Plastic Zones Formation under Different Types of Loading Conditions

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The plastic zone formation under the fracture surface in materials possessing a Body-Centered Cubic Lattice (BCC) structure (steel 20, 40, 45, St 3, 15X2MΦA) and materials possessing a Face-Centered Cubic Lattice (FCC) structure (aluminium alloy D16 and austenitic steels 40Г18Φ, 40X4Г18Φ, 03X13AГ19, 07X13H4AГ20) was studied by the X-Ray Diffraction method. Specimens were tested under a static, impact, high-speed impulse, cyclic (fatigue) and impact-cyclic loading conditions at the wide temperature range.

It was shown that two plastic zones were formed under all above types of loading conditions if the plane stress state was attained at the crack tip. Only one micro-plastic zone is formed under the plane strain deformation state.

A scheme of two plastic zones formation at the crack tip of specimens tested under a static, impact and impulse types of loading conditions is presented.

Besides that, it was found that both impulse and impact-cyclic loadings resulted in not only plastic zones formation but work hardening of the material of specimens.

KEY WORDS: fracture; plastic zone; X-ray diffraction technique; plane stress state; plane strain state.

1. Introduction

The X-ray diffraction analysis of fracture^{1,2)} is often used (in addition to conventional methods of macro- and micro-fractographical analyses) in studies to determine the failure mechanism of metallic components. This method allows the depth of plastic zones under the fracture surface to be determined and also the structural variation of the material within these zones.^{3,4)} The analysis of plastic zones gives valuable information on i) the local stress state of the material at the crack tip, ii) the level and characteristics of the applied load and iii) the mechanism of failure. These are the main reasons why the X-ray diffraction analysis is a perspective technique for diagnostic of material failure in structural

components.

The first part of this paper presents regularities of the plastic zones formation at the crack tip of the material with a BCC-lattice structure and FCC-lattice structure caused by following loading conditions i) static, ii) impact, iii) high-speed impulse, iv) cyclic and v) impact-cyclic. The second part of the paper presents the employment of the X-ray diffraction analysis for diagnostics of the failure.

2. Materials and Experimental Techniques

Materials employed in this study were steel 20, 40, 45, St 3, 15X2MΦA with a BCC-lattice structure and aluminium alloy D16, austenitic steels 40Г18Φ, 40X4Г18Φ, 03X13AГ19, 07X13H4AГ20 with a FCC-

Table 1. Chemical composition of the steels studied. (mass%)

Material	C	Mn	Si	P	S	Cr	Ni	V	Mo	N
Steel 20	0.18	0.50	0.30	0.04	0.04					
Steel 40	0.39	0.60	0.30	0.04	0.04					
Steel 45	0.45	0.50	0.25	0.04	0.04					
St 3	0.20	0.50	0.20	0.05	0.05					
15X2MΦA	0.15	0.60	0.27	0.02	0.02	2.75	0.40	0.35	0.80	—
40Г18Φ	0.42	17.96	0.20	0.02	0.01	—	—	1.22	—	—
40X4Г18Φ	0.43	18.00	0.20	0.01	0.01	4.20	—	1.41	—	—
03X13AГ19	0.03	19.35	0.50	0.01	0.01	13.50	0.74	—	—	0.17
07X13H4AГ20	0.06	21.87	0.45	0.01	0.01	14.86	4.89	—	—	0.14

lattice structure. The chemical composition, thermal processes and mechanical properties are given in **Tables 1 to 3**.

Mechanical tests included the following procedures:

(1) Fracture toughness tests as shown in **Fig. 1a** were conducted employing compact tension specimens (CT) having a thickness of $t=2 \times 10^{-2}$ m. Specimens manufactured from steel 20, 40, 15X2MΦA, 03X13AΓ19, 07X13H4AΓ20 were tested at the temperature interval ranging from -196 to $+150^{\circ}\text{C}$. Compact tension specimens manufactured from the hardened and aged alloy D16 having a various thickness were tested at room temperature.

