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STRUCTURAL LEVELS OF THE NUCLEATION AND GROWTH OF FATIGUE CRACK IN 17MN1SI STEEL PIPELINE AFTER LONG-TERM SERVICE

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Abstract. The majority of modern gas pipelines in Ukraine, Lithuania and Russia have been operating for more than 30–40 years. The problem of forecasting residual life-time of materials comprising such gas pipelines calls for study of their degradation kinetics as well as requires to determine its relationship with the strain-force loading parameters. The aim of the paper is to study the kinetics of fracture in order to range mechanisms of cyclic deformation of 17Mn1Si steel at nucleation and growth of a fatigue crack. Flat specimens were cut out from a fragment of 17Mn1Si steel pipe after 40 years of service. Microstructures of specimens were examined. In the paper, an attempt was made to apply the combined approach to study of deformation and fracture based on the following research parameters from nonlinear fracture mechanics: physical mesomechanics and numerical fractography.

Keywords: pipeline; steel; fatigue crack; crack nucleation; crack growth; steel structure.

Introduction

The majority of modern gas pipelines in Ukraine, Lithuania and Russia have been operating for more than 30–40 years (Abdullin, Gareev 1993; Maruschak *et al.* 2013a, 2013b, 2014). The problem of forecasting residual life-time of materials comprising such gas pipelines calls for study of their degradation kinetics as well as requires to determine its relationship with the strain-force loading parameters. This is the basic physical and mechanical background which causes the development of the phenomenological approaches to study of cyclic crack-growth resistance and micromechanisms of fatigue fracture, where the kinetics of the fracture is assumed to be governed by the evolution of stress and deformation fields (Ivanova 1982; Okipnyi *et al.* 2015).

It is known that the kinetics of fatigue failure is controlled by processes of structural damage accumulation and the development of cyclic plastic deformation, whose scale levels depend on the composition, structural state, degree of heterogeneity and resource of the material ductility (Elsukova, Panin 1996; Panin *et al.* 2013).

It is also known that structural materials demonstrate a continuous decrease in fatigue strength with operation under cyclical loading, because of the accumulation of dispersed structural defects and origin of a main crack. Thus, it becomes clear why the operational defects formation are the main reason of fatigue failure (Chen *et al.* 1996).

The problem of correct estimation of fatigue lifetime is determined by mechanisms of the material structure evolution and directly depends on the kinetics of the deformation process at various structural levels of the pipe wall material in a gas pipeline (Nykyforchyn 1997). The influence of plastic deformation is ambiguous: it is the reason for the accumulation of damages and crack growth, on the one hand, and stress relaxation areas, on the other hand (Botvina, Tyutin 2007).

There are several theoretical approaches to interpretation of deformation processes of polycrystalline materials. The concept of multi-level descriptions con-

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*Editor-in-Chief of the Research Journal TRANSPORT; the manuscript was handled by one of Associate Editors, who made all decisions related to the manuscript (including the choice of referees and the ultimate decision on the revision and publishing) siders a solid as a hierarchically organized system (Elsukova, Panin 1996; Panin *et al.* 2013; Chausov *et al.* 2015), which is the most dynamically developed. It allows not only establishing the structural levels of material deformation but also to develop a series of physical-mathematical approaches to forecast the integrity of materials and structures.

The following research problem statement is offered. For structural analysis of metal pipelines, especially after long operation, it is necessary to estimate and understand the nature of their resistance to fatigue crack growth. By comparison with that of material in initial state (non-operated), conclusions about its current mechanical state and prediction of residual service life can be drawn.

The aim of the paper is to study the kinetics of fracture in order to range mechanisms of cyclic deformation of 17Mn1Si steel at nucleation and growth of a fatigue crack.

1. Experiment

Flat specimens of dimension 70×10×1 mm were cut out from a fragment of 17Mn1Si steel pipe with a diameter of 1020 mm and wall thickness of 10 mm after 40 years of service (Fig. 1). Central holes with a diameter of 2 mm were mechanically drilled in specimens as a stress concentrator. Specimens were tested for cyclic tension using servo-hydraulic machine Biss UTM 150 at $\Delta\sigma$ = 250 MPa. The load ratio $R = P_{min}/P_{max}$ was kept equal to 0.1, frequency of loading f = 10 Hz. During the process of cyclic testing, optical images of specimens were recorded using the digital SLR camera *Canon D550*.

The overall cyclic durability of specimen (N = $1.43 \cdot 10^6$ cycles) can be divided into two diagnostic periods:

- preliminary cyclic running-time – during this period, there are no structural, mechanical and deformation (like strain induced relief formation) changes ($N_1 = 1.03 \cdot 10^6$ cycles) are observed on the surface of the specimen;
- period of fatigue crack identification and observation of defects. At this stage, there are changes in a specimen surface state that are detected as well as when nucleation and growth of a fatigue crack ($N_2 = 40 \cdot 10^3$ cycles) were revealed.

