NEAR-THRESHOLD GROWTH OF SHORT FATIGUE CRACKS

O. N. Romaniv, V. N. Simin'kovich,
and A. N. Tkach

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It is known that the behavior of cracks in cyclic loading is described by the kinetic fatigue failure curve, while the conditions of nonpropagation of a crack are determined by the threshold range of the stress intensity factor ΔK_{th}. Determination of ΔK_{th} is normally done in studying slow ($v \sim 10^{-10}$ m/cycle) growth of a long (more than 2-4 mm) fatigue crack grown from the base of a mechanical notch. At the same time, there is unquestionable practical interest in information on the development of short surface fatigue cracks since such defects may easily originate in slip bands on a smooth surface and also from very small stress raisers (scratches, galling, etc.) formed during production of machine parts and elements of structures.

The purpose of this work was a study of the features of growth of short fatigue cracks and establishment of the rules of formation of the threshold stress intensity factors for such cracks.

Material and Method of the Investigations. The experiments were made with samples of technical grade iron, 20Kh13 steel in two structural conditions, after annealing and after oil hardening from 980°C, Yu3 austenitic steel, and AMG-61 wrought aluminum alloy. The tensile tests, determination of fracture toughness K_{Ic}, and construction of kinetic fatigue failure curves were done in air at room temperature. The fracture toughness K_{Ic} of all of the materials other than hardened 20Kh13 steel was determined by the J-integral method with subsequent recalculation of J_{Ic} and K_{Ic}. For the fatigue tests using a starting-from-zero cycle with a frequency of 20-35 Hz, use was made of unnotched prismatic samples with a height of 15 mm, a thickness of 6 mm, and a length of 130 mm in which an original edge crack with a length of $a = 0.2$-2.0 mm had been created in advance. The original crack was made in the following manner. First fatigue cracks with different lengths were grown in 16.5-mm-high samples with a V-shaped notch with a depth of 1 mm and a radius at the base of $\rho = 0.1$ mm, stopping this process at levels of ΔK close to ΔK_{th}. Then a portion of the samples was ground on the side of the notch (plan in Fig. 1), leaving a smooth surface with a boundary crack of specified length.

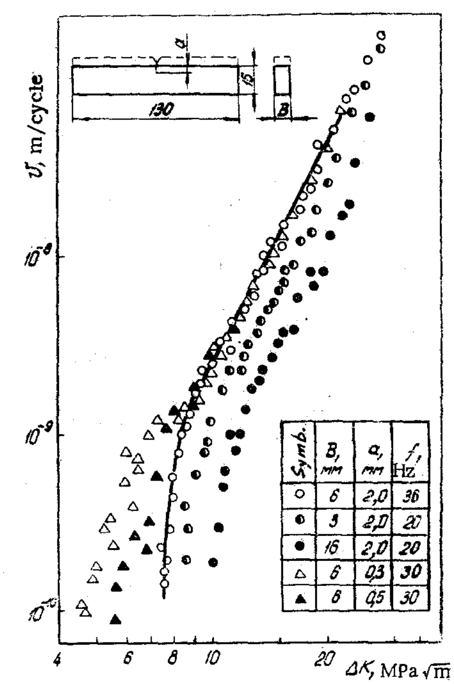

Fig. 1. Kinetic fatigue failure curves of samples of technical grade iron with different thickness and initial crack length a.

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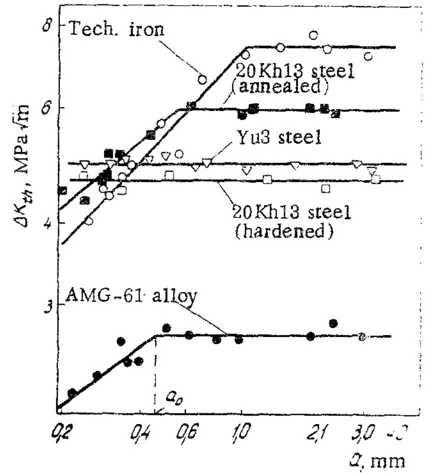

Fig. 2. Relationships of the threshold stress intensity factors ΔK_{th} to initial crack length a.