(2) Impact strength tests as shown in **Fig. 1b** were performed on bend specimens with edge notch and preliminary grown fatigue crack. The depth of the notch with a fatigue precrack was equal to 2×10^{-3} m. Specimens manufactured from steel 45 had sizes $(1.5 \times 1.5 \times 5.5) \times 10^{-2}$ m, from 40Γ18Φ and 40X4Γ18Φ steels— $(1.0 \times 1.1 \times 5.5) \times 10^{-2}$ m. Tests were conducted at the temperature interval ranging from -196 to $+150^{\circ}\text{C}$.

(3) High-speed impulse tests were performed employing the method on the ring specimens (the inside diameter is equal to 6.3×10^{-2} m, the outside diameter is equal to 15×10^{-2} m) with thickness of $t=1.8 \times 10^{-2}$ m made from steel St 3 and with a thickness of $t=2.5 \times 10^{-2}$ m made from 40Γ18Φ steel (**Fig. 1c**). Two fatigue cracks into the inside surface of ring specimens were grown through 180° . Specimens were fractured employing the inside pressure as shown in **Fig. 1c**. Tests were conducted

at temperature 20, -120 and -170°C .

(4) Fatigue tests were conducted employing compact tension specimens (**Fig. 1d**). Specimens manufactured from steel 20 with a thickness of $t=2.0 \times 10^{-2}$ m were tested at a load ratio $(P_{\min}/P_{\max}) R=0.5$ and at the room temperature. Specimens made from the D16 alloy with a thickness of $t=1.0 \times 10^{-2}$ m were tested at the load ranging from $R=0.1$ to 0.6 . Two schemes of tests were used (**Fig. 2**). First of them when $\Delta P=(P_{\max}-P_{\min})$ is a constant and second when $P_{\max}$ is a constant. Tests were conducted at the room temperature. Specimens manufactured from the D16 alloy with various thickness ranging from 1.0×10^{-2} to 5.0×10^{-1} m were loaded at $R=0.5$ and room temperature. Specimens with a thickness of $t=2.0 \times 10^{-2}$ m from steels 03X13AΓ19 and 07X13H4AΓ20 were tested at temperatures $T=-196^{\circ}\text{C}$, $T=-80^{\circ}\text{C}$ and $T=20^{\circ}\text{C}$.

(5) Impact-cyclic tests were conducted on the single edge notch bend with a thickness of $t=1.2 \times 10^{-2}$ m employing 4 point bend test at $R=0$. Nominal stress of cycle was equal to $\sigma_n=235$ MPa and $\sigma_n=410$ MPa. Specimens were manufactured from steel 45. All

Table 2. Chemical composition of the aluminium alloy. (mass%)

Alloy	Cu	Mn	Si	Mg	Zn	Fe
D16	4.5	0.6	0.2	1.5	0.12	0.23

Fig. 1. Shapes of specimens and loading scheme under static (a), impact (b), high-speed impulse (c), cyclic (d) and impact-cyclic (e) types of loading conditions.

Table 3. Thermal treatment and mechanical properties of the materials studied.

Material	Thermal treatment	σ_6 (MPa)	$\sigma_{0.2}$ (MPa)	δ (%)	ψ (%)
Steel 20	annealing	450	260	24	59
Steel 40	hardening + intermediate tempering	1 400	1 200	8	39
Steel 45	annealing	590	320	20	50
	hot-rolled	610	360	16	40
St 3	hot-rolled	470	270	23	55
15X2MΦA	hardening + high tempering	700	530	20	59
D16	hot-rolling	233	117	12	—
	hardening + ageing	440	345	18	—
40Γ18Φ	hardening	960	350	48	45
40X4Γ18Φ	hardening	900	400	55	50
	hardening + ageing	950	600	50	50
03X13AΓ19	hardening	670	380	40	45
07X13H4AΓ20	hardening	685	365	74	62

Fig. 2. Loading scheme of aluminum D16 alloy under fatigue test. P , load; $P_{\max}$, maximum load on cycle; $\Delta P = P_{\max} - P_{\min}$; $R = P_{\min}/P_{\max}$, load ratio; τ , time.

impact-cyclic tests were carried out at a room temperature.

Both static and cyclic tests were conducted on the hydraulic test machine MK-30, the impact-cyclic tests were made with DC0-150 machine.