Microstructures of specimens were examined after chemical etching, using the 5% nitric acid solution. Specimen's surface micrographs were registered with the help of *Carl Zeiss Axiovert 25 CA* and *EPIQUANT* optical microscopes, as well as scanning electronic microscope *Carl Zeiss EVO 50*.

2. The Results of the Experiment

2.1. Microstructure

In the initial (as supplied) state, specimens of 17Mn1Si steel have ferrite-pearlite structure with an average grain size of 30–50 μm (Fig. 2) that ensures their high strength and ductility. The structure of the material before deformation was ferrite; one can observe pearlite colonies located in various parts of ferrite grains.

2.2. Application of Strain Criterion of Fracture Mechanics

It is known that the opening angle of a crack tip enables to determine the material state and does not require additional calculations (Jadhav, Maiti 2010). Let us analyse data on Crack Tip Opening Angles (CTOA) (Fig. 3). One can see that for a 'physically short crack' the open-

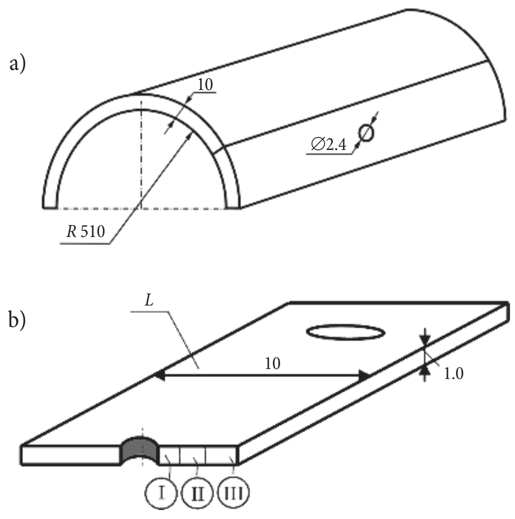

Fig. 1. Schemes cutting of specimens with a fragment of the main gas pipeline (a) and to illustrate observation of fracture surface of the failure specimen (b): I – Stage of crack nucleation; II – Stage of crack growth; III – Stage of quasi-static rapture

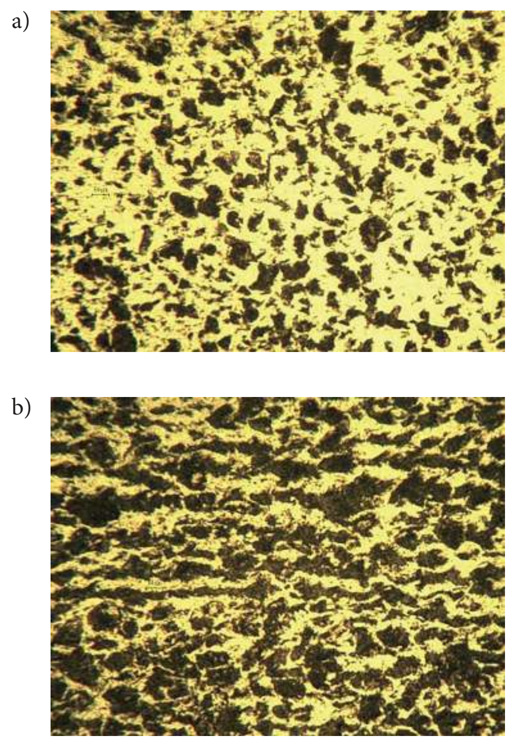

Fig. 2. Ferrite, pearlite structure of 17Mn1Si steel specimens (×400) transversely (a) and longitudinally (b); etching was produced in alcohol solution of 5% nitric acid

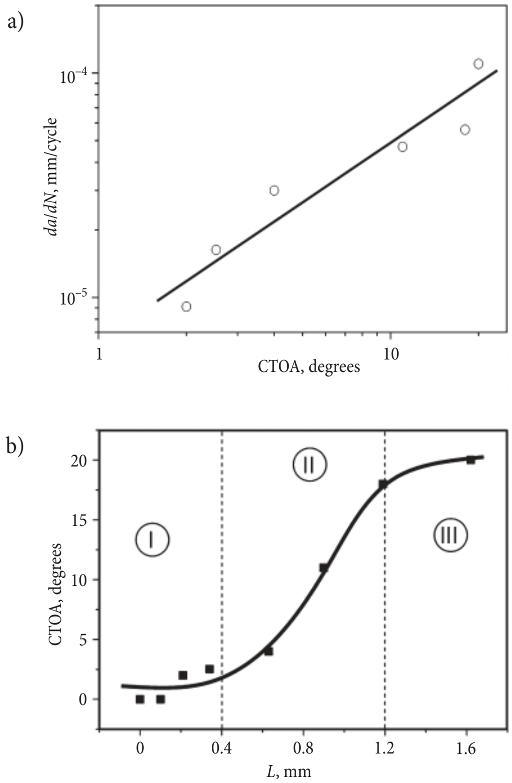

Fig. 3. Dependence of fatigue crack growth rate on CTOA (a) and on its length (b)

ing angle has low value CTOA = 2°. It indicates high crack-growth resistance of a material. The 'critical' value of the CTOA (at the pre-fracture stage) is higher than 20°. Dependence of fatigue crack growth rate on the value of the crack tip opening angle in double logarithmic coordinates can be fitted by a straight line. In doing so, under describing data shown in Fig. 3b, it is should be noticed that the opening of a crack being characterized by the dependence of CTOA versus its length, is a stage-like process that can be characterized through the evolution of scale levels of strain.

