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THE PLASTIC DEFORMATION DEVELOPMENT IN THE CRACK VICINITY OF A LOW-CARBON STEEL

An “in situ” investigation has been performed on plasticity zone evolution in a loaded specimen in the vicinity of crack tip. The crack in the samples were grown by cyclic loading. The test material was located in different states: in the initial state, after the electric pulse treatment and after heat treatment. The deformation fields in the area of stress concentrator were numerically calculated. In the process of plastic flow of material the self-organizing structures at the crack tip have been installed. In the process of deformation of the self-organizing structure are capable of to disappear and reappear.

Key words: *self-organizing structures, plastic deformation, stress concentrator, space-time periodicity, plastic material, plastic flow evolution*

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Introduction

It has been found recently that the space-time distributions of localized strains observable at the macrolevel by homogeneous flow exhibit wave-like regular features. On the strength of these observations Zuev et al. (1994), Zuev and Danilov (1997, 1999) and Zuev and Zavodchikov (1999) proposed a self-excited wave model of plastic flow evolution. However, the nature of self-excited plasticity wave generated remains obscure so far. It is a received fact that the generation of this type of wave is related to stress concentrators in the neighborhood of which plastic flow is initiated; however, up to now no direct observations for acts of this kind have been available. In this field the problem pertaining to the nature of deformation and fracture is treated as one in which primary significance should be attached to stress concentrators of meso- and macroscopic scales. Among these are ductile cracks, which are characterized not only by size but also by instantaneous configuration of the surrounding zone (Schultheisz et al., 1998); therefore, they should be regarded as stress concentrators of prime importance. Of great interest are also data on strain distribution in the plastic flow zone proper.

Experimental method

The present experimental study was carried on by modeling a stress concentrator using a fatigue crack in a plastic material. The aim of the study was in situ examination of the shape and size of the plasticity zone ahead of the propagating crack by ductile fracture and establishment of the regular features for the dynamics of material's flow within the crack. The test specimens having dimensions 90x20x10 mm^3 were cut from a 10 mm hot-rolled steel sheet (0.08 % C by weight); these had a V-shaped notch rounded at the apex (notch depth 8 mm; rounding radius 0.2 mm). The specimens were subjected to loading by cyclic bending to cause a fatigue crack about 2 mm long to grow at the notch apex. The material tested was in three different states: (a) as-received (AR), l_{cr} = 2 mm; *(b)* after thermal treatment (TT) for 1 hr at the temperature of 600° C, l_{cr} =1.82 mm, and (c) after electric pulse treatment (EIT), l_{cr} = 2.2 mm. The loading of specimens prepared in the manner specified above was conducted on a versatile «Instron-l185» testing machine following a three-point bending loading program.

The measurements were carried on by steps every 100 μm of movable support translation from the onset of plastic bending stage to specimen fracture. The displacement vectors were measured to an accuracy of ~ 1 μm.

An analysis of the plastic behavior of the material in the vicinity of the crack can be conveniently performed in the framework of linear fracture mechanics (Sih and Liebowitz, 1968). For the case of a plate with a normal bond-failure crack the relation *U(r)* (polar coordinates *r* and *φ)* has the form

$$U_r = \frac{K_I \sqrt{r}}{4G}\left[(2k-1)\cos\frac{\varphi}{2}\cos\frac{3\varphi}{2}+\ldots\right]. \qquad (1)$$

Here *r* is the distance counted off along the ray from the crack tip *O; φ* is the angle between the direction of the ray *r* and that of crack growth *y; G* is the shear modulus; K_I is the coefficient of stress intensity, and *k* is a constant dependent on the Poisson's ratio of the material and on the kind of stressed state. Obviously, in the elastic region, $U \sim r^{1/2}$. At the elastic/plastic zone boundary the above proportionality will be disturbed.

