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Diagnostics of critical states of constructions operated under low temperature conditions

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Abstract. Characteristic changes in the stress-strain state of the material in the region in front of the propagating brittle crack in samples of steels and cast irons of machines and constructions by X-ray diffractometry was established. The angular displacements of the peak and the change in other characteristics of the profile of the diffraction lines reflected from the elastically deformed regions of the material are stably fixed. The characteristics of the diffraction lines profiles reflected from the samples surface of steels and cast irons of different chemical composition differ qualitatively and indicate the instrumentally determined influence of the substructure of steels and cast irons on the processes of their resistance to nucleation and propagation of cracks. The efficiency of using the X-ray strain measurement method for nondestructive testing of the stress concentration region to determine the bearing capacity and the residual life of constructions was experimentally established.

1. Introduction

The operation of machines and equipment, main gas and oil pipelines and other technical systems in the climatic conditions of the arctic and subarctic regions of the Russian Federation is associated with the fulfillment of a number of special technical requirements for machines and constructions, and for maintaining their reliable operability during the guaranteed period [1-4]. Theories and practical applications of the fracture mechanics of high-strength structural materials used in critical constructions are the scientific basis of special technical requirements. However, the extension of the provisions and methods of fracture mechanics to high-duty constructions and products is hampered by the poor knowledge of the processes of material deformation at the microstructural level, the absence of acceptable tools for the full utilization of the service properties of materials.

2. Problem Statement

According to experts [4-10], the required reliability of machines and constructions during their operation can be achieved by operative diagnostics of the loss of bearing capacity of machine parts and structural elements using nondestructive testing methods. An expansion of the economic activities of enterprises and organizations in the arctic and subarctic regions of the country with a long period of low climatic temperatures increases the importance of the methods of nondestructive testing and assessment of the state of pre-destruction of metal structures and machinery.

However, a number of methodological issues related to the use of X-ray diffractometry methods for diagnosing the bearing capacity of the exploited constructions of various technical systems, determining the state of pre-destruction of elements of metal structures remain poorly studied [5-8]. In particular, problems of instrumental determination of deformed regions by substructural changes in the metal of the exploited constructions require a careful consideration.

The aim of this work is to establish a qualitative connection between the stress-strain state of samples of structural materials and the characteristics of the profile of diffraction lines that represent microplastic deformation at the substructure level.

3. Research Methods

To achieve this purpose, we measured the characteristics of the X-ray diffraction line profiles reflected from the blocks of the polycrystalline structure of laboratory samples of structural materials (30KHGSA, 60S2A, 65G steels, 08 ps steel; SCH20, CHVG40 cast irons). The nature, levels and types of loading of the test samples corresponded to the action of operational loads. Measurements of the characteristics of X-ray diffraction line profiles were made on two groups of samples in which a stress-strain state was created with special types and loading levels similar to the actual operational state.

The first group consists of plane rectangular samples of 30KHGSA, 60S2A, 65G steels and SCH20, CHVG40 cast irons with an edge fatigue crack loaded with a three-point bending before failure. The fatigue crack on these samples was grown by a cantilever shock-cyclic transverse bending simulating the operating mode of loading hammers of crushing machines [11]. This method of loading laboratory samples was adopted to obtain the characteristics of profiles of X-ray diffraction lines, indicating the propagation of plastic deformations from the fracture surface. The profile characteristics were measured at certain points on the lateral face of the samples (figures 1, 2).

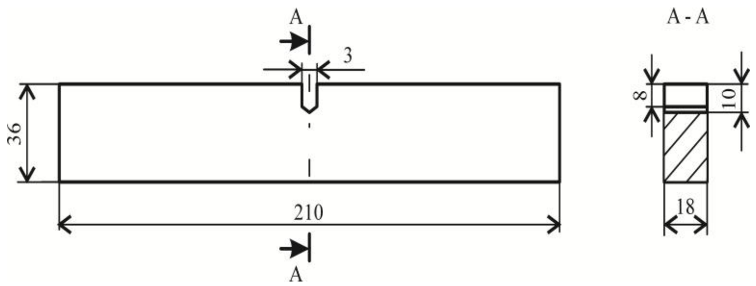

Figure 1. The type and geometric dimensions of the samples for investigating the propagation of microplastic deformations with the growth of a fatigue crack and subsequent failure.

