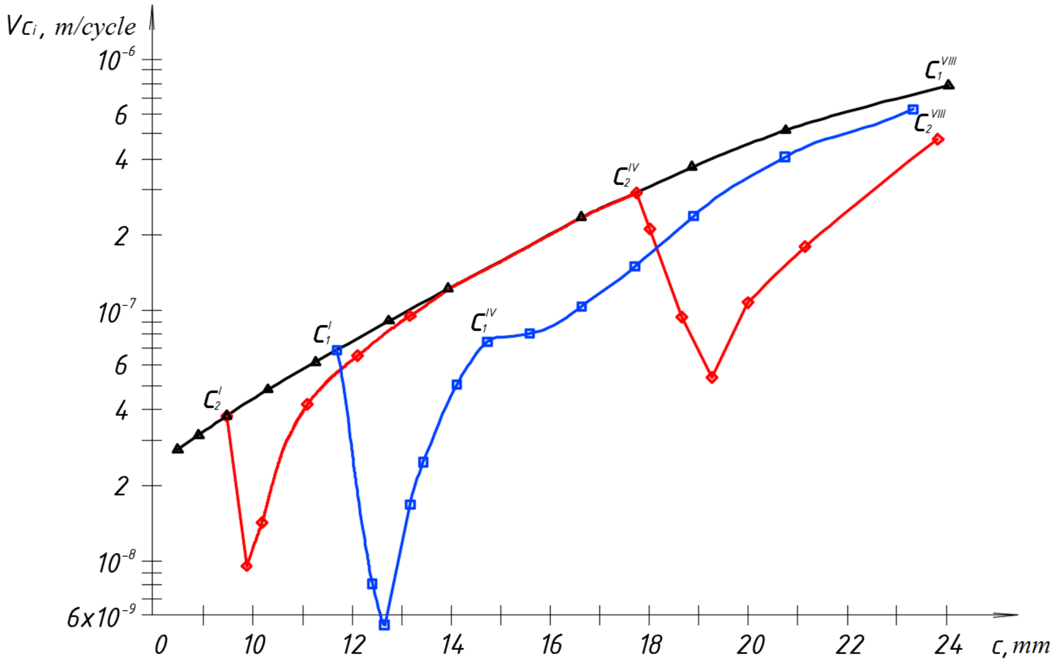


Figure 4. Curves of growth rate change of surface points propagation of the contours of cracks: Δ – under regular cyclic loading; □ – after overloads (cracks I); ◊ – after overloads (cracks II)

The change in growth rate $V = dc_i/dN$ during crack propagation along the surface axes c_1 and c_2 is presented in Fig. 4. Immediately after tensile overload Q_{OL1} = 1,67 the fatigue crack growth rate along the c_2 axis decreases approximately by 5 times and along the c_1 axis by more than 10 times. This indicates a complex transition process that occurs after overload in surface cracks with complex geometry contour. In canonical surface cracks the growth rate along the semi-axes on the surface is the same and decreases by 3,8 times.

In summary, we note that the growth retardation of surface cracks of canonical and non-canonical shape after the action of overloads depends primarily on the initial and current parameters of the cycle and the properties of the material. These values in experimental studies are the same. The main difference is the shape of the contour of surface non-canonical cracks. Along the front of such cracks a stress field and the corresponding values of stress intensity factors are formed [12], which are significantly different from the SIF for surface cracks of canonical shape [12]. In the case of non-regular loading with tensile overload, the working stresses along the curvilinear contour interact with the residual compressive stresses arising from the plastic deformations after the application of overloads [12]. The resulting stress fields obviously form the changes in the crack front and in the intensity of retardation N_D, presented in this paper.

Conclusions. On the basis of experimental researches we have established: overload in cracks with a complex geometry contour leads to retardation in crack growth; retardation in cracks growth along the contour is not uniform, which leads to the change in its contour with subsequent constant amplitude loading; these processes (retardation of crack growth and change of its contour) are significantly more intense for surface cracks with a complex geometric contour in comparison with surface semi-elliptical cracks of canonical shape.

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ДОСЛІДЖЕННЯ РОЗВИТКУ ПОВЕРХНЕВИХ ТРІЩИН ЗІ СКЛАДНИМ ЗА ГЕОМЕТРІЄЮ КОНТУРОМ ПІСЛЯ ВПЛИВУ ПЕРЕВАНТАЖЕНЬ РОЗТЯГОМ

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Резюме. *Проведено експериментальні дослідження кінетики розвитку поверхневих тріщин зі складним за геометрією контуром (неканонічні поверхневі тріщини). Форма контуру таких макротріщин* *моделює процес злиття менших поверхневих тріщин. При цьому утворюється сідловидний контур. Досліджено вплив однократних навантажень різного рівня (Q_{OL} = 1,67 та Q_{OL} = 1,5) на перехідні процеси, що відбуваються після їх прикладання при подальшому циклічному навантаженні. Після дії перевантаження відбувається гальмування розвитку поверхневої тріщини по всьому його контуру. Це явище характерне як для наскрізних тріщин, так і поверхневих тріщин. Отримані результати затримки росту поверхневої тріщини зі складним у плані контуром свідчать, що число циклів сповільнення їх росту у кілька разів більше, ніж для подібної півеліптичної тріщини з гладким контуром та однаковими за розмірами півосями. Встановлено, що затримка росту поверхневих тріщин є різною вздовж складного за геометрією контуру, що приводить до інтенсивної зміни фронту неканонічної форми. Контур неканонічної тріщини в процесі циклічного навантаження після дії перевантаження різного рівня набуває обрисів близьких до прямокутної форми. це пов'язано з особливостями напружено-деформівного стану вздовж фронту поверхневої тріщини. Найшвидше після гальмування росту всього контуру відбувається розвиток фронту в напрямках, що відповідають параметричному куту φ = 30 ÷ 35º. Найпізніше з-під впливу перевантаження виходить область більшої за розмірами частини тріщини при параметричному куті φ = 60 ÷ 65º. Встановлені кількісні значення зміни росту тріщини одразу після перевантаження та до моменту закінчення перехідних процесів, пов'язаних з впливом перевантаження. Зазначимо, що мінімальні швидкості росту тріщин, що встановлюються одразу після перевантаження залежать від рівня перевантажень і є меншими при їх більшому рівні. Одночасно мінімальні швидкості росту тріщин неканонічної форми є суттєво меншими при такому ж рівні перевантажень у порівнянні з відповідними точками контуру поверхневої тріщини канонічної форми. Це й визначає більшу затримку росту тріщини неканонічної форми у порівнянні з подібною за розмірами поверхневою тріщиною з канонічним контуром. Таким чином, як було встановлено за даними експериментальних досліджень вплив перевантаження в поверхневих тріщинах зі складним за геометрією контуром приводить до затримки росту втомної тріщини, що є суттєво більшою (у кілька разів), ніж для звичайних поверхневих тріщин з аналогічними півосями, а також до значних змін контуру, які є непритаманними півеліптичним тріщинам.*

Ключові слова: *регулярне циклічне навантаження, одиничне перевантаження, поверхнева тріщина, неканонічний контур, швидкість росту тріщини.*

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