Development of Ideas About Graded Nature of Material Deformation Affected by Network of Thermal Fatigue Cracks

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Abstract. *Within the concept of physical mesomechanics of materials and fracture mechanics, the peculiarities of deformation and failure of heat resistant steel 25Kh1M1F with a network of thermal fatigue cracks are investigated. The main regularities and characteristic stages of the deformation process in specimens from steel 25Kh1M1F affected volumetrically by a network of cracks under localisation of plastic strain are found and described numerically.*

Introduction

It is known that some concepts of mechanics of a deformable solid body, in particular, the hypothesis about the continuity and uniformity of the medium, do not allow taking into account the peculiarities of the internal structure of the material and the effect of its structural components on deformation processes [1]. The use of the physical mesomechanics approaches allows introducing the structural hierarchical levels in the medium analysis, due to which the structure of real objects is described in a more faithful way [2]. In other words, using physical regularities is the basis of the structural approach, which allows considering the graded nature of the deformation process, taking into account the internal structure of the material and its external loading [3]. At the same time, the Appendix to the investigations of materials with multiple defects [4] does not throw light on the main factors causing changes in the deformation behaviour and material properties.

Up to now, the universal models, which would describe truthfully the accumulation of damage in various materials with a network of cracks under the complex stress state, have not been constructed [5]. This is explained by a great variety of mechanisms of nucleation and coalescence of cracks depending on the stress state type, and the initial structure of the material, including the defective one. These factors account for the need in the development of new approaches to the evaluation of the material efficiency at the stage of accumulation and development of multiple failures, which precedes the nucleation of the main crack.

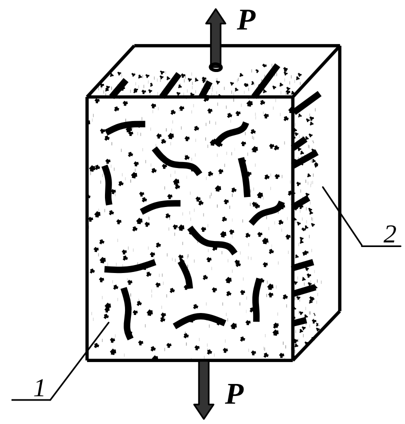
The purpose of this work is to use the approaches of fracture mechanics and physical mesomechanics for the analysis of the graded nature of static deformation of the material affected by a network of thermomechanical fatigue cracks.

2. Research technique. Prismatic specimens with the width b = 40 mm and thickness t = 10 mm were tested; the height of the specimen was L = 50 mm. The tests were carried out under conditions of the uniaxial tension on the ZD 100Pu hydraulic test setup. For the measurement of the axial strain of specimens the strain gauge method was used with the measurement accuracy up to 10^{-3} mm. The digital photography of the loaded specimen surface was also performed, and the automated analysis of the cracking geometry was carried out using the software package “Crack analyzer” [6]. The effect of cracking on the processes of deformation was evaluated by variation of the relative area of the main crack and multiple defects in the process of loading. The relative area of cracking was determined as a ratio of the sum of crack areas to the area of the section investigated (observed) [6]:

$$\nu = \frac{\sum_{i=0}^{n} f_i}{S_{surf}}, \tag{1}$$

where $\sum_{i=0}^{n} f$ is the sum of areas of thermal fatigue cracks identified on the surface image analysed, mm^2.

a



b

Fig. 1. Scheme of testing the specimen with a network of thermal fatigue cracks: 1 – external layer; 2 – internal layer

Material deformation due to plastic yielding of the matrix and opening of multiple defects can be characterised as follows [7]:

$$\varepsilon = \varepsilon^{\text{int}} + \sum_{i=1}^{p} \frac{\delta_i}{L}, \tag{2}$$

where ε^{int} is the deformation of the material islands located between cracks; δ^i is the opening of the i^{th} crack; p is the number of cracks within section L analysed.

Tests were carried out by the static tension scheme, under which the stress-strain state of the specimen material is similar to that of the continuous billet casting machine (CBCM) roller metal under operating loading. The TOMSC optical-television measurement system [8] was used to study the peculiarities of their deformation behaviour.