All the fracture surfaces were subjected to fractographical and X-ray diffraction analysis. Micro-fractographical studies were carried out with a JSM-U3 scanning electron microscope. X-ray diffraction analysis was made with a diffractometer DRON-1.5 and DRON-2.0 in the $\text{Fe K}\alpha$ and $\text{Co K}\alpha$ radiations. The X-ray irradiated area depends on shape and size of fracture surface and also problem. When static and impulse fracture surfaces were investigated the X-ray irradiated area was equal to $(2.5 \times 10) \times 10^{-3} \text{ m}$. When the impact fracture surface was investigated, it was equal to $(2.5 \times 6.5) \times 10^{-3} \text{ m}$. Under investigation of the fatigue fracture surface, the beam in the form of narrow split is directed to the fracture surface. The narrow split is parallel to the crack propagation line. X-ray irradiated section width in direct of crack propagation is equal to $8.0 \times 10^{-4} \text{ m}$.

About the change of the crystalline structure distortion we judged on the change of the diffraction line breadth $(220)\text{K}\alpha$, for materials with BCC-lattice structure, and $(311)\text{K}\alpha$ for materials with FCC-lattice structure.

The depth of the layer of plastic zones under the fracture surface and variations of the material structure within these zones were studied employing chemical etching method. The fracture surface of tested specimens was subjected to the X-ray diffraction at several locations. The fracture surface was then etched chemically, and was again subjected to the X-ray diffraction.⁶⁾ The series of these processes were repeated. The etched surface layer thickness was defined using the capacitance method,⁷⁾ permitting to account for changes of the profile of the fracture during the etching process. The perpendicular section to the fracture surface was subjected to X-ray

Fig. 3. Correlation between diffraction line width (β) and etched layer thickness (h). a—linear coordinates; b—logarithmic coordinates; 1—micro plastic zone h_{yh} is formed under fracture surface; 2—micro plastic h_{yh} and macro plastic zone h_y are formed under fracture surface; 3—transition state.

diffraction when the plastic zone had a large depth.⁶⁾

Then a scheme showing the variations in width (broadening) of the diffraction line as a function of the thickness of the etched metal layer from the fracture surface was drawn. Some of the relations between distance from fracture surface (h) and diffraction line width (β) are shown in Fig. 3. One can see β value is highest on the fracture surface. It decreases with the increase in depth. If two plastic zones are formed under the fracture surface the depth of highly-deformed micro plastic zone h_{yh} (or the depth of cyclic plastic zone under fatigue failure) was regarded as a distance from the fracture surface where the curve 2 becomes the first horizontal plateau. The depth of lowly deformed macro plastic zone h_y (or the depth of monotonic plastic zone under fatigue failure) was regarded as a distance from the fracture surface where β becomes nearly equal to half-peak breadth of X-ray diffraction line β_0 obtained from the non-strained material. If only one plastic zone is formed under the fracture surface (curve 1) the distance from the fracture surface where β is equal to β_0 is regarded as the depth of micro plastic zone h_{yh} .⁹⁾ But sometimes to divide of plastic zone under the fracture surface into two plastic zones (h_{yh} and h_y) may be difficult (curve 3).

3. Results of Measurement and Discussion

3.1. Plastic Zones Formation under a Static, Impact and High-speed Impulse of Loading Conditions

Both static and impact specimens made of steels 20, 40, 45 and 15X2MΦA were tested within the ductile-brittle transition region. Fractured specimens were subjected to X-ray diffraction. Only one micro plastic zone (h_{yh}) under the brittle fracture surface was evident. Under the ductile fracture surface two plastic zones: a highly deformed micro plastic zone (h_{yh}) and lowly deformed macro plastic zone (h_y) were evident. The

Table 4. The BCC lattice structure material fracture toughness test results and determination of the depth of the micro (h_{yh}) and macro plastic (h_y) zone under the fracture surface, and the ratio h_{max}/t .