At the Stage I, the CTOA has low values because the material has high crack growth resistance and strength.

At the Stage II, the change of the slope angle of the CTOA–L curve manifests not only the influence of initial defects in the material but also the decrease of its shear resistance with crack growth.

Stage III demonstrates the pre-fracture state of the material (Fig. 4b). The main feature of the pre-fracture stage of the steel under study is to possess a sufficient long time of 'under-critical' slow crack propagation. This testifies for the gradual exhaustion of the material ability to elastoplastic deformation in the region located close to the crack tip (Golub, Plashchynska 2005). This makes it possible to fix a high enough angle of the crack opening. Another special feature to be noticed is the formation of plastic zones and pre-fracture region near the crack tip. In order to take into account and describe this complex non-linear state, the physical mesomechanics approach was employed.

2.3. Physical Mesomechanics Description

With the use of specimen surface images, there was established the dependence of a fatigue crack growth with changing geometry of plastic deformation zone in its tip. Information obtained under cyclic loading makes it possible to understand the influence of fatigue crack propagation onto development of deformation and fracture (Maruschak *et al.* 2013a, 2013b).

First of all, formation of bands of localized plastic deformation takes place while the stress concentrator in the crack tip acts as the source of the bands. In doing so with cyclic loading localized deformation bands were formed to be produced due to heterogeneity of stressed state of a solid with gradients of plastic deformation (Fig. 4a, b).

One can see that shear bands have a V-shaped form (Fig. 4b). The character of their propagation in regard to the direction of applied load is in a good agreement with literature data (Deryugin *et al.* 1999; Derevyagina *et al.* 2010). Localization of deformation to be caused by the action of stress mesoconcentrators may be accompanied by effects of material softening as well as the additional activation of slip systems (Lasko *et al.* 2000; Makarov *et al.* 1998).

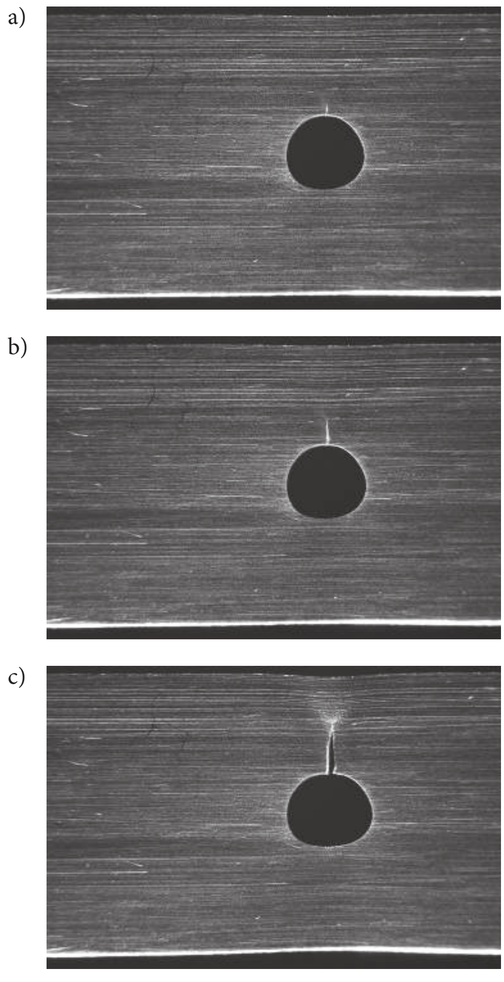

Fig. 4. Optical images characterizing fatigue crack growth: a – crack nucleation zone; b – zone of brittle-ductile fatigue crack growth; c – quasi-static rapture

Significant plastic deformation gradients give rise to the stress concentration sufficient for the generation of dislocations in adjacent grains leading to 'blurring' and increase of scale of localized shear bands. The growth of the fatigue crack is accompanied by increased rate of localized deformation. In doing so, a substantial distortion of strain fields along the deformation localization area takes place, especially near the tip of the fatigue crack.

2.4. Mechanisms of Crack Nucleation

For polycrystalline materials, plastic deformation sustains large-scale transitions from the formation of dislocation substructure towards the development of deformation structural elements of a larger scale. This process develops until the latter exhaust relation ability and become centres of fracture zones (Lasko *et al.* 2000; Makarov *et al.* 1998). Such fracture zone was formed near the surface of the specimen, i.e. during the cyclic deformation process, structural microdefects are formed and accumulated within the surface layer. They give rise to microcrack nucleation and cleavage with a smooth wavy pattern (Fig. 5). Study of a crack nucleation in the 17G1Si steel specimen has shown that at macroscale level, the fracture surface in zone I (Fig. 5) has a wavy pattern that is characteristic for quasi-ductile fatigue fracture (Fig. 5a).