Experimental results and discussion

The experimental evidence suggests that the evolutionary behavior of the plasticity zone nearby the crack tip as observed for the investigated material in the three different states has similar features. Consider the former two states, AR and TT, in greater detail. Figure 1 illustrates the positions of plasticity zone boundaries *r(x, y)* obtained for four different values of sample sag (f_i) using the technique described above. As is seen from Fig. 1, with increasing *f* the dimensions and shape of the plasticity zone change gradually. It should be noted that at first the evolution of the plasticity zone occurs preferentially along the direction of the initial crack *(y).* Moreover, near the yield point the zone becomes anomalously elongated along the directions *φ* = 20...25° (Fig. 1, curve *a).* The zone boundary in the remaining part of the half space is more smooth and is close in shape to a semi-elliptical one. As the load increases and the sag grows by as little as 100 μm, the plasticity zone becomes elongated along the directions *φ* = -25...30° (Fig. 1, curve *b).* Upon further straining the intense growth of the zone along the above directions ceases gradually and the zone assumes a more symmetrical shape (Fig. 1, curve *c),* with the dimensions of the main part of the same zone increasing along the direction *y (φ* = 0) more slowly than along the direction *x (φ* = ±90°). Upon further loading no significant changes occur either in the dimensions or the shape of the zone investigated and the same picture persists until the final stage of straining. However, an intriguing situation arises as soon as the applied load reaches its critical value and crack initiation thus becomes imminent. At this instant of time the plasticity zone increases dramatically along the axis *y* across specimen by about 2 mm (Fig. 1, curve *d).*

A similar picture of plasticity zone evolution is observed for the aged material under loading (Fig. 2). As a result of thermal treatment the dimensions of the investigated zone decrease substantially, especially in the early stage of loading (Fig. 2, curve a), although the zone evolution will continue in a pulsatory fashion for a prolonged period of time during specimen loading. Upon further straining the irregular growth of the plastic zone is arrested so that it assumes a more symmetrical shape (Fig. 2, curve c). Analogous to the latter case, during specimen loading the resulting picture will remain virtually unaffected for a certain period of time to change crucially when the critical load is attained which corresponds with the maximal sag of the specimen, i.e. the dimensions of the plasticity zone will increase dramatically by as much as ≈ *2* mm (Fig. 2, curve *d).*

Thus the above observations suggest that the evolutionary behavior of the plasticity zone ahead of the crack tip suffers no significant change during loading no matter what state of the material; moreover, as soon as the stress intensity factor reaches a critical value, the zone examined undergoes similar qualitative changes related to the dimensions of the plasticity region along the direction of the crack. However, one of the most important characteristic of the material, i.e. its

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crack resistance, is closely related to the material's state, which is most clearly demonstrated for the material subjected to EIT.

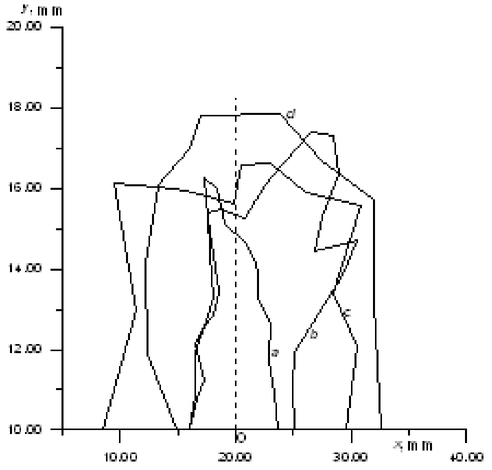

Fig. 1. The position of plasticity zone boundary for the sags: a – 0.7 mm, b – 0.8 mm, c – 1.2 mm, d – 2 mm.

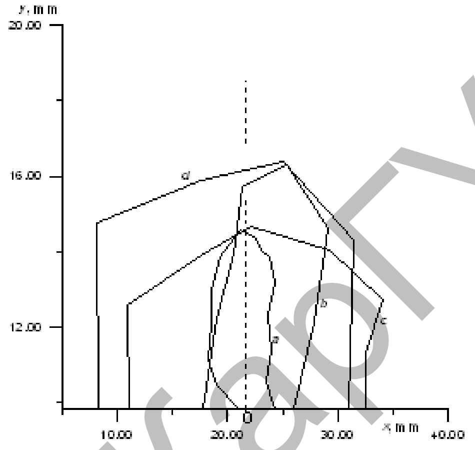

Fig. 2. The position of plasticity zone boundary for the sags: a – 0.38 mm, b – 1.12 mm, c – 2.13 mm, d – 2.23 mm.