3. Experimental results. The investigation into the development of multiple failure at various scale levels requires finding out and formulating single regularities in the accumulation and propagation of defects. In this work, an attempt is made to establish some general regularities in multiple failure.

Most topical problem in mechanics of a deformable solid body is the analysis of the material deformation behaviour at the stage of prefailure, which corresponds to the development of the plastic strain macrolocalisation process in the specimen neck (the cross-section, in which the main crack propagates) [9]. Within the zone of the minimum cross-section, the material sustains most intensive plastic deformation and fails. In order to clarify the physical mechanisms of plastic deformation and failure of materials, the kinetics of the specimen mechanical behaviour in the strain macrolocalisation zone, where failure takes place, is of principal importance [10].

The localised plastic yielding is initiated in the zones of tensile normal stresses, in which the material sustains a strongly nonequilibrium state. Moreover, the nature of the plastic yielding localisation can be described only when the deformable solid body is considered as the multilevel system [11].

The analysis of data presented in Fig. 2 allows distinguishing five basic regularities. First, the external loading decreased gradually for the most part of the test duration, which is most probably connected with the determinative effect of opening of the main defect, i.e. the main crack. Second, the drop of load within section 3-5 can be approximated by a straight line, i.e. it has the linear character. Third, the above mentioned gradual reduction in loading is accompanied by the gradual softening of the material, which must be connected with the growth of defects. Fourth, local drops of load are observed on the descending branch of the curve (section 5-6) even at the stage of macrolocalisation. Fifth, local drops of load are observed with a certain frequency on the curve for the whole duration of loading, which is most probably connected with a start and further arrest of a macrodefect. Let us consider the characteristic sections of the curve designated with numbers 1-6 in the figure.

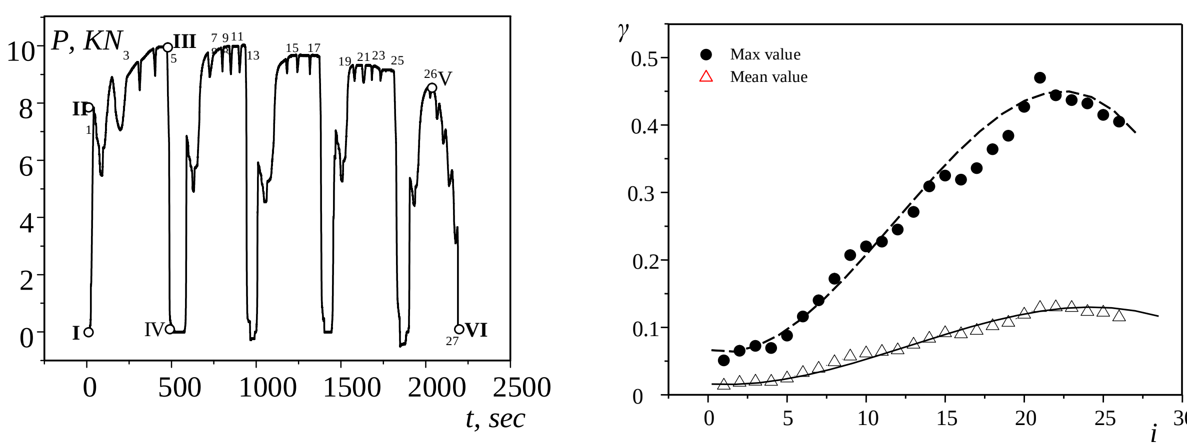


Fig. 2. Dependence of specimen loading P on duration of deformation t (a) and shear strain intensity at measurement point i (b)

I-II. Section of elastic deformation. This section is characterised by a uniform deformation of the material, which is loaded predominantly elastically.

II-III. Beginning of opening of the largest defect against the “stochastic behaviour” of the secondary, smaller cracks. In this case, it is the crack located normally to the loading axis that opens. However, its further propagation does not take place, because it is surrounded by the undamaged material with a sufficient strength and high ductility. Despite the crack opening and the drop of the specimen liability, the redistribution of stresses takes place in the material, and deformation continues. Moreover, due to significant relaxation processes an additional effort is required in order to ensure further deformation of the material.