The process of cyclic deformation is related to formation of facets of quasi-brittle cleavage, which are the location of further nucleation of fatigue crack in 17G1Si steel (Fig. 5a). It should also be stressed that the material under study had the banded texture that is characteristic of pipe rolled steel products. Formation of facets indicates that the structural embrittlement takes place under substantial (long) cyclic operating (Nykyforchyn 1997). Facet ridges are oriented perpendicularly to the front of fatigue crack propagation.

On the fracture surface at the crack start zone, deep facets are clearly visible. There are also secondary cracks at their bottom (Fig. 5). Basically, they are concentrated near the central hole (stress concentrator) within the inner layer of the specimen. Facets are rather massive and size-wise comparable with structural components such as ferrite and pearlite grains. Obviously, they are formed as a result of the shear fracture of certain crystallographic planes. This can be explained by the action of a complex mechanism of deformation and macrocrack growth, when the latter happens simultaneously along all edges of facets. On the basis of the results obtained, it might be assumed that microfracture and macrocrack growth under cyclic loading comes from coalescence in the system of short cracks (Gliha *et al.* 2013).

2.5. Fatigue Crack Growth

Although fatigue fracture surface in the zone II is covered with facets, the latter do not longer form a wavy pattern, and are randomly oriented. While on the surface, a number of cavities with clear boundary facets are evident. In Fig. 6a and b, two different types of facets are presented. Smaller ones – close to a surface; and a few

a)

b)

c)

d)

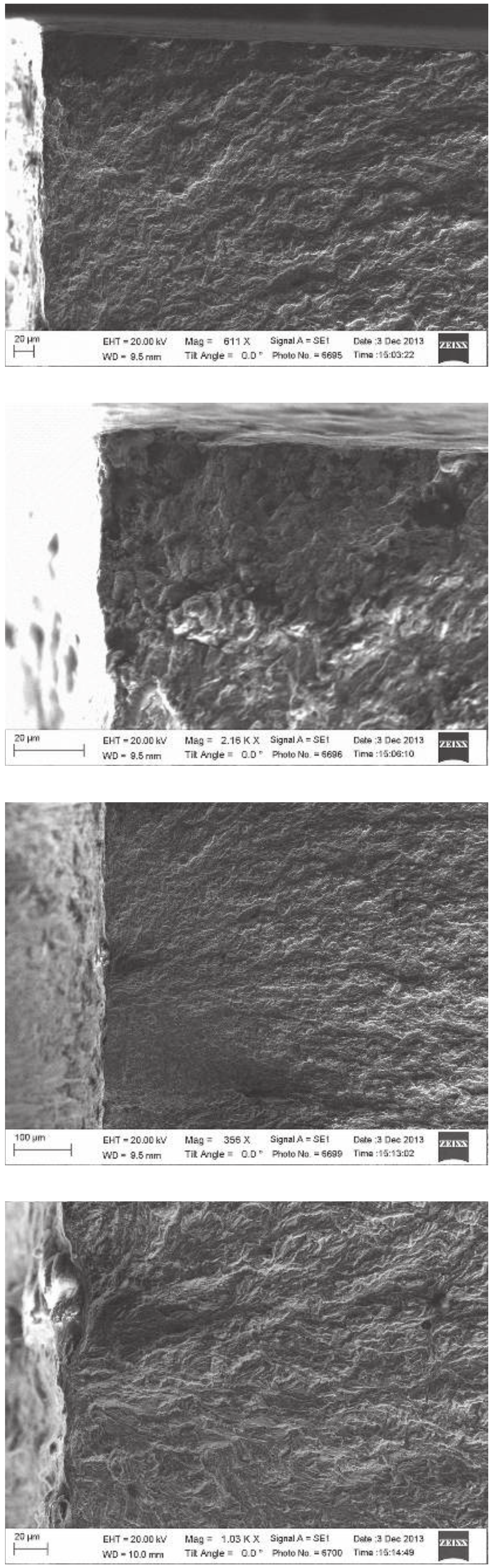

Fig. 5. Micrographs illustrating the crack nucleation in subsurface layer (a) and in internal ones (b) of 17Mn1Si steel specimen with a central hole: a – nucleation of crack; b – cyclically deformed surface; c – wavy pattern; d – facets

elongated – at the specimen centre. Both types tend to have a brittle-ductile pattern. Obviously, this is due to the different hardness of the surface layer and internal ones of material. The first was preliminary subjected to cyclic deformation and, consequently, fracture has higher pronounced brittle character.

Fatigue striations, which appeared as a result of the fatigue crack growth, are visible on individual facets. A certain pattern of facets might be characterized as having certain characteristic features. It is assumed that at the initial stage the crack propagates towards the specimen surface due to the tunnelling effect (Ivanova 1982). The general mechanism of fracture is realized by the nucleation and propagation of fatigue microcracks along sliding planes, oriented at an angle of 45° to the axis of loading. Facets are covered by fatigue striations; in doing so, the orientation and size of the individual facets are comparable with the size of grains.

