DAMAGING OF A STRUCTURAL STEEL UNDER MONOTONIC AND CYCLIC DEFORMATION

G.G. Pisarenko, O.V. Voynalovich A.M. Mailo

G.S. Pisarenko Institute for Problems of Strength, National Academy of Sciences of Ukraine

Abstract. The paper presents the characteristics of inelastic properties of the surface material of laboratory specimens under monotonic deformation and fully reversed cyclic loading. The comparative results are shown for calculating the values of the surface layer inelastic strains determined based on the fractal parameterization method for statistically non-uniform surfaces of the material for two states of the deformation-induced relief under identical conditions of elasto-plastic deformation in specimens. The kinetic characteristics of discrete strains in the material at the stage of non-localized damaging are presented.

Introduction. It is shown in [1] that, under cyclic deformation, the mechanical properties of an elasto-plastic material are changed in the first cycle of loading. Under elastic deformation, a cyclic change (hardening-softening in fatigue) in the mechanical properties of a structural steel becomes apparent due to a local non-linearity of the deformation characteristics of microstrucural elements that accompanies damaging. The action of the damaging mechanism is due to the non-uniformity of distribution of local plastic shears in the material [2].

The effect of non-uniformity of the mechanical properties under loading discovered by Bauschinger takes place because of the spatial mismatch in the mutual orientation of structural elements and manifests itself in the reduction of the mechanical properties of a metal under monotonic loading as well. The material ability to resist dispersed or non-localized damage is determined by the parameter of stress distribution in local volumes of the surface layer of the deformable polycrystalline object under deformation.

According to the damage model proposed in [3], under cyclic loading, the fracture develops first by the dispersed damage mechanism with a subsequent change in the fracture mechanism – from the micro- and meso-levels to the macro-level - and is completed by macrocrack formation in the surface layer, with the process transition to internal volumes of the material according to the self-similar mechanism [4]. Under monotonic loading, the process of fracture in structural components is also localized in the stress concentrator zone of the surface layer [3]. In both cases, the sequence of change in the damage mechanism scale at a macro-crack tip is identical. The main difference lies in the volumes of the loaded material and time of action of the effective stress amplitude value.

The goal of this paper is to reveal the regularities in damaging under cyclic and monotonic loadings of structural steels determined using the criterion of accumulated damage in the surface layer of the laboratory specimen.

Investigation procedure. The investigations were performed using specimens of austenitic steel Kh18N10T (an analog of steel SAE321) as an example [5], which is widely used in engineering; its physico-mechanical properties are summarized in Table 1.

Table1. Physico-mechanical properties of steel Kh18N10T.

$\sigma_{0.2}$, MPa	$\sigma_{\text{ultimate strength}}$, MPa	$\boldsymbol{E}$, MPa	$\boldsymbol{\sigma_{-1}}$, MPa
314	628	$2{,}4\cdot10^5$	230

The analysis of material damage kinetics was carried out on standard flat specimens of hour-glass shape. The specimens were subjected to mechanical loading in monotonic tension and uniform tension-compression with fully reversed stress cycles. Values of stress amplitudes were chosen based on the results of [2]. The chosen range of cyclic stress levels is below the proportionality limit. The characteristics of Fig. 1 approximate the variations in the inelastic strain amplitude of the specimen. The surface area of 1.0 mm^2 was scanned by a resonant scanner at 12-point locations. Each point in Fig. 1 represents a statistical data set of 1000 units in size [6].

A dimensionless index of the fractal dimension of micro-plastic strain amplitudes, which is a kinetic characteristic of the cumulative inelasticity in the surface layer and is defined by the Hurst parameter H [6] by the below formula, was chosen as a parameter characterizing the metal damage:

$$\frac{R(t)}{S(t)} = \frac{[X(t)]\max - [X(t)]\min}{S(t)}$$

where: *R/S* is the normalized range, R is the deviation range X, (X) max is the maximum value for X, (X) min is the minimum value for *X*.