TABLE 1

Material	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	σ_{-1}, MPa	ψ, %	K_{Ic}, MPa·$\sqrt{m}$	r_f, μ
Tech. iron	335	242	—	140	763	82,8	50,3
AMG-61 alloy	340	180	10	85	—	38,5	11,9
20Kh13 steel, annealed	730	335	33,4	185	52	42,3	17,03
20Kh13 steel, hardened	1165	1030	26	670	49,8	32,2	1,1
Yu3 steel, normalized	750	550	40	240	25	199 7	4,3

TABLE 2

Material	ΔK^0_{th}, MPa·$\sqrt{m}$	a_0, mm	r	a_c, mm
Tech. iron	7,45	1,03	0,419	0,9
AMG 61 alloy	2,7	0,46	0,309	0,3
20Kh13 steel, annealed	6,0	0,56	0,317	0,3

For samples with long cracks, the value of ΔK_{th} was determined by the method of reducing the load while observing known method recommendations [1]. To find the threshold stress intensity factors for short fatigue cracks, a series of samples with cracks of the same length a was cyclically aged, providing at the mouth of the crack the spectrum $\Delta K \leq \Delta K_{th}$. Then the value of ΔK at which the fatigue crack growth rate did not exceed 10^{-10} m/cycle was taken as the threshold value ΔK_{th} for short cracks with a length of a. This procedure was conducted for several groups of samples of each material differing in original fatigue crack length.

Results of the Experiments. The mechanical properties of the investigated materials are shown in Table 1. The kinetic fatigue failure curves of technical grade iron (Fig. 1) and also the relationships of ΔK_{th} to original crack length (Fig. 2) drawn from the results of tests of 6-mm-thick samples differing in original fatigue crack length a showed that there is some limiting crack length a_0 below which there is a drop in ΔK_{th} with a decrease in crack length. The change in ΔK_{th} for short cracks with a length of $a \leq a_0$ may be described by the exponential relationship $\Delta K_{th} = \Delta K^0_{th}\ (a/a_0)^r$, where ΔK^0_{th} is the threshold stress intensity factor for a long crack, a_0 is the limiting original crack length above which the crack length does not influence ΔK_{th}, and r is an exponent. The values of ΔK^0_{th}, a_0, and r for the investigated materials are presented in Table 2.

Fatigue tests were also made of 3- and 1.5-mm-thick samples containing cracks with an original length of 2 mm (a = 2 mm), which indicated that a decrease in sample thickness causes an increase in the threshold stress intensity factor (Fig. 1).

The results obtained in studying the influence of original fatigue crack length in samples of annealed 20Kh13 steel and AMG-61 aluminum alloy on ΔK_{th} were similar to those obtained for iron. The limiting original crack length for 20Kh13 steel a_0 = 0.54 mm and for AMG-61 alloy a_0 = 0.46 mm. The tests of Yu3 austenitic steel and of hardened 20Kh13 steel with a martensitic structure showed that a decrease in original fatigue crack length is not reflected on the values of ΔK_{th}, which remain constant with a change in a from 0.2 to 2.0 mm (Fig. 2).

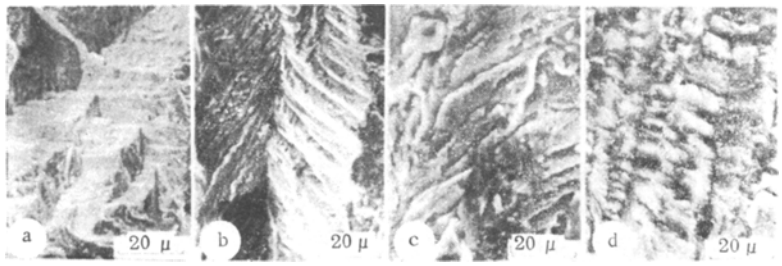

Fig. 3. Microstructure of fatigue fractures of samples of technical grade iron (a, b) and AMG-61 aluminum alloy (c, d): a, b) $a = 0.3$ mm, $\Delta K = 4$ MPa$\cdot\sqrt{m}$; c) $a = 0.6$ mm, $\Delta K = 2.7$ MPa$\cdot\sqrt{m}$; d) $a = 0.3$ mm, $\Delta K = 2.3$ MPa$\cdot\sqrt{m}$.

Microfractographic analysis of portions of the fractures of samples of technical grade iron corresponding to the near-threshold areas indicates that propagation of short fatigue cracks ($a < a_0$) occurs primarily by slip with the occurrence of characteristic areas of failure in slip planes (Fig. 3a, b). The development of long fatigue cracks ($a > a_0$) in this area is accompanied by the formation on the fracture surface of specific fatigue striations and stringer formations, the mechanisms of creation of which were described earlier [2]. In the fractures of samples of annealed 20Kh13 steel containing short fatigue cracks, areas of slip advance of cracks are absent. Growth of a long fatigue crack at a near-threshold rate in samples of AMG-61 alloy is accompanied by the formation of a complex relief on the fracture surface (Fig. 3c). In tests of samples with short original cracks, individual areas of slip fracture also appear in the fracture (Fig. 3d). According to the data of microfractographic analysis of fractures of Yu3 and hardened 20Kh13 steel, the micromechanisms of fracture in propagation of cracks at near-threshold rates are identical for long and short fatigue cracks in these steels.