The data obtained makes it possible to discuss the influence of the expressed texture in 17Mn1Si steel onto its deformation behaviour, as grain conglomerates have an ordered crystallographic orientation. Thus, it should be emphasized that defect orientation regarding the axis of loading plays essential role on the surface cracks growth in the pipe material for main gas pipelines. These factors affect the intensity of the material interaction with the environment as well as determine substantial differences in material its estimated durability.

Heterogeneity of plastic deformation over the cross section of the specimen is caused by the:

- property of the cyclically deformed surface layer;
- change of deformation development character in the core which is related to the peculiarities of deformation development around inclusions;
- variety of grain boundary and other mechanisms of the microscale level, to develop in the investigated specimens.

2.6. Mechanisms of Under Critical Growth

At the Stage III, the presence of massive inclusions gives rise to local ductile fracture by the dimple fracture mechanism. With the increase of fatigue crack growth rate, the inter-striation distance rises as well as the number of secondary cracks. It should be noticed that the complex stress state in the cyclically deformed plastic zone ahead of the crack tip defines the orientation of fatigue striations; however, it can substantially differ in adjacent structural elements (Maruschak *et al.* 2013a, 2013b, 2014).

Analysis of fracture surfaces allows to reveal features to characterize the influence of high plastic deformations on fracture mechanisms: there are small dimples present on the fracture surface with particles inside them (Fig. 7a). Formation of secondary dimples is observed as well (Fig. 7b). Significant concentration of micropores testifies the fact of influence of activation-type accumulation and development of scattered damage onto plastic deformation (Fig. 7c). Micrographs of fracture surface in the subsurface layer of failed specimen demonstrate the local heterogeneity of deformation. In these places, the fracture develops mainly by

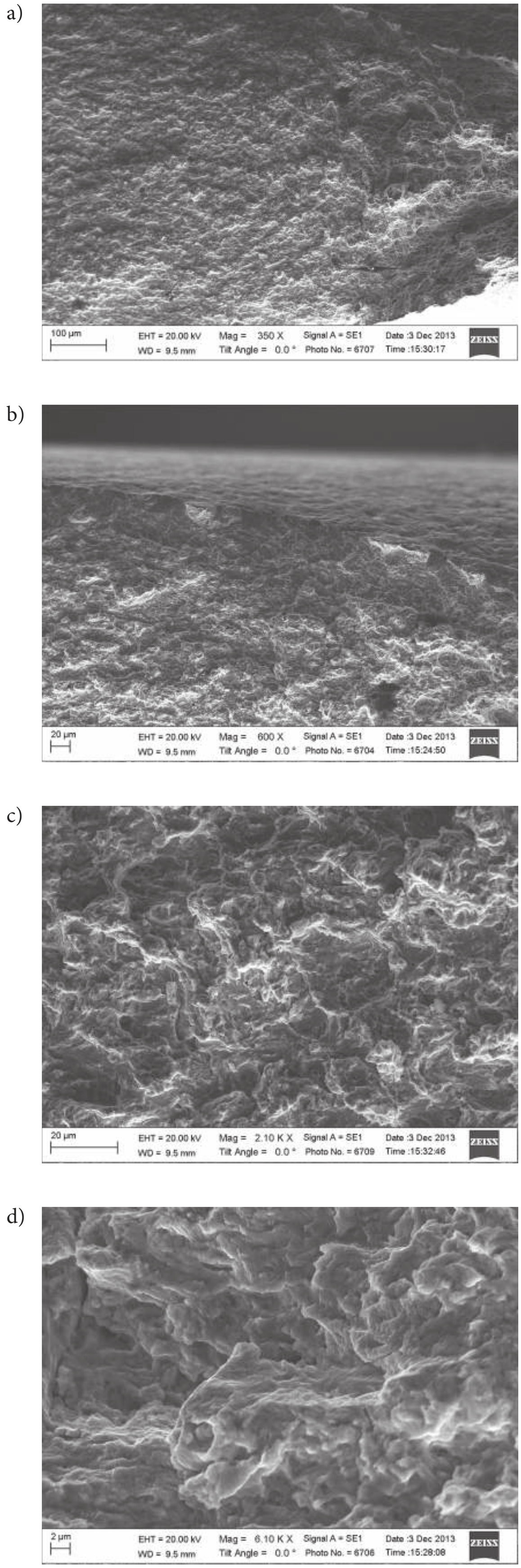

Fig. 6. Micrographs illustrating mechanisms of crack growth into the subsurface layer (a, b) and internal layers (c, d) of the flat 17Mn1Si steel specimen with a central hole

shear mechanism, but in the inclusion zones – by dimple fracture (Fig. 7d). Mechanisms of cyclic deformation and fracture are summarized in Table.