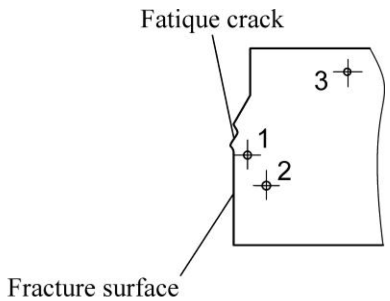

Figure 2. Measuring points of the characteristics of the profiles of X-ray diffraction lines on samples to study the propagation of microplastic deformations with the growth of the fatigue crack and subsequent destruction.

The static loading of the second group of samples is carried out in an open atmospheric platform and indoors to establish the effect of climatic factors on the change in the characteristics of the X-ray diffraction line profiles of sample material in the range of elastic stresses that constanly act for a long time. As the structural material studied, the widely used structural steel 08ps is used, the crystal structure of which has a body-centered cubic (bcc) lattice. Primary acts of microplastic deformation in such a structure are observed over close-packed slip planes of the second order, in particular, *hkl* = (220).

Static loads developed by loads of different weights are applied to assemblies consisting of 3 identical samples connected in series (figure 3). The assembly of 3 identical samples into a single line loaded with one load is caused by the need for an X-ray analysis of the central region of the gage area of each of the 3 samples. Weights masses are chosen so that in the cross-section of each sample of one assembly tensile stresses equal to $\sigma = 0.3\ \sigma_{0.2}$ (yield strength). For the second assembly, the load mass provides stresses in the cross-section of the samples $\sigma = 0.5\ \sigma_{0.2}$, and, respectively, for the third assembly $\sigma = 0.7\ \sigma_{0.2}$, for the fourth assembly $\sigma = 0.9\ \sigma_{0.2}$. Thus, from January 2013 to the present, under the action of tensile static loads on an open atmospheric platform, there are 4 assemblies of steel samples, indoors in a similar way to a set of 4 sample assemblies.

Figure 3. The scheme of loading the assembly from 3 samples tensile by loads of various masses (rotated by 90°).

For the X-ray analysis the sample assembly is unloaded and disassembled for the period of time necessary for X-ray analysis. Previously samples are visually inspected, the measurement of geometric dimensions is carried out. X-ray analysis of statically loaded samples is performed periodically every 6 months since June 2013.

Characteristics of X-ray diffraction line profiles are recorded on a Rigaku Ultima IV X-ray diffractometer manufactured by Rigaku International Corporation (Japan) with a high-precision horizontal goniometer. Analyzed sample is fixed horizontally in a goniometer, scanned by an X-ray generator and a scintillation counter that rotates in a vertical plane along the goniometer guide.

The diffraction spectrum is analyzed according to the scanning scheme θ-2θ with Bragg-Brentano focusing in Co radiation (λ = 0.179020 nm wavelength). A secondary beam uses a graphite monochromator. The width of the slit bounding the incident beam: horizontally 10 mm, vertically 0.5 mm. Soller's slit on the incident and diffracted beams are 5°; the width of the slit that bounds the diffracted beam vertically in front of the receiving slit is 0.5°.

Operating mode of the X-ray source: U = 40 kV; I = 40mA; scanning speed: 0.1 deg/min; step: 0.01 degree; scanning axis: 2θ/θ. The diffraction line profile in the coordinates "intensity-angle 2θ", the angle 2θ (in degrees) of the profile peak, the interplanar spaces d (in angstroms), the maximum intensity Imax of the reflected radiation (in imp/s), the half-width of the FWHM profile (in degrees) and other characteristics are output automatically by the PDXL-2 program.

Instrumental broadening was recorded on reference samples of 30KHGSA, 60S2A, 65G, 08 ps steels and SCH20, CHVG40 cast irons, the reference microstructure of which was obtained by recrystallization annealing in a vacuum furnace.

Based on the stated goal of the study, the first group included laboratory samples of steels and cast irons widely used for the manufacture of parts of machines and other technical systems experiencing sufficiently high operational loads that can cause the fatigue cracks initiation and propagation. Fatigue cracks initiation, as a rule, is observed in the stress concentration zones of those present in any construction and being observation objects of safekeeping of the constructions operability by methods of nondestructive testing.