Discussion of Results. Correctness of Use of the Approaches of Fracture Mechanics for Determining ΔK_{th} at the Tip of a Short Fatigue Crack. According to the generally accepted requirements for correct description of the mechanical condition in the vicinity of a crack tip by the stress intensity factor, the fulfillment of two conditions is necessary [1]. First, that the crack length substantially exceed the dimension of the structural parameter of the material and, second, that the size of the plastic zone at the fatigue crack tip be at most a fifth of the crack length [3]. It is probably desirable to choose the structural parameter of the material based on the data of fractographic investigations since the micromechanism of crack development makes it possible to identify that structural component of the material failure of which determines the crack growth rate. Taking into consideration that with levels of ΔK close to ΔK_{th} in all of the samples a crack propagates intragranularly, it is logical to assume that for annealed 20Kh13 steel, Yu3 steel, and AMG-61 alloy the structural parameter may be the subgrain, the dimension of which for the majority of materials does not exceed 5 μm [4]. For hardened 20Kh13 steel, in which with ΔK close to ΔK_{th} intergranular crack growth is absent, the structural parameter is probably the width of a martensite crystal ($\sim$0.1 μm). Then, if it is assumed that the length of the crack must be an order of magnitude more than the structural parameter, the minimum crack for the investigated materials satisfying the first condition is 50 μm.

To verify the second condition, a calculation is made of the zone of plastic deformation at the tip of a fatigue crack using the known expression $r_f = 1/6\pi(K_{max}/\sigma_{0.2})^2$. The calculation results showed (Table 1) that in all cases even the minimum original crack length ($a = 0.2$ mm) is five times more than the zone of plastic deformation in tests in the near-threshold area, that is, the experiments were made without violation of the formal requirements controlling correct determination of ΔK. An analysis of the zone of plastic deformation at the tip of a short and a long fatigue crack made earlier [5] established that the length of the crack (0.5 mm and more) does not change its shape and size, which is determined entirely by the value of K_{max}. It is known that a decrease in crack length may lead to a reduction in the degree of constraint of plastic deformation at its tip, which must be reflected on the values of ΔK_{th} determined for samples with short cracks. A reduction in the degree of constraint of deformation at a crack tip also occurs with a decrease in sample thickness, which makes it possible to simulate the influence of this factor on ΔK_{th} in samples with short original cracks. Special investigations of samples of different thicknesses of technical grade iron containing long original cracks have indicated that with thinner samples a decrease in the degree of constraint of deformation causes an increase in ΔK_{th}. In addition, failure of 6-mm-thick samples occurs with the formation of a right-angle and with a thickness of 1.5 mm with an oblique fracture even with crack growth rates close to the threshold. Therefore, there is no basis for stating that the tests of samples with a short crack were made with violation of the conditions of self-simulation at its tip and that the effect noted of the reduction in ΔK_{th} with a decrease in crack length was caused by incorrectness in determination of the stress intensity factor.

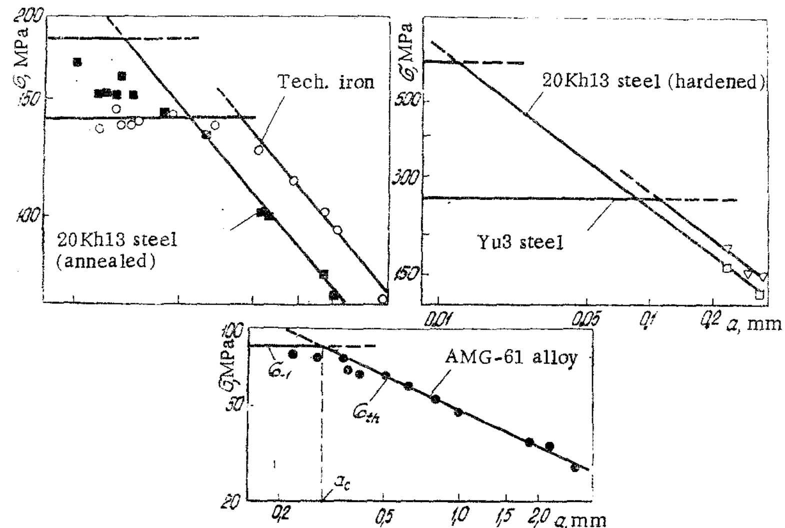

Fig. 4. Relationship of the nominal stresses in a sample corresponding to the threshold stresses ΔK_{th} to crack length a.