III-IV. The specimen is unloaded in order to determine the variation of the elastic properties of the material in the process of failure. The nature of variation of the elasticity module under the repeated static loading depending on the relative strain is illustrated by Fig. 2. Obviously, the elasticity module decreases appreciably with an increase in strain. This allows for the correct determination of the specific energy spent on the macrocrack start. Thus, the problem of considering the “composite material” becomes simple, since it is possible to determine both the moment of the crack start and the penetration of the macrodefect.

V-VI. Attainment of the ultimate state and failure of specimen. The shape and fractures of the specimen under hard loading conditions (equilibrium deformation) allow for a precise determination of the specimen failure moment. The considered method for the evaluation of the deformation properties of the material with multiple defects is based on using the complete stress-strain curves.

Discussion of results. The regularities in deformation of the material with multiple defects. The results obtained will be interpreted from two perspectives: from the point of view of fracture mechanics and physical mesomechanics. The immediate interest in such an interpretation is explained by the fact that this will allow for an in-depth consideration of the deformation mechanisms and quantitative description of the regularities in the material failure [11] within the hierarchical complex approach.

It is known that any deformation of the macrospecimen is connected with the appearance of the shear γij and tension eij components in it, as well as the accumulation of the shear energy Aγ in the form of the potential energy, and the linear strain energy Ae. In this case, it is assumed that under the uniaxial tension the material deformation in the direction of loading application will be the consequence of both the elongation and turn of local volumes of the material. Thus, every strain tensor component of the individual material fragment can be considered as a result of the linear and shear strains, and can be written as follows [12]

$$\varepsilon_{ij} = \gamma_{ij} + e_{ij}.$$

Mean values of the stress and strain components describe the macroscopic stress state of the material. Moreover, within the local areas, the corresponding stress and strain components can accept both positive and negative values, i.e. the stress-strain state of the material is nonuniform [11].