4. Findings

Characteristics of profiles of X-ray diffraction lines indicating the propagation of plastic deformations developing upon the failure of laboratory samples with pre-grown fatigue cracks were obtained by X-ray analysis of individual points on the lateral face of plane samples of 30KHGSA, 60S2A, 65G steels and SCH20, CHVG40 cast irons (figure 2). The point of analysis 1 is adjacent to the surface of the fatigue crack propagation, so the crystal structure deformations revealed by the analysis will characterize the stress-strain state at which the fatigue crack continued its propagation. At point 2, the deformations of the crystal structure are likely to be due to the stress-strain state caused by the application of the load at the fracture of sample by a three-point bending. For comparison, an X-ray analysis was carried out at point 3, in which residual plastic deformations achieved at the maximum level of the stress-strain state of the sample with known loading conditions and geometry should be observed.

Numerical values of the characteristics of the diffraction line profiles obtained as a result of X-ray diffractometry of these points on the lateral face of samples 30KHGSA, 60S2A, 65G steels and SCH20, CHVG40 cast irons, automatically processed by the program PDXL-2, are given in table 1. As can be seen, the numerical values of the characteristics of the diffraction line profiles: profile maximum 2θ°, interplanar space *d*, nm and *FWHM* broadening vary depending on the position of the X-ray analysis point relative to the fatigue tip crack and the distance from the fracture surface (fracture). Such a pattern of microstructural changes determined by the stress-strain state of the material was detected in [8-10].

The features of the substructure of the deformed material are expressed most clearly by the actual graphical profiles of the diffraction lines. A joint study of the diffraction line profiles obtained during survey at different points of the lateral face of the studied sample makes it possible not only to reveal the inhomogeneity of the stressed-deformed state, but also to determine the effect of microstructural features on the course of elementary acts of plastic deformation.

Table 1. Characteristics of the profiles of the diffraction lines from the planes (220) at points 1, 2 and 3 of the lateral face of the investigated samples 30KHGSA, 60S2A, 65G, SCH20 and CHVG40.

Grade	Point number	2θ°	*d*, nm	*FWHM*
30KHGSA	1	123,839	0,101382	0,492
	2	123,842	0,101380	0,482
	3	123,876	0,101364	0,471
	standard	123,928	0,101339	0,275
60S2A	1	124,012	0,101300	0,494
	2	124,049	0,101283	0,477
	3	124,017	0,101298	0,471
	standard	124,067	0,101276	0,256
65G	1	123,815	0,101393	0,607
	2	123,796	0,101402	0,494
	3	123,803	0,101399	0,477
	standard	123,949	0,101333	0,229
SCH20	1	123,949	0,101333	0,229
	2	124,079	0,101269	0,558
	3	124,121	0,101249	0,431
	standard	124,234	0,101197	0,181
CHVG40	1	124,066	0,101275	0,491
	2	124,097	0,101261	0,559
	3	124,119	0,101250	0,423
	standard	124,127	0,101247	0,159

Figure 4 shows the profiles of the diffraction lines recorded at points with different stress-strain states and superimposed on each other, obtained on laboratory samples of cast irons SCH20 and

CHVG40. Comparison of the general form of diffraction profiles of cast iron samples SCH20 and CHVG40 reveals a significant difference in the intensity of the peaks. Vermicular iron has a higher intensity of reflection from the crystallographic plane (220) both in the annealed state (standard) and at point 3 without obvious traces of plastic deformation. At the same time, the intensity of the cast iron profile of CVG 40 at a given point is much higher than in the diffraction profile of the same region of the sample of grey cast iron SCH20.

It should be noted that the diffraction profiles taken from the planes (220) at point 2 have a coincidence in their type and characteristics for cast iron with flake and vermicular graphite (curves 2 in figure 4, table 1). Probably, this is due to the common ferritic-pearlitic metal base of the investigated cast irons, with an equal ratio of the areas of ferrite and perlite. On the contrary, the profiles of the crystallographic planes (220) at point 1, far from the surface of the fatigue crack at a distance of 1 ... 2 mm, are significantly broadened in comparison with the *FWHM* standards (samples in the annealed state) and point 3. This difference revealed by diffractometry is explained by high gradients of stresses and strains, under which the influence of the form of graphite inclusions in the common ferritic-pearlitic base of cast irons is intensified.