Material	T (°C)	$\sigma_{0.2}$ (MPa)	K_{Ic} (K_c) (MPa $\sqrt{m}$)	$t/\left(\frac{K}{\sigma_{0.2}}\right)^2$	$\frac{P_{max}}{P_Q}$	l_c (%)	h_{yh} (10^{-4} m)	h_y (10^{-3} m)	h_{max}/t
Steel 20	−196	840	30	15.3	1.05	0.3	0.45	—	2.31×10^{-3}
	−70	520	29	6.3	1.05	0.3	1.2	—	6.11×10^{-3}
	20	260	36	1.2	1.12	1.5	0.8	2.5	1.28×10^{-1}
	50	250	42	0.7	1.12	2.5	1.6	5.2	2.65×10^{-1}
	100	230	49	0.4	1.15	2.5	2.5	8.3	4.26×10^{-1}
	150	210	52	0.3	1.18	3.0	3.6	11.3	5.08×10^{-1}
Steel 40	−196	1 550	57	14.4	1.00	0	0.82	—	2.80×10^{-3}
	20	1 200	62	7.3	1.05	0.5	1.1	—	5.60×10^{-3}
15X2MΦA	−196	1 200	50	11.5	1.05	0.3	1.0	—	5.00×10^{-3}
	20	530	90	0.7	1.16	2.6	5.0	4.0	2.20×10^{-1}

Table 5. The FCC lattice structure material fracture toughness test results and determination of the depth of the micro (h_{yh}) and macro-plastic zone (h_y) under the fracture surface, and the ratio h_{max}/t .

Material	T (°C)	$\sigma_{0.2}$ (MPa)	t (10^{-2} m)	K_{Ic} (K_c) (MPa $\sqrt{m}$)	$t/\left(\frac{K}{\sigma_{0.2}}\right)^2$	$\frac{P_{max}}{P_Q}$	l_c (%)	h_{yh} (10^{-4} m)	h_y (10^{-3} m)	h_{max}/t
D16	20	345	4.0	22.0	9.8	1.02	1.26	3.5	—	8.80×10^{-3}
	20	345	3.0	22.5	7.1	1.05	1.50	1.0	0.40	1.30×10^{-2}
	20	345	2.0	23.0	4.5	1.12	2.22	1.4	0.65	3.20×10^{-2}
	20	117	1.5	17.6	0.7	1.42	3.93	9.0	3.60	2.40×10^{-1}
03X13AГ19	−196	720	19.5	60.8	4.8	1.10	1.30	1.5	0.53	2.70×10^{-1}
	20	380	19.5	69.0	0.6	1.40	6.70	2.0	5.00	2.56×10^{-1}
	150	350	19.5	68.0	0.5	1.80	13.90	4.0	5.80	2.97×10^{-1}

scheme of the plastic zones formation is shown in Fig. 3.^{8,9)}

Two plastic zones under the fracture surface of materials having BCC lattice structure are formed at the lower critical temperature of brittleness (T_{br}^l). The depth of plastic zones and severity of the material crystalline structure distortion within these zones^{8,9)} increase with a test temperature, but only within the ductile–brittle transition region. At the upper critical temperature of brittleness (T_{br}^u) the depth of zones and structural variations of the material reach a critical maximum value and little change is noted with a further increase of the test temperature. This phenomena is the basis for the conclusion reached in¹⁰⁾ where by the X-ray diffraction method the lower and upper critical temperatures of brittleness were determined.

Let us compare results of the test from materials having a BCC lattice structure with the depth of plastic zones under the fracture surface. One can see (Table 4) if the fracture mechanics criterion,^{11,12)} $t/(K/\sigma_{0.2})^2 \geq 2.5$, the plane strain deformation condition (PD) satisfied, one micro plastic zone (brittle fracture) is formed under the fracture surface. Two plastic zones are formed (ductile–brittle and ductile fracture) if this criterion is not satisfied. To use the ratio of the maximum depth of the plastic zone h_{max} to the specimen thickness t as a criterion for evaluation of the material local stress state at the crack tip has been suggested in.⁹⁾ If two plastic zones, h_{yh} , and h_y , are formed under the fracture surface, we considered that $h_{max} = h_y$. If under the fracture surface one plastic zone is formed we considered $h_{max} = h_{yh}$. As

shown in Table 4 the ratio $h_{max}/t < 10^{-2}$ when the brittle fracture is observed. The ratio $h_{max}/t > 10^{-1}$ when the ductile–brittle and ductile fracture are observed. So the change of the stress state from plane strain deformation to plane stress state at the crack tip take place in the BCC lattice structure materials at the lower critical temperature of brittleness.