Reverting to the investigation of plasticity zone it should be noted that the plastic zone in the vicinity of a normal bond-failure crack's tip evolves non-homogeneously both in specimen space and over the time of load application, with the spatial heterogeneity being more strongly pronounced at early stages of loading. The possible reason for the pattern observed is the inhomogeneous behavior of plastic deformation in general brief mention of which has already been made in the foregoing. The expansion of plasticity zone boundary observed herein is similar in nature to the well-known Lueders bands (McLean, 1963) which evolve at the yield point plateau in materials with a well-defined yield point. The «jagged» boundaries of plasticity zones might also be due to the spatial heterogeneity of plastic flow. However, the above results suggest that plastic flow exhibits an inhomogeneous behavior not only in space but also with time. Local shear macro bands may be arrested in motion and disappear in a certain direction to nucleate and;start evolving in quite a different direction.

Therefore, shifting of portions of the plasticity zone boundary is likely to occur rather than steady expansion of the zone ahead of the crack over the entire half space. The plastic flow front differs significantly from the flat front of Lueders bands in that its propagation occurs inhomogeheously due to a more complicated stressed state at the crack tip.

Of greatest importance are the data on material behavior in the vicinity of the stress concentrator. These were obtained during an in situ investigation of the evolution of the fields of deformation tensor components observed for a planar case in the course of loading

$$\varepsilon_{ij} = \begin{vmatrix} \varepsilon_{rr} & \varepsilon_{r\varphi} \\ \varepsilon_{\varphi r} & \varepsilon_{\varphi\varphi} \end{vmatrix} . \qquad (2)$$

Deformation tensor components can be obtained by differentiation with respect to the coordinates from experimental data on the data array $U(x,y)$ (Hill, 1950). The terms, $\varepsilon_{rr},\varepsilon_{r\varphi},\varepsilon_{\varphi r}$

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and $\varepsilon_{\varphi\varphi}$ of (2) are deformation tensor components in the polar coordinates, with $\varepsilon_{rr} = \partial U_r / \partial r$; $\varepsilon_{\varphi\varphi} = 1/r\,(\partial U_\varphi / \partial\varphi) + U_r / r$; $\varepsilon_{r\varphi} = \varepsilon_{\varphi r} = 1/2\left[1/r(\partial U_r / \partial\varphi) + \partial U_\varphi / \partial r + U_\varphi / r\right]$. The values $\varepsilon_{rr}, \varepsilon_{r\varphi}$ and $\varepsilon_{\varphi\varphi}$ were calculated by the method of numerical differentiation for each point of the specimen at which *U* values had been obtained at different instants of loading. These are illustrated in Fig. *3 a-d as* spatial distributions of the radial component ε_{rr} for the respective values of specimen bend corresponding to the same positions of the plastic zone boundary as in Fig. 1. Clearly, the shear strain within the above zone shows an essentially inhomogeneous distribution. At the initial stage of loading (Fig. 3 *a)* the field ε_{rr} has a stochastic aspect, with extreme values being shifted to the zone boundary. As the specimen bend increases, the localized shear nuclei are shifted from the periphery of the zone to the crack tip (Fig. 3 *a-d).*

