Influence of Local Stress Condition on the Micromechanism of Crack Propagation of Metal Materials under Single Loading Conditions

N.A. Klevtsova

Orenburg State University, Pobeda Pr., 13, Orenburg, Russia, 460018, Inshtet@mail.ru

ABSTRACT. *The purpose of the present study was to establish general regularities of the influence of local stress condition on the micromechanism of crack propagation and the plastic zone formation at the crack tip in materials with BCC-and FCC lattice structures under single loading (static, impact, high-speed impulse) conditions. As materials with BCC lattice we used carbon steels and also alloy steel; as materials with FCC lattice were aluminium deformed alloy and austenitic steels. Mechanical tests of samples were tested in the temperature interval ranging from -196 to +150* ^{0}C*. Fracture surfaces were investigated by macro and micro fractographic methods. Quantity and also depth of plastic zones under a fracture surfaces were determined by X-ray method. As a criterion for definition of a local stress state at the crack tip the ratio of the maximum plastic zone depth under the fracture surface to the sample thickness* h_{max}/t *was used. Schemes of plastic zones formation under plane deformation, plane stress, and in transient region from plane deformation to plane stress are proposed. It was shown the micro mechanism of the crack propagation, and also the quantity and the size of plastic zones formed at the crack tip are independent of the type of a crystalline lattice of the material and the kind of single loading conditions, and are dictated by only the local stress state of a material at the crack tip.*

INTRODUCTION

It is known [1], the local stress state of a material in a predestruction zone determines both micromechanism of crack propagation, and quantity, size and shape of plastic zones formed at the crack tip. It is impossible to clearly indicate the border of transitions of the local stress state of a material from plane deformation to the transitive region and from transitive region to the plane stress due to the continuous of evolution process of the size and quantity of plastic zones which give the most objective information on the local stress condition of a material. Recent results indicate [1-3] that possible quantitative criteria for estimation of the local stress state of a material at the crack tip under single kinds of loading conditions can serve the ratio of the maximum plastic zone depth under the fracture surface to the sample thickness h_{max}/t.

The purpose of the present study was to generalize results of our research and to establish general regularities of influence of the local stress condition on the micromechanism of crack propagation and the plastic zone formation at the crack tip in materials with BCC-and FCC lattice structures under single loading (static, impact, high-speed impulse) conditions.

MATERIALS AND TECHNIQUES

As materials with BCC lattice structure were used carbon steels 15, 20, 40, 45, St3 and the alloyed steel 15Kh2MFA; as materials with FCC lattice - aluminium deformed alloy D16 and austenitic steels N32T3, N26T3, N26Kh5T3, 40G18F, 40Kh4G18F, 03Kh13AG19, 07Kh13N4AG20. The Chemical composition of materials studied is given in tables 1 and 2.

Table 1. Chemical composition of the materials studied (wt %)

Material	C	Mn	Cr	Ni	V	Mo	Ti	N
Steel 15	0,15	0,45	-	-	-	-	-	-
Steel 20	0,18	0,50	-	-	-	-	-	-
Steel 40	0,39	0,60	-	-	-	-	-	-
Steel 45	0,45	0,50	-	-	-	-	-	-
St3	0,20	0,50	-	-	-	-	-	-
15Kh2MFA	0,15	0,60	2,75	0,40	0,35	0,8	-	-
N32T3	0,03	-	-	32,10	-	-	3,20	-
N26T3	0,035	-	-	26,60	-	-	3,18	-
N26Kh5T3	0,03	-	4,2	26,00	-	-	2,70	-
40G18F	0,42	17,96	0,09	-	1,22	-	-	-
40Kh4G18F	0,43	18,00	4,20	-	1,41	-	-	-
03Kh13AG19	0,03	19,35	13,50	0,74	-	-	-	0,17
07Kh13N4AG20	0,06	21,87	14,86	4,89	-	-	-	0,14

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

Alloy	Cu	Mn	Si	Mg	Zn	Fe
D16	4,50	0,60	0,20	1,50	0,12	0,23

The materials were analyzed both in the furnish state (hot-rolled), and after various kinds of thermal treatments. It provided a wide range of structures and properties of the materials were investigated. Thermal treatments and mechanical properties are given in Table 3. All austenitic steels had a single-phase austenitic structure after quenching. Cooling up to temperature -196 ^{0}C induced no martensitic transformations in all steels, except for N26T3. In the quenched steel N26T3 cooling martensite started to formed at a temperature of -20 ^{0}C. Ageing led to hardening of the austenitic steels and stabilization of the austenitic structure. However, during samples loading strain-induced martensite was formed in many quenched and aged austenitic steels in plastic zones at the crack tip [2].