Influence of Crack Length on ΔK_{th}. The appearance of a reduction in ΔK_{th} with a decrease in crack length has been experimentally recorded in tests of aluminum [6] and its alloys [7], of copper [8], and of low-carbon [9-11] and high-strength [12] steels. Frost [6] established that for samples with a crack the value of $\sigma \cdot a^{1/3}$ (where σ is the applied amplitude of stresses and a is crack length) has a definite critical level below which a crack does not propagate, that is, actually the reduction in ΔK_{th} with a decrease in crack length below some critical value was predicted.

It has also been shown [3, 10] that stability of ΔK_{th} is provided only if the nominal stresses σ_{th} occurring in a sample and necessary for reaching the value of ΔK_{th} at the mouth of the crack do not exceed the fatigue limit of the material. Since with a decrease in crack length to maintain ΔK_{th} a constant increase in σ_{th} is required, then there is some limiting crack length $a = a_c$ at which equality of σ_{th} and σ_{-1} is established and a further decrease in crack length leads to the fact that $\sigma_{th} > \sigma_{-1}$ (Fig. 4). In such a situation the fatigue failure process is controlled by the fatigue limit and not by the value of ΔK_{th} of a short fatigue crack. The condition of equality of stresses in a sample to the fatigue limit of the material has been used [13, 14] for determining a certain constant of a given material, the crack length $a_c = 1/\pi(\Delta K_{th}/\sigma_{-1})^2$. Formal calculation of this constant in calculating the stress intensity factor at the mouth of a crack $\Delta K = \sigma\sqrt{\pi(a+a_c)}$ has made it possible, in essence, to eliminate the influence of crack length on the threshold values of ΔK_{th}.

To calculate the critical crack length a_c we made circular bending fatigue tests of 6-mm-diameter cylindrical unnotched samples of 20Kh13 steel after annealing and after hardening of Yu3 steel, and of AMG-61 alloy making it possible to determine their fatigue limits σ_{-1} using a base of 10^7 cycles. The fatigue limit of technical grade iron was taken from [4] taking into consideration the ferritic grain size. Drawing of the relationship of σ_{th} ($\sigma_{th} = \Delta K_{th}/Y(a)\sqrt{a}$ (1), where $Y(a)$ is a coefficient dependent upon the geometric dimensions of the sample) to the length of the original fatigue crack and simultaneous plotting on the curve of the line corresponding to the fatigue limit made it possible to determine for each of the materials the limiting crack length a_c below which a drop in ΔK_{th} must occur with a decrease in a ($a < a_c$). For any of the materials the parameter a_c may also be calculated from Eq. (1) with $\sigma_{th} = \sigma_{-1}$.

In the calculations of a_c we disregarded differences in loading asymmetry of unnotched samples ($R = -1$) and of samples with a crack ($R = 0$) since it is known [15] that within the limits of $-1 < R < 0$ cycle asymmetry does not have any marked influence on ΔK_{th}. A comparison of the experimental a_0 and calculated a_c crack lengths showed (Table 2) their satisfactory agreement despite the marked differences in loading asymmetry. From Fig. 4 the reasons for the absence of the influence of original crack length on ΔK_{th} for Yu3 and hardened 20Kh13 steels also become clear. For these materials the values of a_c, equal to ~ 0.12 and 0.012 mm, respectively, are much less than the minimum crack length ($a = 0.2$ mm) used in our experiments. We should note that $a_c = 0.012$ mm for hardened 20Kh13 steel is of the same order of magnitude as the limiting original crack length for 4340 steel in the high strength condition [12]. If the calculation of σ_{th} is made for cracks of less than the critical length ($a < a_0$), substituting the experimental values of ΔK_{th} for short cracks in Eq. (1), then the calculated stresses σ_{th} approach the fatigue limit of the materials (Fig. 4). This analysis is convincing evidence that for all materials there is a limiting original fatigue crack length which depends upon their microstructure

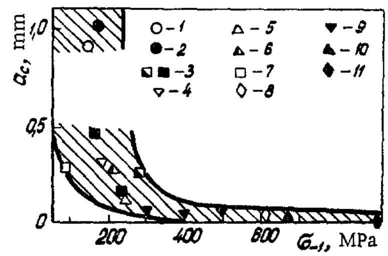

Fig. 5. Relationship of the limiting crack length a_c to the fatigue limit of the materials σ_{-1}: 1) technical grade iron; 2) mild steel [12]; 3) low-carbon steels [11, 14]; 4) 20Kh13, annealed; 5) Yu3; 6) aluminum alloy [6]; 7) AMG-61; 8) 45KhN2MFA, tempered at 400°C; 9) 75KhGST, annealed structure; 10) 20Kh13, hardened; 11) 4340 steel [12].

and therefore is the physical boundary of applicability of the traditional approaches of fracture mechanics for predicting the life of parts with cracks.