a *b* *c* *d*

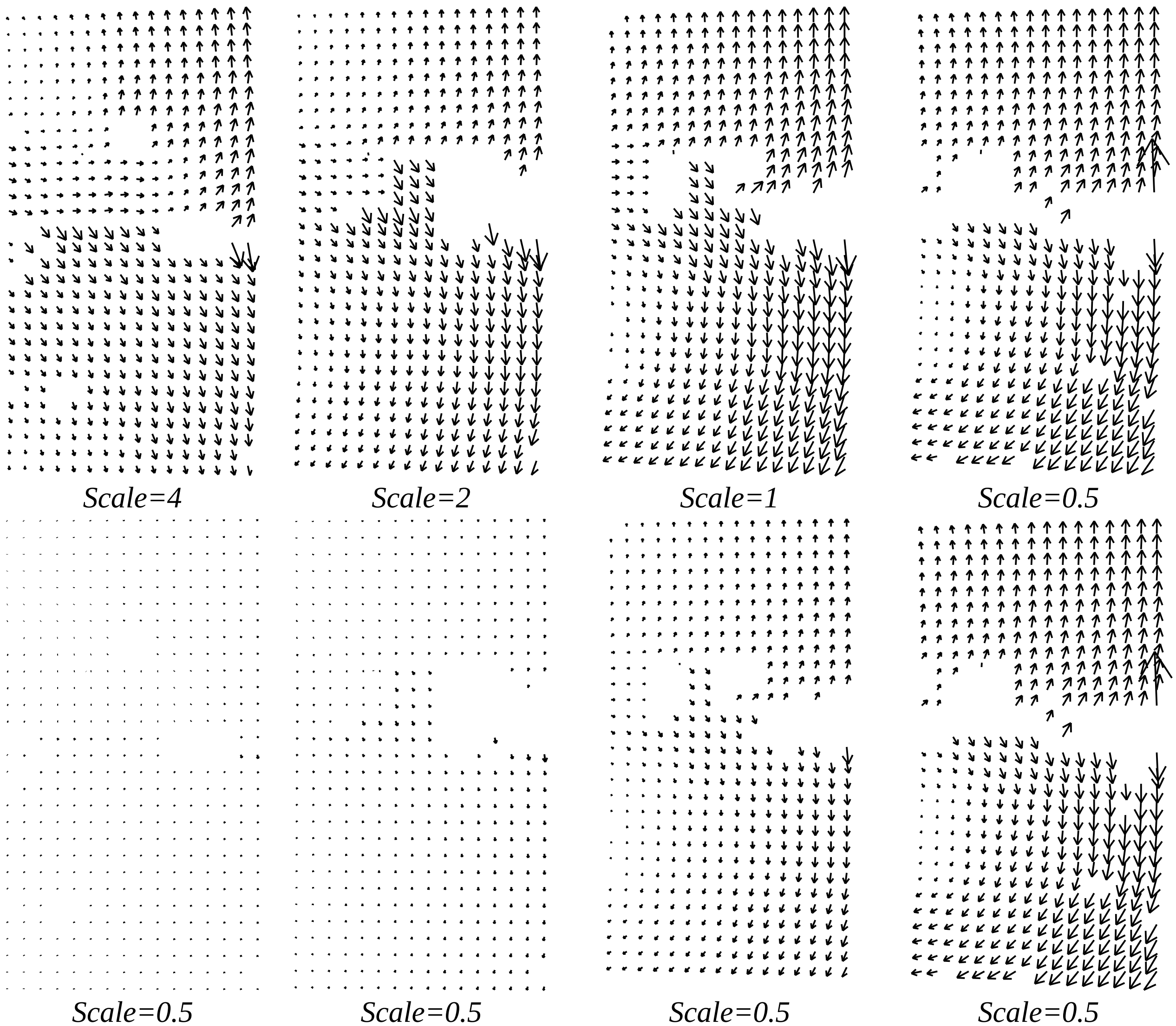


Fig. 3. Damage accumulation kinetics in the material with a network of thermal fatigue cracks

Let us analyse the stress-strain curve (Fig. 2,a) taking into account the above mentioned regularities. As is seen from Fig. 3, the elastic deformation of the material takes place, moreover, the deformed body can be considered as the quasiuniform one at the macrolevel. Further tensioning of the specimen (Fig. 3,b) is characterised by the material deformation with the activation of individual fragments located between the largest cracks, which is depicted in the change of their orientation (Fig. 4).

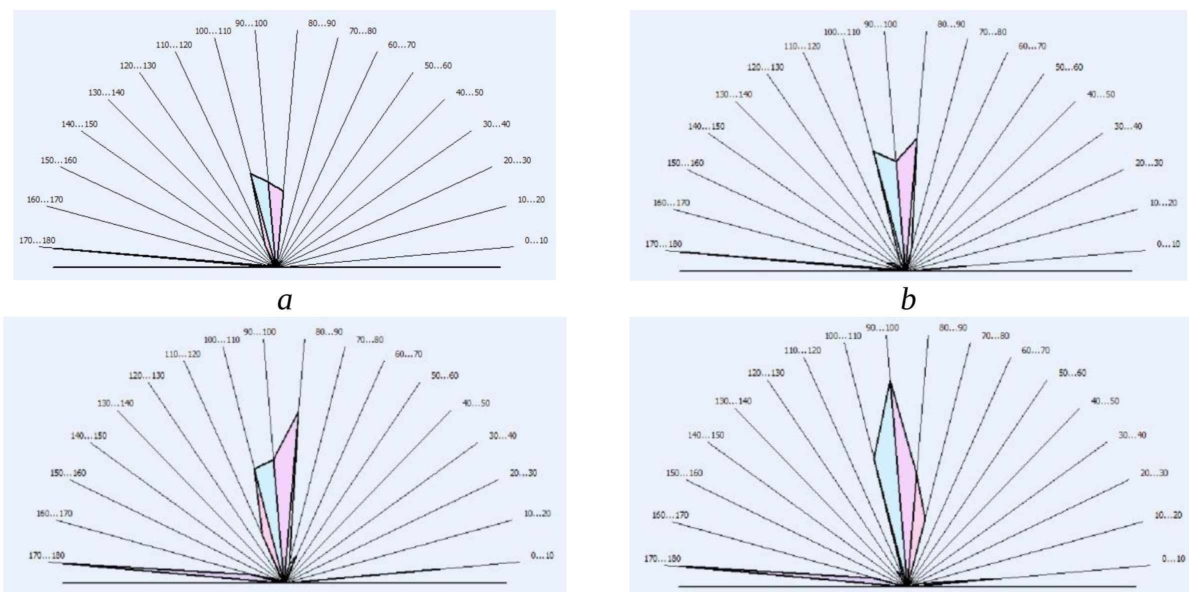
Shears of the material fragments occur due to the opening of cracks, which leads to the nonuniform distribution of strains along the working specimen surface. The material acquires properties of the breakup-block medium [3]. The “exhaustion” of the shear deformation potential in the process of deformation of the material with a system of cracks leads to the localisation of strain and start of the macrocrack (Fig. 3b).