Analysis of fracture surface micrographs allows identifying deformation localization zones, since, despite of the fact that the specimen is generally failure by mixed brittle-ductile mechanism, but detachments of inclusion are observed rather often. Presence of ridges of microplastic deformation and micro-cleavage facets testifies for the fact of local plastic flow of the material in the vicinity of inclusions (Maruschak *et al.* 2013a, 2013b, 2014).

Near the outer subsurface layer of the specimen, individual secondary tears and elongated dimples are observed. These phenomena are most likely related to severe plastic deformation due to significant shrinkage in the neck of the specimen. Crack growth is accompanied by involvement of rotation moments, which, in their turn, provides rotations and tearing of grain conglomerates.

a) c) b) d)

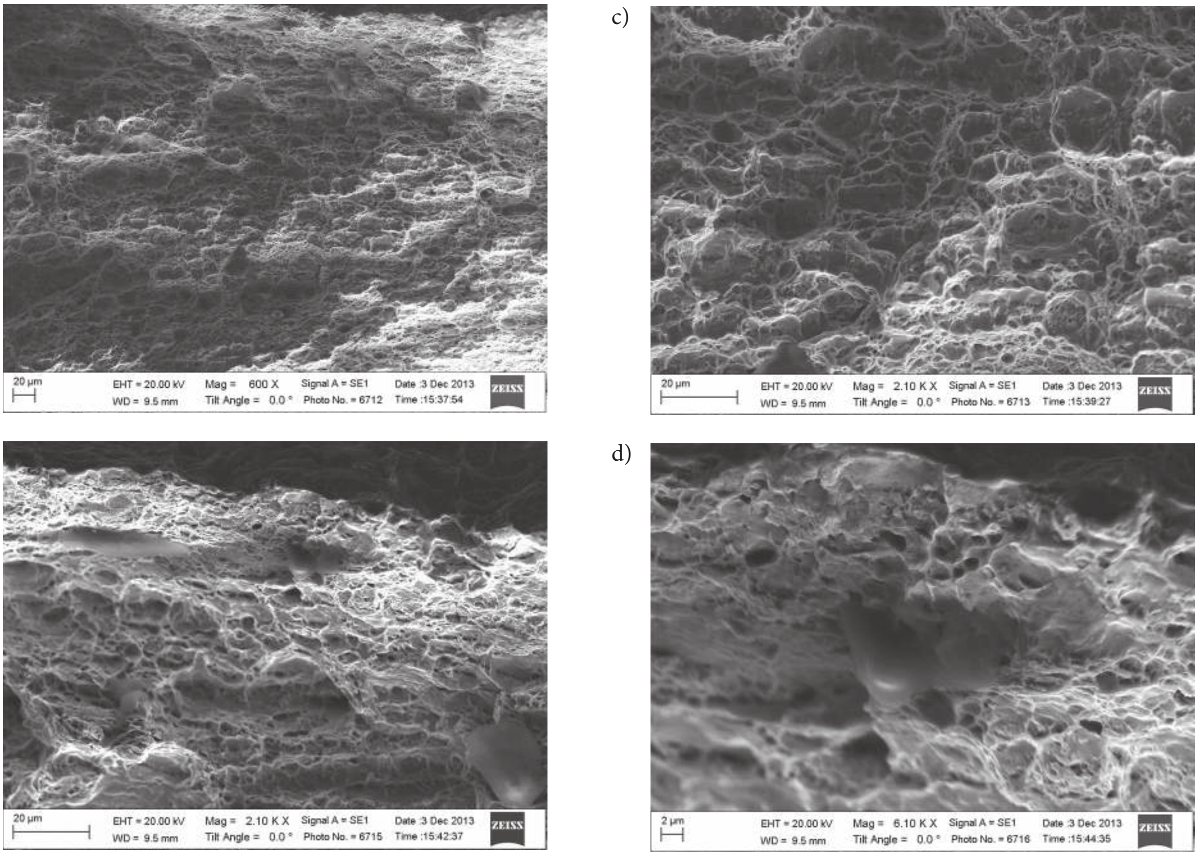

Fig. 7. Micrographs to illustrate micromechanisms of crack growth in a subsurface (a, b) and in internal layers (c, d) of a flat specimen of the 17MN1Si steel with the central hole

Table. Characteristics of deformation and fracture type of 17Mn1Si steel specimens under fatigue loading

Fracture zone	Characteristic features of deformation development	The type of fracture	The key structural levels of deformation and fracture
I	Cyclic microplastic deformation and shears localized within the individual grains caused by dispersed hardening of the initial structure	Fatigue fracture with formation of the facets	Key level: *Micro-* The area of crack growth origin has small size at fracture surface, and is formed by the uniting of structural defects of microlevel.
II	Involvement in the deformation of a substantial number of the structure elements, first of all, at the crack tip with formation of visible zone of developed plastic deformation	Fracture with formation of facets and fatigue striation	Key level: *Meso-* Growth of a fatigue crack ensures involvement of deformation and fracture processes at several structural levels simultaneously with development of rotation modes of plastic deformation with crack propagation.
III	Involvement of rotational mode and macroscale deformation of material	Ductile mechanism of fracture with formation of brittle – ductile fracture surface (dimples + quasi-brittle rapture)	Key level: *Macro-*

3. Discussion of the Results

In this paper, an attempt was made to apply the combined approach to study of deformation and fracture based on the following research parameters:

- from nonlinear fracture mechanics: the Crack Tip Opening Angle (CTOA);
- from physical mesomechanics: Shear Strain Intensity (SSI);
- numerical fractography: Fracture Surface Analysis (FSA).

