METALS FRACTURE MICRO MECHANISM AND PLASTIC ZONES FORMATION AT THE CRACK TIP

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Fracture micro mechanisms, plastic zones formations and local stress state at the crack tip in materials possessing a BCC-lattice structure and FCC-lattice structure were studied by the X-ray diffraction method. Specimens were tested under single, cyclic and impact- cyclic fracture modes.
It was shown two plastic zones are formed under the ductile fracture in plane stress state condition (PS). One plastic zone is formed under the brittle fracture in plane deformation condition (PD).
Generalizing scheme of plastic zones formation at the crack tip according to load ratio R is presented.
Under single and cyclic fracture modes in plane stress state condition (PS) and plane deformation condition (PD) martensitic transformation after crack propagation is possible. Character of martensitic phases distribution in plastic zones under the fracture surface is connected with fracture micro mechanism and local stress state at the crack tip.

Introduction

Today, requirements to both structural materials and techniques for evaluation of material reliability and quality are very high. A special attention is spared to elaboration of new, physical grounded criterions of mechanical behaviour of materials. Elaboration of new, physical grounded criterions of strength and plasticity is possible only on the basis of physics, material science and fracture mechanics that is within the limits of new scientific direct – fracture micromechanics. Using of ideas and methods of micro mechanics for study the nature of strength and fracture is connected with local methods of fracture investigation. X-ray diffraction analysis is one of these methods allowing investigate plastic zones under the fracture surface, determine the depth of these zones, crystalline structure distortion, phase transformation and also phase distribution within plastic zones. Plastic zones forming at the tip of propagating crack are binding link between structure and mechanical properties of metal and also characterize the behaviour of material under loading condition. A local stress state at the tip of propagating crack influences on the crystalline structure distortion, and, consequently, on martensitic transformation taking place during both deformation and fracture. And the distortion of crystalline structure and, in particular, martensitic transformations at the crack tip influence on kinetics and fracture mechanism. However, martensitic transformations in plastic zones at the crack tip are studied not enough. Results of complex investigation of the interrelation between local stress state, local heating at the crack tip, plastic zones formation, distribution of martensitic phases within plastic zones, and, also fracture micro mechanism are presented.

Materials and experimental techniques

Materials employed in this study were steels having Body-Centered Cubic Lattice (BCC) structure: carbon steels - Steel 15 (0.15 %C), Steel 20 (0.18 %C), Steel 40 (0.39 %C), Steel 45 (0.45 %C), St 3 (0.2 %C), medium-alloyed steel 15Х4МФА (0.15 %C, 2,75 %Cr, 0.8 %Mo, 0.6 %Mn, 0.4 %Ni) and materials with Face-Centered Cubic Lattice (FCC) structure: aluminum deformed alloys - D16 (4.5 % Cu, 0.6 %Mn, 0.2 %Si, 1,5 %Mg, 0.12 %Zn, 0.23 %Fe), AK6 (2.22 %Cu, 0.6 %Mn, 0.9 %Si, 0.6 %Mg, 0.5 %Zn, 0.7 % Fe, 0.1 % Ni), austenitic steels – H32T3 (0.03 %C, 32.1

%Ni, 3/2 %Ti), Н26Т3 (0.035 %C, 26.6 %Ni, 3.18 %Ti), Н26Х5Т3 (0.03 %C, 4.2 %Cr, 26.0 %Ni, 2.7 %Ti), 40Г18Ф (0.42 %C, 17.96 %Mn, 0.09 %Cr, 1.22 %V), 40Х4Г18Ф (0.43 %C, 18.0 % Mn, 4.2 %Cr, 1.41 %V), 03Х13АГ19 (0.03 %C, 19.35 %Mn, 13.5 %Cr, 0.74 %Ni, 0.17 %N), 07Х13Н4АГ20 (0.06 %C, 21.87 %Mn, 14.86 %Cr, 4.89 % Ni, 0.14 % V), 110Г13Л (1.06 % C, 15.18 % Mn, 0.2 %Cr, 0.4 %Ni).