The range is cumulative deviation over N periods or the difference between the maximum and minimum calculated values of the parameter H:

$$X = \sum_{i=1}^{t}(n_i - M_N)$$

where X is cumulative deviation over N periods, n_i is the deviation during a period of loading, M_N is the mean n_i over N periods.

Results and their discussion. Figure 1 depicts the results for discrete measurements of cumulative inelastic strain range over the surface area of 1.0 mm^2 of the specimens after loading. According to the model presented in [7], the local fracture initiation occurs at the stage of dispersed damage in the zone of maximum strains accumulated as a result of the exhaustion of the local plasticity margin. The position of the upper portions of kinetic characteristics 1 and 2 in Fig. 1 corresponds to this state of specimen dispersed damage.

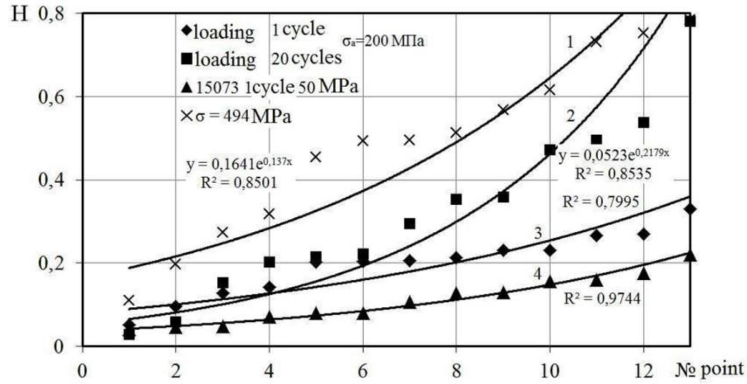

Fig. 1. Influence of the monotonic tension (curve 1) and cyclic tension-compression (curves 2-4) on the amplitude of the accumulated range of inelastic strain amplitudes (parameter H).

The range of the point values on curve 1 (the values of the parameter H) characterizes the dispersion of the inelastic strain amplitudes determined by the growth kinetics of surface strain defects in specimens under mechanical loading.

The damaging of the specimen material subjected to the action of 20 cycles of loading with the amplitude of 200 MPa corresponds to the maximum value of the parameter H = 0.8 (Fig. 1, curve 2). For the specimen subjected to one fully reversed stress cycle σ = 200 MPa (Fig. 1, curve 3), the maximum value of the parameter H is H = 0.3.

The 20 cycle loading with stress amplitude σ = 200 MPa caused a 60%-increase in the maximum value of H. The values of the parameter H in the range of the points representing the natural state (called non-uniform state) of the material are within H_{min} / H_{max}=0.1.

The regularities in the inelastic strains accumulated under monotonic tensile loading (***σ*** = 494 MPa) and in tension-compression (***σ**a*** = 200 MPa), as shown in Fig. 1 (curves 1 and 2), are similar in amplitude of the maximum distribution values and kinetics of the parameter H. The noted regularity in the accumulation kinetics of strain defects under quasi-static and alternating loading expressed in terms of the damage parameter H, can define the limiting state of the material and its ability to resist damage under different loading conditions irrespective of the loading history and rate [9].

It follows from the analysis of the results obtained that the value of the parameter H in the data sample increases monotonically, characterizes the non-uniformity of strain defects accumulated in the surface layer of the specimen material and reaches the maximum in-sample value before local fracture. Under monotonic tension, the increase in the parameter H is determined by the stress amplitude, whereas under reversed cyclic tension-compression loading, its value is determined by the number and duration of tension cycles defining the dwell time at the maximum amplitude of tension cycle, during which the parameter H of the material reaches the maximum value.

As a result of the elasto-plastic deformation, irrespective of the loading conditions, the surface of metal in a specimen and structural component is subjected to changes governing the service life, which appear in the form of a deformation-induced surface strain relief and can influence the results of measuring the state of inelastic strains in the surface layer, as reported in [8]. To assess the influence of the strain relief condition, Fig. 2 shows the dependence characteristics of the parameter H on the amplitude of discrete strains on the specimen surface. The characteristics are obtained for three surface geometries: with the surface roughness corresponding to class 7, after monotonic loading above $\boldsymbol{\sigma_{0.2}}$ and for the polished surface after loading. The measurement data on the discrete inelasticity of the specimen under investigation are compared with the initial state after mechanical polishing for eliminating discrete surface deformation-induced defects (the amplitude is less than 3.2-6.3 μm). The influence of the deformation-induced relief was determined from the change in the highest in-sample value of the parameter H [8].