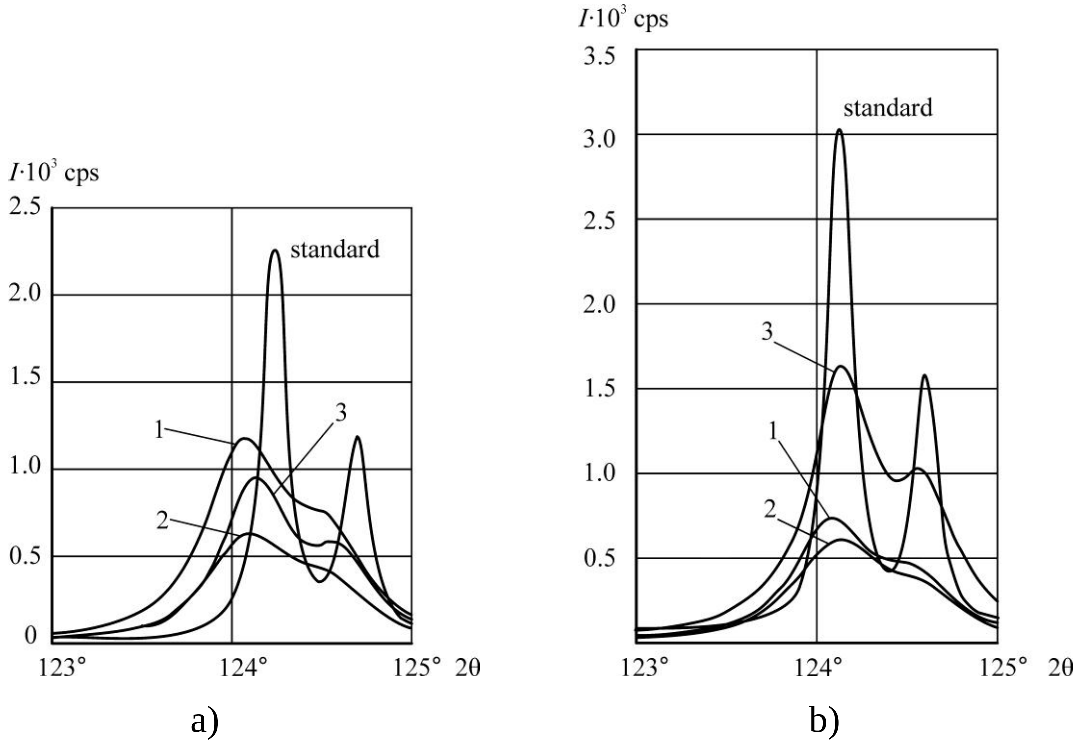

Figure 4. The profiles of the diffraction lines of deformed regions of cast iron samples SCH20 (a), CHVG40 (b): 1 - the area adjacent to the propagation plane of the fatigue crack front; 2 – the area adjacent to the fracture surface; 3 – the area with residual plastic deformations.

It is noticeable that the intensity of the diffraction profile of the crystallographic c planes (220) in the ensemble with the vermicular shape of the graphite inclusions is much lower than for the ensemble of a ferritic-pearlitic base with a flake form of graphite inclusions. This significant difference is probably due to a lower energy expenditure on the crack propagation at a single level of stressed-deformed state. The small shift in the peak of the profile of the diffraction line reflected from the planes (220) in the region 3 of the frontal plane of the cast iron sample of CHVG40 is probably due to microstructural features, namely, the vermicular shape of the graphite inclusions because the quantitative ratio of the flake and vermicular shapes in the investigated cast iron grades is the same.

There is a significant change in the interplanar spaces d depending on the location of the analysis area on the frontal plane of the samples and depending on the cast iron microstructure (table 1). The interplanar spaces d increase in accordance with the stress-strain state of the investigated regions. The increase in interplanar spaces due to a combination of distortions of crystals from microstresses and their dispersion is 30 percent or more.

The obtained results not only correspond to the assumptions concerning the role of flake graphite in cast irons, but also give grounds for a possible quantitative assessment of expenditure of energy of crack propagation in such structures [9-11].