Carbon steels were subjected to following treatments i) steel 15 and steel 20 – annealing ii) steel 40 – hardening +intermediate tempering, iii) steel 45 – annealing + hot-rolling iv) St 3 - hot-rolling v) 15Х4МФА – hardening + high tempering vi) D16 – hot-rolling + quenching + aging. Austenitic steels were solution heat treated by heating at 1100 °C (40Г18Ф, 40Х4Г18Ф), 1050 °C (110Г13Л), 1150 °C (other steels) followed by water quenching. After quenching steels Н32Т3, Н26Т3, Н26Х5Т3, 40Г18Ф, 40Х4Г18Ф were subjected to an aging treatment both at different temperature and aging time. The steels 03Х13АГ19, 07Х13Н4ФГ20 and also steel 110Г13Л were used after quenching. After all heat treatment specimens were tested under static, impact, high-speed impulse, cyclic and also impact-cyclic loading conditions at the temperature interval ranging from -196 to +150 °C. The fracture surfaces of all specimens were observed by macro and micro fractography. Both plastic zones depth under the fracture surface, change of the crystalline structure distortion and martensitic transformations within plastic zones were determined by X-ray diffraction method employing improved by authors chemical etching technique [1].

For determination of the material local stress state at the crack tip improved by authors criterion h_{max}/t was used [2, 3], where h_{max} – maximum plastic zone depth under the fracture surface, t – sample thickness. If the fracture occurs under i) a plane deformation (PS) the ratio $h_{max}/t < 10^{-2}$; ii) a plane stress state (PS) the ratio $h_{max}/t > 10^{-1}$; iii) transition from PD to PS the ratio $10^{-2} < h_{max}/t < 10^{-1}$.

Plastic zones and material local stress state under simple loading conditions. Plastic zones forming at the crack tip under simple loading conditions in PD and PS are distinguished by both form and size that effect on both fracture mechanism and crack propagation resistance. Moreover, under investigation of plastic zones formation during fracture ought to take in consideration next circumstances. In first, during some materials fracture (for instance, in materials with FCC – lattice during combined fracture), besides limited values of material local stress condition, the transition from PD to PS at the crack tip can be realized [4]. Second, according to many experimental data [1-4], two plastic zones i) lowly deformed macro plastic zone h_y and ii) highly deformed micro plastic zone h_{yh} distinguishing by size and degree of crystalline lattice distortion are formed at the crack tip during fracture under PS and also sometimes under transition from PD to PS. Elaborated by authors the scheme of plastic zones formation under the plane stress state is shown in Figure 1 [1, 2].

Thus, during fracture of materials having both BCC-lattice structure and FCC-lattice structure under PS condition two plastic zones i) h_y and ii) h_{yh} are formed at the crack tip. The ratio $h_{max}/t > 10^{-1}$. The ductile fracture in a micro-void coalescence manner is observed.

Only one plastic zone h_y is formed at the crack tip when the fracture occurs under PD condition. The ratio $h_{max}/t < 10^{-2}$. Materials having BCC-lattice structure are fractured under PS condition always by cleavage (transcrystalline fracture) or intergranular mechanism; materials having FCC-lattice structure – by intergranular mechanism or combined mechanism, but intergranular mechanism or cleavage is predominate. Such fracture mechanisms cause lower level of crystalline structure distortion (determined on diffraction line width) in plastic zone as compared with ductile mechanism. In case when material fracture occur under transition state from PD to PS the ratio $10^{-2} < h_{max}/t < 10^{-1}$. Lowly deformed plastic zone depth h_y under the fracture surface is much lower then under PS condition. Still to distinguish micro and macro zones is difficult because of small size of these zones. Mainly materials with FCC-lattice structure fracture in transition state from PD to PS, and, as a rule, by combined mechanism. Under combined fracture mechanism crystalline structure distortion on the fracture surface commensurable with crystalline structure distortion in highly deformed plastic zone under ductile fracture. Apparently, low materials fracture energy under combined fracture mechanism is conditioned by little micro plastic zone size.