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

Материал	Thermal processing	$\sigma_в$, MPa	$\sigma_т (\sigma_{0,2})$, MPa	δ, %	ψ, %
Steel 15	Normalization	460	350	25	55
Steel 20	Annealing	450	260	24	59
Steel 40	Quenching +intermediate tempering	1400	1200	8	39
Steel 45	Annealing	590	320	20	50
	Hot-rolled	610	360	16	40
St3	Hot-rolled	470	270	23	55
15Kh2MFA	Quenching +high tempering	700	530	20	59
D16	Hot-rolled	233	117	12	-
	Quenching +ageing	400	345	18	-
N32T3	Quenching	700	290	30	70
	Quenching +ageing	820	470	-	70
N26T3	Quenching	600	250	60	75
	Quenching +ageing	900	500	20	30
N26Kh5T3	Quenching	520	240	40	75
	Quenching +ageing	980	500	35	70
40G18F	Quenching	960	350	50	45
	Quenching +ageing	990	600	40	38
40Kh4G18F	Quenching	900	400	55	50
	Quenching +ageing	950	600	50	50
03Kh13AG19	Quenching	670	380	60	60
07Kh13N4AG20	Quenching	680	365	74	62

Mechanical tests of the samples were performed in the temperature interval from 150 to -196 ^{0}C. To perform static resistance tests, the samples with different thickness were subjected to off-center stretching by INSTRON machine. Impact toughness tests were performed on prismatic samples by MK-30 pendulum impact testing machine. High-speed pulsed tests of the ring samples by internal pressure was performed using a pneumatic-powder impact testing machine with a plunger velocity of 200 m s^{-1}.

The microfractographic investigations were performed by JSM-U3, REM-200 scanning electron microscopes and X-ray diffraction analysis of fractures was carried out using a DRON-2.0 difractometer in FeK_{α} and CoK_{α} radiations. Quantity and depth of plastic zones under the fracture surface was determined by X-ray technique described in [1-3].

As a criterion for definition of a local stress state at the crack tip the ratio of the maximum plastic zone depth under the fracture surface to the sample thickness h_{max}/t was used. If the ratio is determined by the expression $h_{max}/t<10^{-2}$, the plane strain deformation (PD) condition is realized at the crack tip during its propagation; if the ratio $h_{max}/t>10^{-1}$ – the plane stress (PS) condition is realized; if the ratio $10^{-2}<h_{max}/t<10^{-1}$ – the transition state from PD to PS is attained [1-3].

RESULTS AND DISCUSSION

It is known, that materials with BCC lattice structure are prone to cold brittleness. This circumstance made it possible to study the crack propagation micromechanism and also kinetics of development of plastic zones in the interval of the ductile-brittle transition in these steels. In materials with FCC lattice structure there is no strongly pronounced range of the ductile-brittle transition. However, the change of the local stress state of the material at the crack tip is caused by the same factors as in materials with BCC lattice structure [3,4].

Figure 1 shows the temperature dependence of the ratio h_{max}/t for single (static, impact, high-speed impulse) loading of BCC and FCC materials. The three previously revealed regions of the local stress state are pronounced in these plots: plane strain, plane stress and transient region from plane strain to plane stress state.

Let us consider some general fracture regularities in each of the above-mentioned regions of local stress state.

Fracture of both BCC and FCC materials under plane strain is accompanied by the formation of only one plastic zone at the crack tip. In this case, the ratio of the maximum plastic zone depth under the fracture surface to the sample thickness is determined by the expression $h_{max}/t<10^{-2}$. Under plane strain, in BCC materials the crack propagates by the cleavage mechanism (transcrystalline fracture) or the intercrystalline fracture mechanism (see, Fig.1).