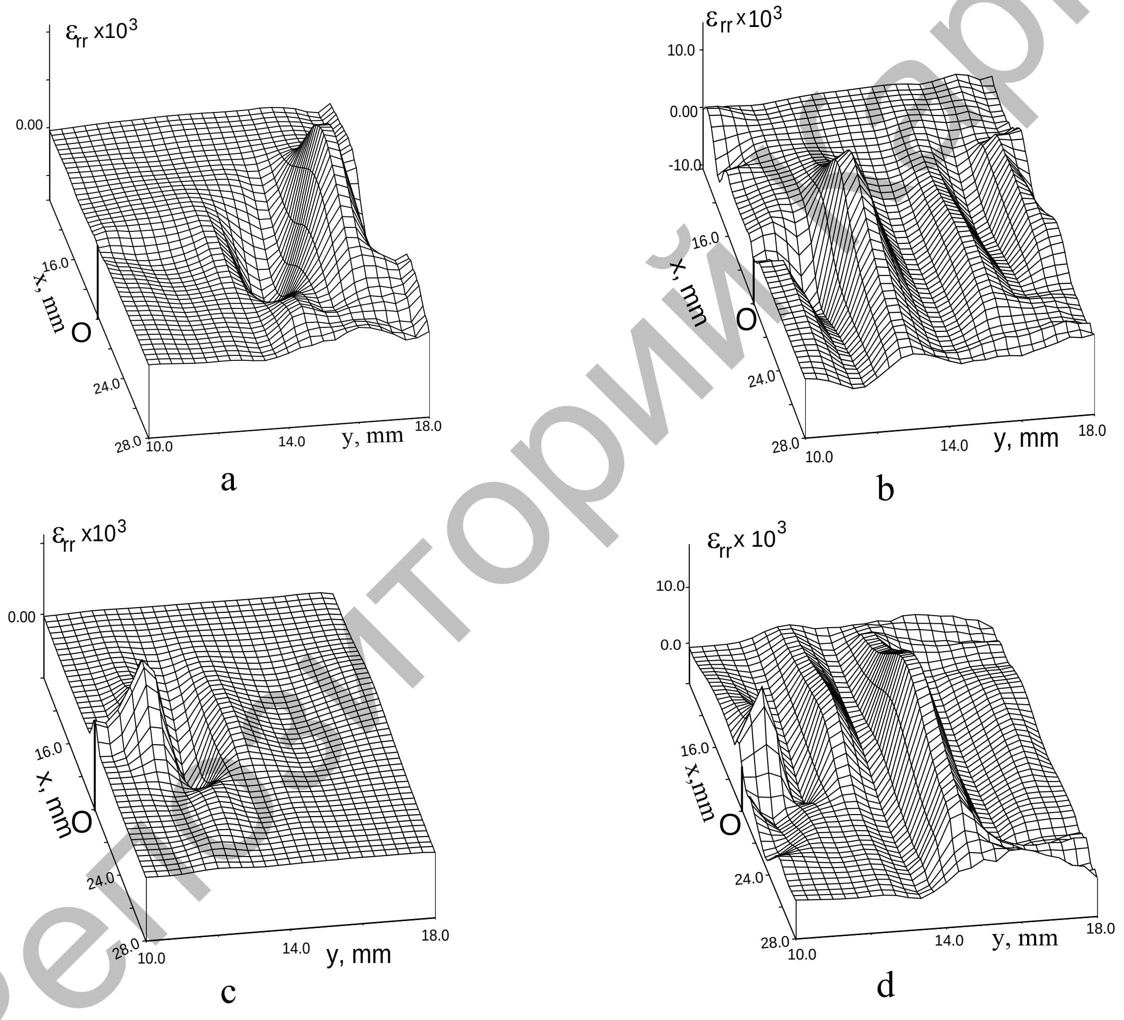

Fig. 3. The evolution of the distribution ε_{rr} in plasticity zone

Of particular interest is the situation observed in the plasticity zone (Fig. 3 *b).* Here emerges an ordered system of localized shear nuclei revealing a space-time periodicity and having maxima at 2...3 mm apart. Such behavior of the plastically deforming material fits well the self-excited wave model of plastic flow evolution.

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Conclusions

Observed process may be thought of as the initial stage of self-organization of plastic flow predicted by Nicolis and Prigogine (1989) via generation of self-excited waves out of the chaotically distributed shears (Zuev and Danilov, 1997, 1999). The waves observed are unstable, they will disappear occasionally to be generated again with increasing straining. In the case of tensile specimens, stable wave pictures are observed; then-existence is associated with interactions of individual wave acts and with formation of a certain type of self-excited wave, e.g. a switching self-excited wave generated by elastic/plastic transition.

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