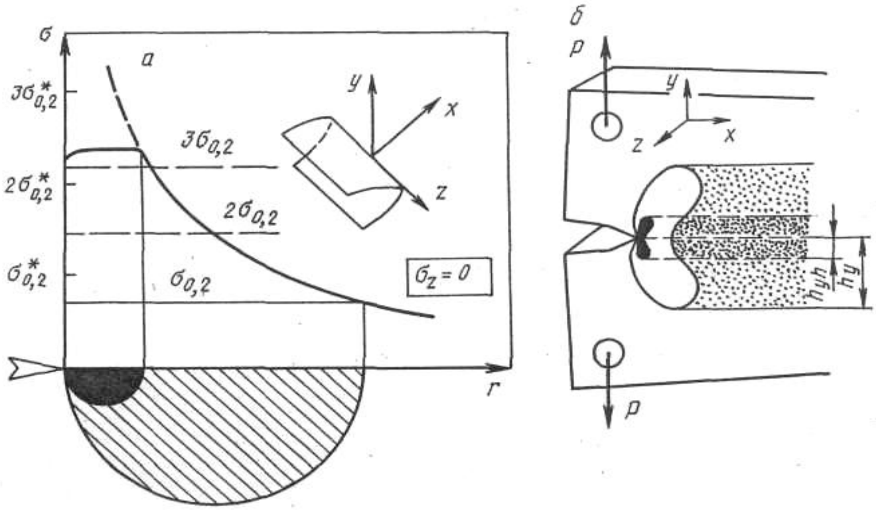

Figure 1. Scheme of plastic zones formation at the crack tip (a) and under the fracture surface during crack propagation (б) under plane stress state when the ratio $h_{max}/t > 10^{-1}$
h_y – the depth of lowly deformed macro plastic zone; h_{yh} - the depth of highly deformed micro plastic zone

The change of material local stress state at the crack tip as was shown in author's works, effect both on plastic zone depth under the fracture surface and level of crystalline structure distortion within this zone. For determination crystalline structure distortion the ratio β/β_0 where β is a diffraction line width obtained by X-ray diffraction of plastic zones, β_0 - diffraction line width obtained by X-ray diffraction of nondeformed metal has been used [1-4]. It was shown, when the fracture is not accompanied by phase transformations in plastic zones, the relations between ratio h_{max}/t and ratio β/β_0 are described by general curves independence from material class and also kind of simple loading condition. The ratio $\beta/\beta_0 \leq 2.0$ under PD condition; $\beta/\beta_0 =$ 2.0-2.1 under transition from PD to PS; $\beta/\beta_0 \geq 2.1$ under PS condition during fracture. It's impossible to determine such correlation between ratio β/β_0 and stress state at the crack tip if martensitic phases or deformation twin are formed on the austenitic steels fracture surface.

Plastic zones formed under cyclic loading. According to Rice's theory [5] two plastic zones i) monotonic plastic zone (or yield zone) h_y and ii) cyclic plastic zone (or reverse deformation plastic zone) h_{yh} are formed at the fatigue crack tip under cyclic loading condition. In recent author's works was shown [1-4] the relation between cyclic plastic zone depth h_{yh} and applied maximum stress intensity factor K_{max} and also the relation between monotonic plastic zone depth h_y and applied stress intensity range $\Delta K = K_{max} - K_{min}$ are independent of material class, loading conditions and also load ratio $R = P_{min}/P_{max}$. These relations are described by general curves to a good approximation to equations [1]: $h_y = 0.0354(K_{max}/\sigma_{0.2})^2$ and $h_{yh} = 0.0012(\Delta K/\sigma_{0.2})$.

Plastic zones formation general scheme under different values of load ratio R and also applied stress σ, including plastic zones formation under compression loading is offered by authors.