On the surface of the specimen, at the crack nucleation stage, a V-shaped zone of strain localization is formed. The kinetics of its development is directly associated with the fracture pattern (Kryven' 2001). If its development is blocked by the plastic flow at the micro- and mesoscale levels, the fracture of specimens is developed by normal fracture under action of normal tensile stresses. If this takes place (at suppression of a material deformation at the micro- and mesoscale levels), the fracture occurs by shear mechanism being influenced by tangential stresses. A certain stage pattern might be followed in the development of plastic zones:

- *Stage 1.* Only a small size 'critical' area at the crack tip is involved in active resistance to external load. At the microlevel, one can observe suppression of deformation development in the bulk of specimen while fatigue crack propagation occurs according to the scheme 'shear + tear off' (Fig. 8a). Obviously, the dislocation deformation at the micro-scale level is suppressed while strong structure heterogeneity and 'composite-like pattern' tends to deformation macro-localization. Pronounced orientation of plastic deformation bands is the characteristic feature of the process. They are oriented at an angle of 45° to the loading axis, being located inter-perpendicularly and passed through the entire cross section of the specimen. In doing so, the bidirectionally oriented ends mesobands become blurred.
- *Stage 2.* The mesoband structures located at opposite sides of the central hole, change their configuration/shape (Fig. 8b). At the top of the fatigue crack, the plastic zone has a pronounced shape, while at the opposite side of the hole, it becomes blurred. This means that within the bands of localized deformation, the maximum value of shear strain intensity is kept, which predefines the path and mechanism of fatigue crack growth (Kryven' 2001; Panasyuk *et al.* 1995).
- *Stage 3.* Pronounced pattern of plastic zone shape at a crack tip becomes more evident while at the opposite side (where presence of fatigue crack growth is not clear) the plastic zone is blurred (Fig. 8c). The maximum concentration of stresses and the highest rate of deformation is located in the vicinity of the fatigue crack tip.

In material under the prefracture state, plastic deformations are accumulated and intensively develop, i.e. changing of deformations and stresses in time occurs (with the increasing cyclic strain). These phenomena were registered and analysed numerically (Fig. 9). It should be noticed that deformation is localized in both bands of plastic deformation located in the vicinity of the crack tip (Fig. 9b), as well as at the opposite side of the central hole. These affect the SSI field calculated for the entire image (Fig. 9a). Besides, substantial physical nonlinearity of deformation development is seen that gives rise to changing of the shape of the central hole (stress concentrator).

Comparison of fields of SSI distribution calculated under cyclic tension testing for the entire vector field as well as for the fragment containing stress concentra-