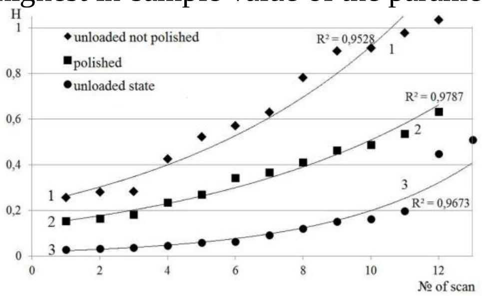

Fig. 2. Influence of discrete plastic deformation in the surface layer on the parameter H

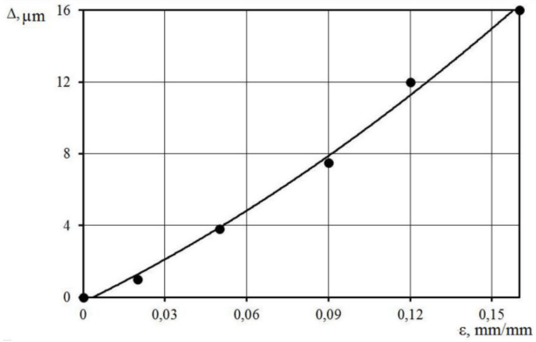

Fig. 3.Kinetics of increase in the amplitude of discrete plastic strain in the surface layer under monotonic loading [10]

The minimum value of H corresponds to the initial state of the accumulated inelastic strain level of the material (Fig. 2). The parameter H value corresponds to the maximum density of strain defects accumulated in monotonic tension for σ_+ = 494 MPa, which corresponds to the value of the parameter H equal to 0.8 (curve 1 in Fig. 2). After removing deformations on the surface of the specimen by way of mechanical polishing up to the level where the specimen surface is in an unloaded state, the maximum value of the parameter decreased down to the level of H = 0.6.

Therefore, the component of the damaging parameter caused by discrete surface deformations is 40% of the initial one. The maximum in-sample value of the damaging parameter H = 0,8 is due to the circumstance that when the specimen is loaded above the yield stress, an increase in the discrete surface strain amplitude up to 16 μm takes place, which has an influence on the increase of the parameter H (Fig. 3) [10]. In the elastic deformation of the specimen under the stress lower than $\boldsymbol{\sigma_{0.2}}$, the influence of the deformation-induced relief will be insignificant , because the roughness amplitude is within 1.0 μm (Fig. 3) [9], which is much below the amplitude of the deformation-induced surface roughness corresponding to class 7 [10] (Fig. 4). From Fig. 4, it follows that the surface roughness of 3.2-6.3 μm or less introduces an error of less than 5% into the non-uniformity of distribution [10].

The results of the analysis of the obtained data provide a basis for assessment of the dispersed damaging of the metal under deformation with consideration of the kinetic features of the non-uniformity of inelastic strains in the surface layer of the specimen. The methodology of the approach is based on the use of the variation with time of the characteristics of distribution of discrete inelasticity in the surface layer material for assessing the damaging of the structural steel [6]. In [9], it is shown that, prior to fracture, this characteristic takes a fixed value whose maximum initiates the localized damage and is independent of the mechanical loading history.