In most cases material fracture took place under transition state from PD to PS when the criterion $10^{-2} < h_{max}/t < 10^{-1}$ or under PS condition when the criterion $h_{max}/t > 10^{-1}$. In case fatigue fracture the general relation between h_{max}/t and β/β_0 is not discovered [1-4]. Therefore may to state using of the ratio β/β_0 as a criterion of the material local stress condition at the crack tip is not possible.

Obtained results have been served basis for elaboration of new scientific direct – X-ray fractodiagnoctics. Due to X-ray fractodiagnoctics knowing plastic zones depth under the fracture surface and also change of crystalline structure in these zones loading parameters causing the fracture can se determined.

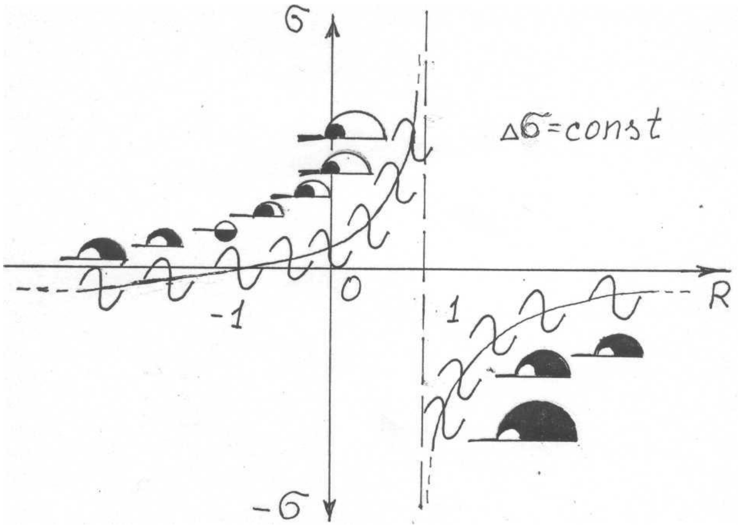

Figure 2. General scheme of plastic zones formation at the crack tip under different values of load ratio R and also applied stress σ (for case when Δσ = const). Local stress state corresponds to bond between PD condition and transition from PD to PS

Regularities of martensitic phase distribution in plastic zones under different types of austenitic steels fracture. In austenitic Fe-Ni steels where take place γ→α martensitic transformation during deformation and fracture, for example, quenched steel H32T3, fractured in PS condition by ductile mechanism α-martensite quality within micro plastic zone h_{yh} is about constant in spite of monotonic change of crystalline distortion through the depth from fracture surface. Quantity of α-martensite decreases quickly under traverse in lowly deformed plastic zone h_y. Described distribution of α–martensite within highly deformed micro plastic zone is conditioned by two main factors i) deformation level and ii) material local heating at the crack tip during the fracture. Deformation is favorable for the martensitic transformation. The local temperature at the crack tip prevents from martensitic phase formation. After crack propagation layers on and near the fracture surface cool down to the test temperature and cooling martensite can be formed in ones. Apparently therefore there is a gap between α–martensite distribution and crystalline distortion gradient.

In plastic zones of quenched Fe-Mn and Fe-Cr-Mn austenitic steels, for example, steel 03X13AГ19 fractured at temperature -196^{0}C by brittle or combined (brittle + ductile) mechanisms, α- martensite and also ε- martensite are formed. ε- martensite is brittle phase apparently. Therefore the strong material local heating is not occur under present steels fracture. Fracture takes place in transition state from PD to PS. Quantity of α-martensite decreases from the fracture surface to the depth of plastic zone in agreement with the crystalline structure distortion change in one. Quantity of ε-martensite increases from the fracture surface to the depth of plastic zone, and, as a role, maximum quantity is discovered on the some depth from the fracture surface where deformation less then fracture surface.