A similar mechanism was offered in [3] in order to describe a displacement of the ice cover sections under the effect of deformation. When the critical strain is attained the system of cracks becomes unstable, the main crack propagates due to the joining of secondary cracks and propagation of the localised deformation zones. The said regularities are confirmed by strain measurements and the analysis of digital images showing deformation of the breakup-block medium under investigation (Fig. 3d).

It should be noted that two competing processes take place in the specimen: the articulated motion of its parts occurs due to the main crack opening, and the structural adaptation of the breakup-block medium takes place due to shears and turns of the “material islands” located between such cracks (Fig. 4). The basic accommodation of the material fragments ends up by the formation of the hierarchical structure, which ensures further deformation due to a mutual turn of the specimen macrofragments without breaking the material. Moreover, the process of macrodeformation takes place by the traditional scheme typical of the body with the macroconcentrator, which is described in many literature sources [13].

The specimen fails after the global loss of the shear stability and transfer of the leading role of deformation to the macroscale level. The external load leads to a start of the macrocrack, besides, the processes of deformation have the accommodative nature during the crack propagation, and the material fails after the exhaustion of its relaxation capacity.

The plastic strain localisation is caused by the opening of defects of the external layer and redistribution of strains on the boundary between the defective layer and the noncracked material. One of the manifestations of the mesolevel mechanisms is the displacement of the material fragments. In this case, deformation is considered as a result of the material components displacement between the elements of the network of cracks, including due to the opening of cracks; in addition, the damage accumulation kinetics is treated as the steady process of the crack area expansion.



a *b* *c* *d*

Fig. 4. Variation of defects orientation in the process of deformation in points I, II, III, IV.

Among the factors, which affect the strain accumulation kinetics in the process of static loading, the stress state type (voluminous stress state) occupies one of the first places. This is most pronounced at the failure localisation stage, when the activation of the macrocrack takes place (Fig. 5).

Diagram “load-absolute strain” obtained during the propagation of a crack in the specimen from steel 25Kh1M1F with cracks is typical of the breakup-block medium. A certain “extension” of the graph along the deformation axis allows tracing transitions between the adjacent stages, as well as the character and quantitative characteristics of the available oscillations, Fig. 5a. It is known that the start of a crack is caused by the local instability of properties in the form of dislocation flows, whereas a transition from the crack start to its propagation features the process of accumulation of the critical defect concentration in a certain volume, which, in the long run, predetermines the process of the specimen failure. In this case, the damage accumulation kinetics can be traced easily by the variation of the specimen liability, Fig. 5b.