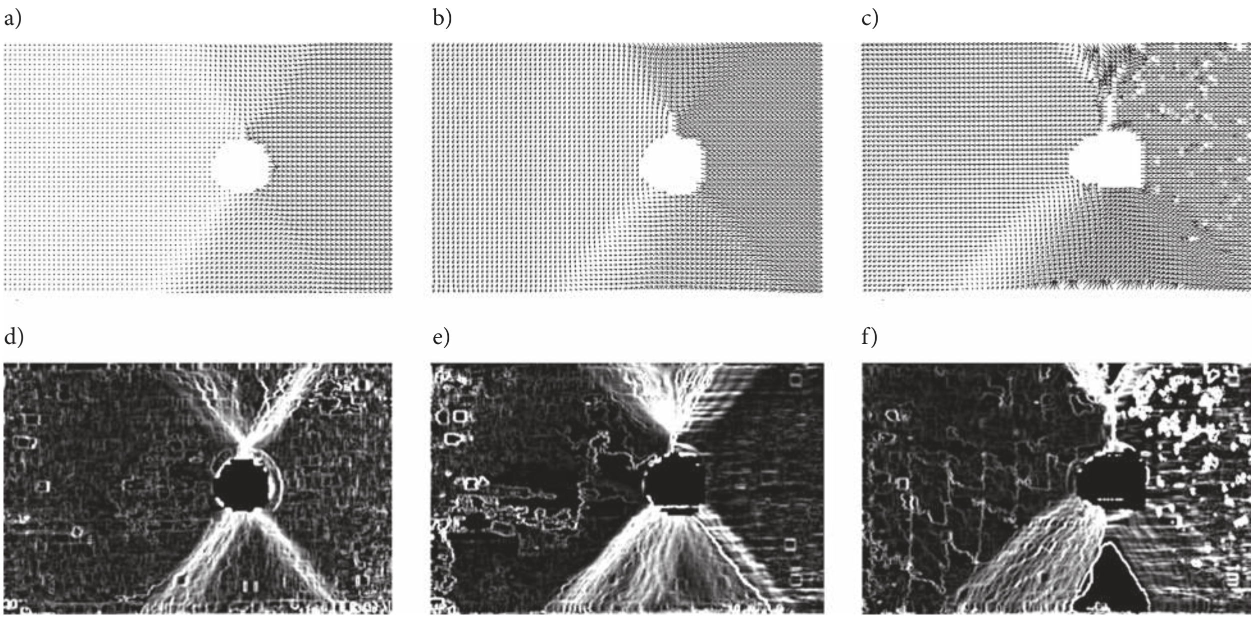

Fig. 8. Development of plastic deformation zones at different stages of fatigue crack growth for zones of: a – nucleation; b – growth; c – quasi-static rapture; d, e, f – corresponding patterns of shear strain intensity distribution

tor region make it possible to confirm that they possess a similar pattern. This testifies for the fact that both methods describe the same physical regularities that newly indirectly confirms the validity of approach used. The distributions obtained are nonlinear with some low valued SSI peak over the area under observation. The presence of the peaks is related to strain localization in shear bands as well as strain gradients to occur within the analysed surface area. Besides, these distributions differ on more complex pattern to have the peak area with a gradual SSI decrease in the region under analysis. At the SSI_{min} diagrams (Fig. 10), one can observe non-smooth changing of strain intensity that testifies for gradual accumulation of microdefects during deformation and their redistribution with cyclic deformation and crack growth.

The similar character of SSI diagram but with smoother pattern of the rising branch of the curve is founded for the data calculated for the crack tip region (Fig. 10). Increasing the ductility of the material is associated with two aspects: the strain concentration at the fatigue crack tip as well as macroscale nature of deformations localization. In doing so, both demonstrate that the material does not lose the ability to deform further. By taking into account physical nonlinearity at calculation of the stress-strain state of specimens, we were able to investigate most accurately the process of their deformation and subsequent fracture.

It is established that the configuration of deformation localization zones at the various stages of the crack growth is considerably different. At the same time, the

a) b)

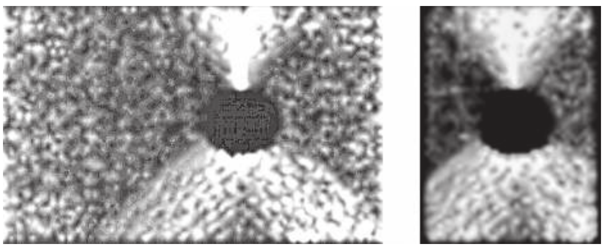

Fig. 9. SSI field for the couple images acquired just before the specimen's failure; calculation over: a – entire vector field; b – in the central hole region

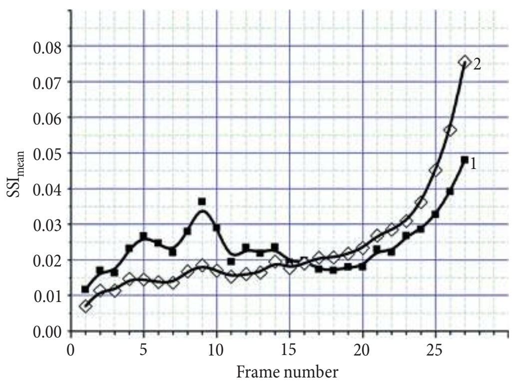

Fig. 10. Changing of average SSI with cyclic loading with calculation: 1 – over the entire area under observation; 2 – over the region of the central hole

symmetry of the bidirectional V-shape of strain distribution in the macrolocalization zones is kept up to fracture. As a result, at the macro scale level, the specimen is fractured by normal fracture mechanism.

Conclusions

The use of optical technique for strain estimation made it possible to assess the configuration of zones of localized plastic deformation and regularities in its development. There are zones with typical bidirectional configuration where the maximum value of the strain intensity occurs in the vicinity of crack tip that gives rise to fatigue fracture initiation. It should be noticed that the size of the fracture zone located perpendicularly to the tension axis depends on the degree to constraint transverse deformation (along the crack front). The constraint degree is affected by the thickness of the specimen: when the latter is increased, the planar stressed state tends to become a volume strain.

Main regularities of the fatigue crack growth in 17Mn1Si steel specimens at different scale levels at the presence of plastic deformation localization in the crack tip have been revealed and quantitatively described.

The fractography analysis data show that the transition of leading role of deformation and fracture from the lower structural level to the greater one has a regular pattern. It is quantitatively shown that increase of fatigue crack length is accompanied by enlargement the size of the plastic deformation zone in the vicinity of crack tip that makes the transition from quasi-brittle fracture to fatigue one with the formation of fatigue striations. The prefracture zone is formed by quasi-brittle mechanism.

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