Summarizing of our own and literature data makes it possible to construct the relationship of critical crack length a_c to the fatigue limit of materials σ_{-1} (Fig. 5). From the curve it follows that there are two areas of values of a_c. The first, characteristic only of pure iron, is characterized by a combination of an increased limiting crack length and low levels of σ_{-1} while the second, which includes information on the most varied materials, reflects the general tendency of an increase in a_c with a decrease in σ_{-1}. These results indicate that for the majority of constructional materials the limiting original crack length is 0.5 mm and, consequently, this value of a_c may be assumed to be the practical boundary above which the approaches of fracture mechanics are applicable for describing fatigue crack development.

Features of the Development of Short Fatigue Cracks. In calculating the ΔK_{th} of a short fatigue crack observation of the condition $\sigma_{th} = \sigma_{-1}$ makes it possible to predict well the relationship of the threshold stress intensity factor to crack length but does not explain the nature of this phenomenon. The possibility of reaching in samples with a short crack nominal stresses equal to the fatigue limit is an indication of the fact that their behavior differs little from the behavior in the fatigue of unnotched samples. At the same time it is known [4] that cyclic loading with stresses close to the fatigue limit causes substantial changes in the substructure of the surface layers of samples. For example, in testing iron samples with an amplitude of stresses close to the fatigue limit the band dislocation structure propagates to a depth of up to 0.45 mm [16]. Therefore in the case of tests of samples containing surface cracks with a depth of $a < a_0$ the structural changes occurring in the surface layers of the metal may have a significant influence on the conditions of formation of the prefailure zone located at the tip of a short fatigue crack and, consequently, on ΔK_{th}. In samples with a long original crack such a picture is not observed since the stresses σ_{th} are always less than σ_{-1}. The intensity and depth of the damage of the surface layer of samples in tests at the level of the fatigue limit is determined completely by the microstructure of the material and on this basis the reason for the occurrence of a broad spectrum of values of a_0 for different materials becomes understandable. As follows from the results of this work, the strongest influence of original crack length on ΔK_{th} occurs in the purest material, technical grade iron. At the same time there is a change in the morphology of the sample fracture; areas of crack slip growth occur. Based on our own and literature data, it may be stated that the appearance of areas of crack slip growth with a near-threshold rate assumes the fulfillment of certain conditions. First, the formation of stable slip bands must be eased [17], which in turn depends upon the packing defect energy of the metal and also upon the morphology and particle size of the dispersed phases [18]. A reduction in the packing defect energy of metals and the presence of dispersed precipitates not cut by dislocations hinders the formation of stable slip bands. Second, a combination of high stresses in the sample with low values of the stress intensity factor, which occurs only in testing samples with short surface cracks, is necessary. High stresses promote intense cycle plastic deformation and the formation of stable slip bands while a low level of ΔK may be insufficient for the occurrence of fracture by rupture. The latter is confirmed by the data of investigations [19] of crack growth with a mixed form of loading (shear–rupture, $K_{II}-K_I$) in iron, in which areas of shear failure were recorded with ΔK of not more than 5.6 MPa$\cdot\sqrt{m}$. It should be noted that the conditions of near-threshold fatigue crack growth in shear and rupture differ substantially and this must be reflected on ΔK_{th}. Nevertheless the absence of areas of shear crack growth in the other investigated materials is an indication of the fact that probably such a failure micromechanism is not compulsory for the appearance of the effect of short cracks.

Therefore in general for a single class of materials the structural changes increasing the fatigue limit must reduce the limiting original crack length a_0 since there will be a decrease in the depth of the surface zone of the metal in which irreversible changes occurred in the substructure during cyclic loading at stress levels close to the fatigue limit. As a result of this from a practical point of view the understanding itself of the limiting crack length obviously loses sense for high strength steels characterized by high values of σ_{-1}, in which the origin of fatigue cracks normally occurs from subsurface inclusions and the size of an embryonic crack exceeds the limiting crack length a_c [12, 20].

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