X-ray diffractometry methods also provide insights into of plastic deformation processes by changing the dislocation density, which may reflect a change in the stress relaxation mechanisms arising in the elements of metal constructions under operational loads [8, 12, 13].

In this paper, in accordance with the goal, change in the dislocation density calculated from the broadening of the profile of diffraction lines reflecting the inhomogeneity of the elastic fields in the samples structure of structural steel 08ps is presented [14, 15]. Characteristics of the profiles of the diffraction lines were obtained periodically every 6 months by X-ray analysis of 08 pc samples, which were subjected to a static (for 5 years) loading on an open atmospheric platform and indoors (see the description above).

Figure 5 shows the curves of the change in the dislocation density ρ depending on the level of elastic stresses σ acting in the cross section of the central part of the 08 pc steel samples from January 2013.

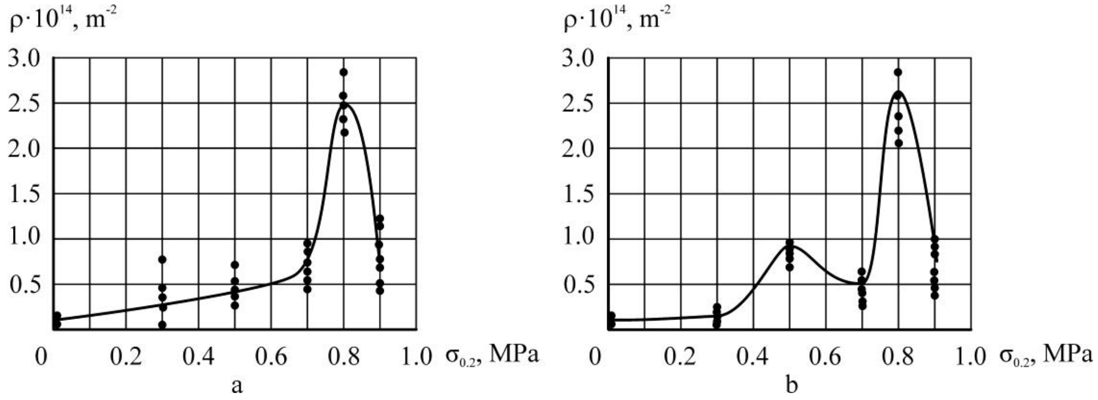

Figure 5. Change in the dislocation density on samples of 08pc steel in the range of elastic stresses: a-indoors, b-on an open atmospheric platform; •-numerical values of ρ calculated by X-ray analysis in the period 2013-2017.

The change in the dislocation density ρ in steel 08 ps samples subjected to static stretching for 5 years is evidence of a nonmonotonic character of resistance to microplastic deformations as the stress level increases from $\sigma = 0$ to $\sigma = 0.9\ \sigma_{0.2}$ (figure 5, a and b). For samples statically loaded on an open atmospheric platform, an increase in the dislocation density is observed at elastic stresses $\sigma = (0.3\ ...\ 0.5)\ \sigma_{0.2}$ and $\sigma = (0.7\ ...\ 0.8)\ \sigma_{0.2}$. In samples of steel 08 ps experiencing the effect of static elastic stresses under stable temperature conditions (18ºC ... 19ºC) for 5 years at low stresses $\sigma = (0.3\ ...\ 0.5)\ \sigma_{0.2}$ the growth of the dislocation density is clearly not expressed.

5. Conclusion

The new laws of the occurrence of elementary acts of microplastic deformation in structural steels in the range of elastic stresses that correspond to real operational loads in metal constructions discovered by the ongoing research program require further analysis.

The characteristics of the diffraction line profiles of deformed structural steels and cast irons reliably reflect not only the deformed regions, but also the relative level of the distortion of crystal.

Concerning the example of cast iron with a single metal base and different forms of graphite inclusions, it is shown that the features of the microstructure of heterophase alloys have a significant effect on the main characteristics of the profiles of the diffraction lines.

X-ray diffractometry of samples of a number of structural steels and cast irons in different stress-strain states caused by a three-point bending to failure, a prolonged static stretching for 5 years in an open atmospheric platform and indoors, reveals the influence of the substructure features of polycrystalline materials on their service properties.

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