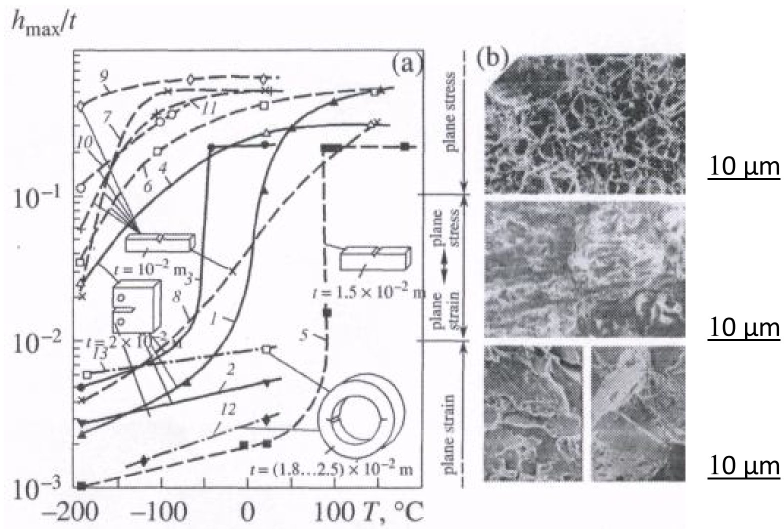

Figure 1. (a) Temperature dependence of the ratio h_{max}/t for materials with BCC lattice structure (dark points) and FCC lattice structure (light points) under (1-4) static, (5-11) impact, (12, 13) pulsed loading, and (b) fracture surfaces under plane strain, plane stress and in the plane strain- plane stress transient region: (1) steel 20; (2) steel 40; (3) 15Kh2MFA; (4) 03Kh13AG19; (5) steel 45; (6, 13) 40G18F (quenching); (7) 40Kh4G18F (quenching); (8) 40Kh4G18F (quenching + ageing), (9) N26T3 (quenching), (10) N32T3 (quenching), (11) N26Kh5T3 (quenching + intermittent ageing), and (12) St3.

Such fracture mechanisms ensure low (in comparison with ductile mechanism) level of crystal structure distortion in the plastic zone. The crack propagation in FCC materials under plane strain conditions occurs either according to the intercrystalline mechanism or the mixed mechanism with dominance of intercrystalline mechanism [2, 4]. At intercrystalline mechanism of the crack propagation the degree of crystalline structure distortion on the fracture surface of FCC materials is comparable with the structural distortion at brittle cleavage fracture of BCC materials [1, 3].

The crack propagation under plane stress in all materials studied is accompanied by the formation two plastic zones under the fracture surface i) a strongly deformed microzone h_{yh} and ii) lowly deformed macrozone h_y. In this case, the ratio of the maximum plastic zone depth under the fracture surface to the sample thickness is determined by the expression $h_{max}/t > 10^{-1}$. Large plastic deformations determine the viscous character of the crack propagation by micro-void coalescence (see, Fig 1). The degree of crystalline structure distortion in lowly deformed macrozone h_y is comparable with that in the plastic zone in the case of brittle fracture. The degree of crystalline structure distortion on the fracture surface at breaks of walls between wells, apparently, reaches a maximum [1]. Under plane stress, both BCC and FCC materials can undergo fracture [1-4].

In BCC materials, the change in the local stress state from plane strain to plane stress is related to the attainment of the low critical brittleness temperature and the formation of the first portions of the viscous component on the fracture surface. The temperature dependences of the ratio h_{max}/t for such materials are S-shaped (see, Fig. 1) similar to serial curves of impact strength or fiber percent in a fracture. For FCC materials these dependences are smoother [2, 3].

In that case when the crack propagates under transient condition from plane strain to plane stress, the depth of plastic zones under the fracture surface will be much less, than under plane stress condition. In this case, as was noted in [1-3], it is not always possible to clearly separate macrozone and microzone under such fracture surface because the plastic zones (primarily, the macrozone h_y) are small. Due to the small sizes of the plastic zones the ratio h_{max}/t is valid: $10^{-2} < h_{max}/t < 10^{-1}$. In transient region from plane strain to plane stress, predominantly FCC materials undergo fracture, generally, according to the mixed mechanism (See, Fig.1). For the mixed fracture mechanism, the degree of crystalline structure distortion on the fracture surface is comparable with crystalline structure distortion in the strongly deformed microzone in the case of ductile fracture. The relatively low fracture energy capacity of materials in the case of the mixed mechanism is caused, apparently, due to the small size of the micro plastic zone.

CONCLUSIONS

1. The micro mechanism of the crack propagation (as well as the quantity and relative size of the plastic zones formed at the crack tip) is independent of the type of material crystalline lattice structure and the kind of single loading (static, impact, high-speed pulsed) conditions, and are dictated by the local stress state of a material at the crack tip.
2. Under PD condition at the crack tip the crack propagates by cleavage or intercrystalline mechanism; under PS condition - by the micro-void coalescence and under transition from PD to PS - by the mixed mechanism.

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