Aged Fe-Ni steels, for example, steel H32T3, fractured by brittle intergranular mechanism in PD condition or near PD condition under low temperatures impact test. In this case quantity of α-martensite decreases from the fracture surface to the depth of plastic zone (Figure 3).

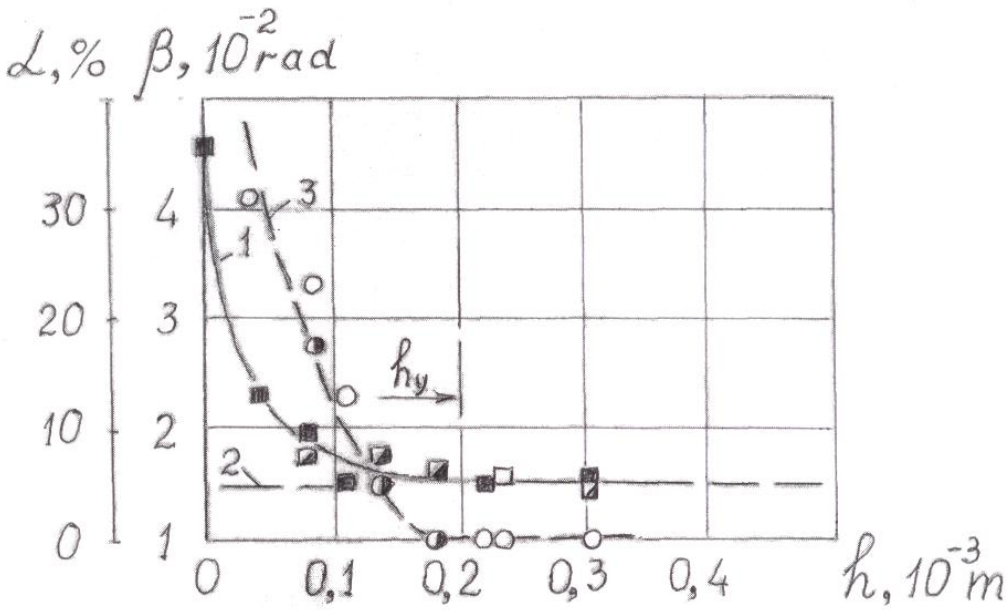

Figure 3. Relation between diffraction line width (311)K_{α} (1, 2), α-martensite quantity (3) and distance from the fracture surface of aged steel H32T3 tested impact under -196 ^{0}C; 1– diffraction line width (311)K_{α}; 2- nondeformed metal diffraction line width (311)K_{α}; 3- α-martensite quantity; Light and dark spots – specimen 1; combined spots – specimen 2

By this means under the ductile fracture of austenitic steels in plane stress condition (PS) after crack propagation line superficial layers cool down and possible the martensitic transformation in one. Under the brittle fracture in plane deformation condition (PD) after crack propagation line in superficial layers possible the martensitic transformation induced the change in the local stress state from PD to PS. Such martensitic phases distribution in plastic zones is typical for all single fracture modes (static, impact and high-speed impulse tests).

Under cyclic test regularity of α-martensite and ε-martensite distribution in plastic zones as well as under single fracture modes although plastic zones formation character is differ in nature (4). Quantity of α-martensite under cyclic fracture surface decreases progressively from the fracture surface to specimen depth. Maximum ε-martensite quantity under fracture surface is occurred where deformation less than on the surface. When the fatigue crack length increases (increase K_{max}) the plastic zones depth increases too. Consequently, the local stress state changes to plane stress state. By this means quantity of ε-martensite under fracture surface is likely to decrease.

Relying on such experiments, it may be inferred that character martensitic phases distribution in plastic zones under the fracture surface is not depends of mode and load speed of austenitic steels specimens, except that depends of the fracture micro mechanism and the local stress state materials at the crack tip. Load speed influence on intensity of martencitic transformation in plastic zones only. Under cyclic test of austenitic steel martencitic transformation intensity on fracture surface low than under single fracture modes.

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