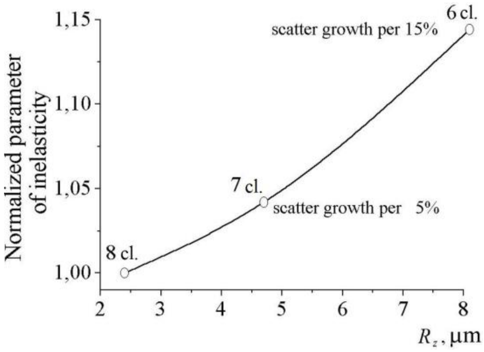

Fig. 4. Influence of the amplitude of discrete surface plastic strains on the inelasticity parameters

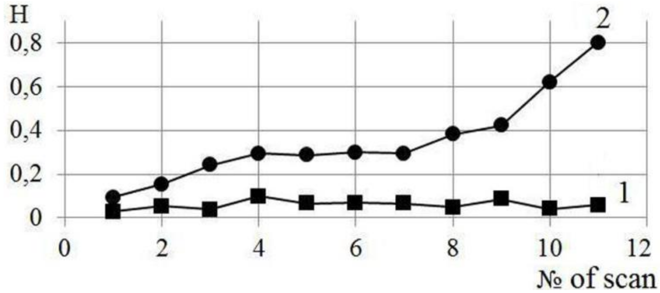

Fig.5. The increasing behavior of the limiting values of descriptive statistics parameters of the sample data set for the coefficient H. 1-H=H_{min}, 2-H=H_{max}.

Figure 5 depicts the monotonic variation behavior of the maximum and minimum values [9] of the parameter H characterizing the amplitude of local variations in the material.

Conclusions

- An approach has been proposed for the analysis of discrete inelastic deformation characteristics of the material under monotonic and cyclic loading of laboratory specimens.
- A general character of the regularities in the dispersed damaging of the structural steel has been revealed for two modes of deformation - in monotonic tension and symmetrical tension-compression – determined by the limiting amplitude criterion in the discrete data set.
- It has been shown that the fractal parameterization method is suitable to describe the damaging characteristics of the surfaces of specimens with a different loading history. This method is appropriate for the parameterization of discrete statistically non-uniform surfaces, owing to which the identity of the damage assessment criteria under the investigated loading conditions is provided.
- The proposed approach can be used for assessing the damaging of structural elements under unsteady operating conditions.

1. J. F. Bell, Experimental Fundamentals of Mechanics of Deformable Solids. Part II. Finite Strains, Moscow, Nauka, 1984
2. Ivanova V.S., et al., in: ***Synergetics and Fractals in Material Science*** [in Russian] Moscow, Nauka, 1994.
3. V.T. Troshchenko, Fatigue of Metals under Nonuniform Stressed State. Part 1. [in Russian],Kiev, Naukova Dumka, 1985.
4. V. I. Danilov, L. B. Zuyev. Macrolocalization of plastic strain and stage character of plastic flow in polycrystalline metals and alloys. *Advances in Physics of Metals* [in Russian], Vol. 9, No 4, pp. 371-422, 2008.
5. Mechanical Properties of Structural Materials in a Complex Stress State (Edited by A.A. Lebedev, Academician of the NAS of Ukraine, “In-Yure” Publishing House, 2003.
6. G.G. Pisarenko, A.M. Mailo. Method for determining the statistical surface properties of nonuniform materials. In: Nadezhnost’ i dolgovechnost’ mashin i sooruzzheniy (*Reliability and Durability of Machines and Structures)*. Issue No.40. pp.158-165, 2015.
7. T.Yu. Yakovleva . Local Plastic Deformation and Fatigue of Metals [in Russian], Naukova Dumka, Kiev, 2003.
8. O. Wouters, W.P. Vellinga, R. van Tijum, J.Th.M. De Hosson. Effects of crystal structure and grain orientation on the roughness of deformed polycrystalline metals, *Acta Materialia*, Volume 54, Issue 10, , pp. 2813–2821, June 2006.
9. G.G. Pisarenko, A.M. Mailo. Amplitude characteristics of inelasticity in steel Kh18N10T under high-cycle loading. *Problems of Strength*, No 2, pp.167-175, 2016.
10. A.M. Mailo. Influence of cyclic deformation on the non-uniformity of the physico-mechanical properties of a surface layer of structural metallic materials under fatigue. *Abstract of the Thesis for a Candidate's Degree of Technical Sciences* [in Ukrainian], Kyiv, 2011.