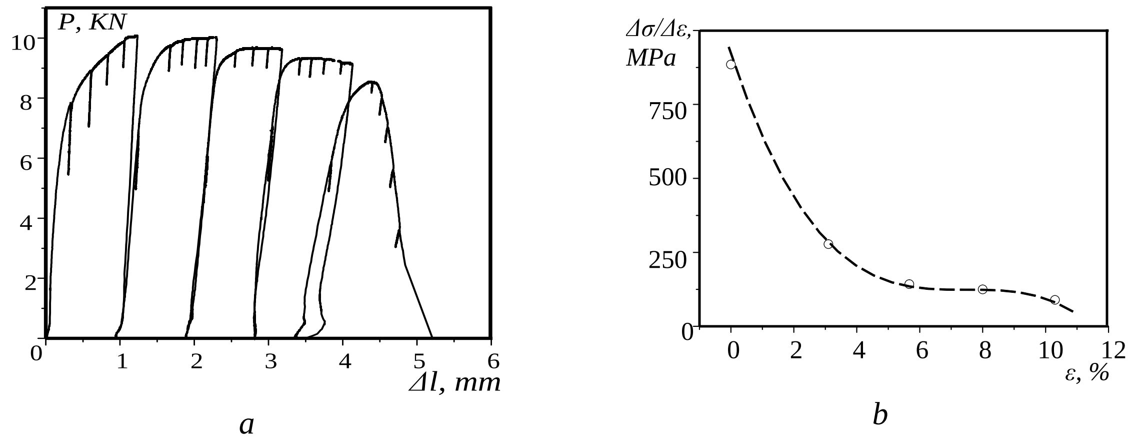


Fig. 5. Stress-strain curve of the material with multiple defects (a) and dependence of variation of the material deformation capacity on the relative strain of the specimen (b)

4. “Composite” structure of the material. The irregularity of sizes of the thermal fatigue crack network elements causes the nonuniformity of the stress-strain state of the material. A difference between the mechanical properties of the external (most cracked) and internal layers of the specimen and the absence of the clear-cut borderline between them leads to the formation of curvilinear sections at crack tips that sustain the effect of three-dimensional tensile (and compressive) normal stresses, as well as the effect of the plastic base and surface layers, which are characterised by the developed multilevel structure. According to literature data [9-11], such a distribution may have the undulatory character. The presence of differently oriented crack-like defects “embrittles” the material, which may lead to strain localisation. In addition, while cracks resulting from the normal separation reduce the material plasticity, the cracks resulting from the transverse shear and oriented in the direction of the maximum tangential stresses may cause an “increase” in plasticity.

In ref. [1], a phenomenological model of damage accumulation in metallic materials under static loading is proposed, according to which the degree of the material damage (loosening) is connected with deformation by the following relation:

$$\varepsilon_p = [1 - 2\mu(\varepsilon)]\varepsilon, \tag{3}$$

where $\mu(\varepsilon)$ - is the current value of the transverse strain coefficient.

The residual strain in the cross-section of the specimen studied did not exceed 3 %, therefore, loosing of the material with multiple cracks is connected only with the opening of cracks and is practically unaccompanied by the plastic deformation of the matrix. This also confirms the hypothesis about the directionality of the crack opening, which is the basis of the equation (cracks open in the direction of deformation without a noticeable variation of the specimen cross-section), according to which:

$$\mu = \frac{\varepsilon_{non}}{\varepsilon_{npo\partial}} \to 0 \tag{4}$$

In this case, $\varepsilon_p = \varepsilon$, which causes a significant macro- and micro-nonuniformity of the structure and, consequently, the fluctuation of the material flow stress and disturbance of stress fields, which predetermines a strong scale effect, scatter of the mechanical properties characteristics, non-linearity of relationships between stresses and strains. Structural levels of deformation processes are generalised in Table 1

Table 1. Structural levels of deformation and stress-strain curve sections under static failure of the specimen with multiple defects

Sections of the stress-strain curve	Factors affecting statistical strength	
	Damage accumulation mechanism	Effect of the network of cracks
0 – I	Elastic-plastic	Stochastic opening of defects and start of the macrocrack
II - III	Decrease in the shear stability of the material	Crack growth, closure of multiple defects
III - IV	Active displacement of material “islands” (increased disorientation of cracks)	Opening of multiple defects
V and further	Attainment of the ultimate state, loss of the residual load-bearing capacity of the material	Growth of the macrocrack

Summary

The physical and mechanical interpretation of the graded nature of deformation processes in the material with multiple defects ensured by the agreement between the material deformation and opening of defects is offered. Taking into account the nonuniform properties of the material with thermal fatigue cracks along the specimen cross-section, a medium of this type can be considered as a composite consisting of disoriented fragments of different sizes, and crack-like defects can be regarded as zones of most pronounced deformation singularity.

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