Transition from plane stress state to plane strain deformation in materials with an FCC lattice structure (in contrast to materials with a BCC lattice structure) is not accompanied by their embrittlement in most cases. This is shown by the data acquired by both fractographic and X-ray diffraction analysis.¹³⁾ Analysing results of tests on static crack resistance performed on materials with an FCC lattice structure (Table 5) one can see that conditions for plane strain deformation according to fracture mechanic criterions,^{11,12)} are realized for specimens made from an alloy D16 with a thickness $t = 3 \times 10^{-2}$ m and $t = 4 \times 10^{-2}$ m. Both ratio P_{max}/P_Q and value l_c do not satisfy PD criterions $P_{max}/P_Q \leq 1.1$ and $l_c \leq 1.5$ for specimens with thickness equal to 2×10^{-2} m. The condition of plane strain deformation is realized when specimens made from steel 03X13AГ19 are tested at -196°C (see, Table 5). In the case when specimens made from an alloy D16 are failed in a state of plane strain deformation ($t = 4 \times 10^{-2}$ m) (see, Table 5) only one micro plastic zone h_{yh} is discovered under the fracture surface. The ratio h_{max}/t is equal to 8.8×10^{-3} . In the case when a ratio $t/(K/\sigma_{0.2})^2$, ratio P_{max}/P_Q and a value l_c do not satisfy the condition for plane strain deformation ($t = 1.5 \times 10^{-2}$ m) two plastic zones h_{yh} and h_y were

discovered under the fracture surface. The ratio $h_{\max}/t$ is equal to 2.4×10^{-1} . Though there are cases with materials possessing an FCC lattice structure when $h_{\max}/t$ approximately equal to 10^{-2} (see, Table 5). It means that specimens failed in a transition field from plane strain deformation to plane stress state. In this case the ratio $P_{\max}/P_Q$ and the value l_c (see, Table 5) do not satisfy the condition for plane strain deformation.

The ratio $h_{\max}/t$ equal to 10^{-2} was found in the following static failure of steel 03X13AГ19 (see, Table 5) and also was found in the following impact failure of austenitic steels 40Г18Ф and 40X4Г18Ф.¹⁴⁾ In these cases transition state of materials from plane strain deformation to plane state is realized.

Under high-speed impulse loading of the ring specimens made from steels St3 and 40Г18Ф the speed of crack propagation ranged from between 786 to 950 m/sec at a temperature of 20°C and it was equal between 2 150 to 2 300 m/sec at -120 and -170°C.¹⁶⁾ Under all test temperatures steels 45 and St3 failed in a brittle manner, and the steel 40Г18Ф failed in a combination of micro-void coalescence+cleavage failure. Only one micro plastic zone h_{yh} under the fracture surface of all specimens was detected. Here, the value of the ratio $h_{\max}/t$ was not larger than 10^{-2} (state of plane strain deformation). Besides that, it has been established,¹³⁾ the impulse loading resulted in work hardening of the material.¹⁵⁾ Such work hardening was found in steel 45 and St3 at 20 and -120°C and also in specimens made from steel 40Г18Ф at room temperature. Impulse loading of the specimens made from steel 40Г18Ф do not cause substantial work hardening at low test temperatures (-170°C) but from 5 to 7%) &-martensite was formed over a whole section of the specimen which substantially increased the hardness of the steel. It seems that impact wave propagation through the specimen is a cause of the work hardening.

Thus one can see that the value of plastic zones forming under the fracture surface of specimens tested under static, impact and high-speed impulse types of loading conditions depends on material local stress state at the crack tip. **Figure 4** shows a schematic of two plastic zones generated when the plane stress state condition is attained at the crack tip. The lowly deformed macro plastic zone r_y is formed at the crack tip before the second zone. Its formation is related to the yield point of the material $\sigma_{0.2}$.¹⁶⁾ The deformational work hardening of the material within this zone is the same as work hardening after between 3 to 5% deformation by strain,⁸⁾ which brings about an increase of the material yield point by between 20 to 30% and up to the value $\sigma_{0.2}^*$. This increase of the yield point brings about the change of the stress state in the material at the crack tip. Then the crack propagates in the deformationally work hardened material. The state close to plane strain deformation state is attained at the crack tip. The highly deformed micro plastic zone r_{yh}^* is formed at the crack tip (see, Fig. 4).

When the stress state close to plane strain deformation state at the crack tip of the material having the yield point $\sigma_{0.2}$ only one micro plastic zone r_{yh} is formed.¹²⁾ If the transition state from plane strain (PD) to plane stress

Fig. 4. Scheme of two plastic zones formation at the crack tip of materials subjected to monotonic of loading sequences and under plane stress state.

Fig. 5. Scheme of plastic zones at the crack tip under PS and PD.
a - materials with BCC lattice structure; b - materials with FCC lattice structure.

(PS) is attained at the crack tip to distinguish highly deformed plastic zone and lowly deformed plastic zone is difficult. This case is shown in Fig. 3 by curve 3.

During ductile failure in PS state of the material with a BCC lattice structure the distortion of the crystalline structure in the lowly deformed macro plastic zone is the same as that in the micro plastic zone forming during the brittle failure in PD state⁸⁾ (Fig. 5a).

When the plane stress state is attained at the crack tip of the material with an FCC lattice structure the distortion of crystalline structure in both highly deformed and lowly deformed plastic zones is approximately the same as that in material with a BCC lattice structure (Fig. 5b). When the plane strain deformation condition is attained at the crack tip of these materials only one micro plastic zone is formed. But the crystalline structure distortion in this zone reaches a critical level for the prefailure which is close to the distortion under PS (see, Fig. 5b).

3.2. Plastic Zones Formation under Cyclic (Fatigue) and Impact-cyclic Loading Conditions

It is known that two plastic zones¹⁴⁾ both cyclic and monotonic are formed at the crack tip under application

of the fatigue loading.¹⁷⁾ Sizes of these zones increase with an increase both applied maximum stress intensity value $K_{\max}$ and applied stress intensity range ($\Delta K = K_{\max} - K_{\min}$). The cyclic plastic zone correlates better with ΔK and the monotonic plastic zone with $K_{\max}$.¹⁸⁻²⁰⁾

Both loading scheme and load ratio R influence with fatigue crack propagation speed and with regularities of plastic zones formation.²¹⁾ As an example the effect of above factors on the crack propagation speed of aluminum alloy D16 will be considered. The crack propagation speed increases with an increase of ratio R when ΔK is constant. It decreases when $K_{\max}$ is constant. It takes place when both $\Delta P = \text{const}$ or $P_{\max} = \text{const}$ (see, Fig. 2). Besides coefficient n in Paris's equation increases with an increase of R independently of the loading scheme (Table 6).

It is interesting to consider how the loading scheme and the ratio R influence on the critical crack lengths. In Fig. 6a they are shown as l_s and l_f . As shown in Fig. 6b if $\Delta P = \text{const}$ l_s decreases with an increase the ratio R . If $P_{\max} = \text{const}$ l_s increases. Critical crack length l_f depends on $P_{\max}$ therefore when $P_{\max} = \text{const}$ l_f is a constant too and it is independent of the ratio R .

However stress intensity values ΔK^s and $K_{\max}^s$ when the fatigue crack length $l = l_s$ are independent of loading scheme but depend on the ratio R (Fig. 6c).

The correlation between the cyclic plastic zone depth h_{yh} , the monotonic plastic zone depth h_y and ΔK , $K_{\max}$ are given in Figs. 7a and 7b. Both the relation $h_{yh} - \Delta K$ and $h_y - K_{\max}$ are independent of the ratio R and loading scheme.

The h_{yh} value is related to the ΔK value as

$$h_{yh} = 9.5 \times 10^{-6} \Delta K$$

Table 6. Relation of the Paris's equation coefficient to the load ratio R and loading scheme for D16 alloy.

R		0.1	0.2	0.3	0.4	0.5	0.6
n	$\Delta P = \text{const}$	1.3	1.6	1.7	1.9	2.4	4.9
	$P_{\max} = \text{const}$	1.3	1.6	1.7	1.9	2.5	—

The h_y value is related to the $K_{\max}$ value as

$$h_y = 2.2 \times 10^{-6} K_{\max}^2$$

Figure 8 shows the relation between the diffraction line width obtained along fatigue fracture surface, β , and two parameters such as amplitude of stress, ΔK , and stress intensity factor, $K_{\max}$. At first β is a constant with the increase of ΔK and $K_{\max}$, then it increases. Comparing values ΔK and $K_{\max}$ at the point where β starts to increase with critical values of ΔK^s and $K_{\max}^s$ at $l = l_s$ (see, Fig. 6c) one can see that $\Delta K = \Delta K^s$ and $K_{\max} = K_{\max}^s$. As β characterizes the severity of crystalline structure distortion we can say that the severity of crystalline structure distortion on the fatigue fracture surface is a constant at $l \leq l_s$ and increases at $l_s < l \leq l_f$ (see, Fig. 6a).

Fig. 6. Scheme of fatigue fracture surface where l_s and l_f are critical crack lengths (a), $l_s - R$ (b), $\Delta K^s - R$, $K_{\max}^s - R$ (c) relations in D16 alloy. Light spots - $\Delta P = \text{const}$; dark spots - $P_{\max} = \text{const}$.

Fig. 7. Relation between cyclic plastic zone depth h_{yh} , monotonic plastic zone depth h_y and ΔK (a), $K_{\max}$ (b) for different ratio R in D16 alloy. $R = 0.1$ (1); 0.3 (2); 0.5 (3). Light spots - $\Delta P = \text{const}$; dark spots - $P_{\max} = \text{const}$.

Fig. 8. Relation between diffraction line (311) K_α width and ΔK (a), K_{max} (b) for different load ratio R in D16 alloy. $R = 0.1$ (1); 0.5 (2); 0.6 (3). Light spots – $\Delta P = \text{const}$; dark spots – $P_{max} = \text{const}$.

If ΔP is a constant, but K_{max} increases with the increase of R (see, Fig. 2a), the severity of crystalline structure distortion on the fracture surface within l_s increases with increase of R (see, Fig. 8). When the load P_{max} is a constant K_{max} is independent of R (see, Fig. 2b). In this case the severity of crystalline structure distortion within l_s is independent of R . Consequently, the severity of crystalline structure distortion within l_s is related to maximum stress intensity factor, K_{max} , and is not related to amplitude of stress, ΔK .

The X-ray diffraction analysis of the impact-cyclic fracture surface of steel 45 have shown that two plastic zones *i.e.* cyclic and monotonic zone are also formed under this type of loading. Though, in contrast to the cyclic loading, during the impact-cyclic loading sequence, we have discovered a deformational work hardening of material, though this work hardening manifested itself to a lesser degree when compared to the impulse loading sequence.

4. Conclusion

The following conclusions have been drawn on the basis of the current investigation.

(1) Failure of materials with both a BCC and FCC lattice structure subjected to monotonic of loading sequences and under a condition of plane stress state (PS) is accompanied by the formation of two plastic zones at the crack tip: i) a highly deformed micro plastic zone, ii) a lowly deformed macro plastic zone. Only one micro plastic zone is observed under conditions of plane strain deformation (PD).

(2) The change in the stress state with a transition from PD to PS occurs at the lower critical temperature of brittleness in materials with a BCC lattice structure. The change in the local stress state with the transition from PS to PD in materials with an FCC lattice structure is not accompanied with embrittlement.

(3) The high-speed impulse and impact-cyclic failures

are accompanied with the deformational work hardening of the material.

(4) The critical length of crack l_s on the fracture fatigue surface depend with loading scheme and ratio R . Critical values of two parameters, such as amplitude of stress, ΔK^s , and stress intensity factor, K_{max}^s , are independent of loading scheme.

(5) The cyclic plastic zone depth h_{yh} increases with the increase of ΔK , and monotonic plastic zone depth h_y increases with the increase of K_{max}^2 . Both the relation $h_{yh} - \Delta K$ and $h_y - K_{max}$ are independent of loading scheme and load ratio R .

Determined regularities of plastic zones formation under different types of loading conditions can be used for X-ray diffraction techniques of failure diagnostics.

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