Study of the fatigue failure process of steel specimens using the metal magnetic memory method

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Abstract

Studies in the field of metals service life at low-cycle fatigue are a challenging issue in the residual life assessment. The goal of the paper is to investigate the effects associated with variations of the specimens' self-magnetic stray field (SMSF) gradients that characterize their resistance to strain under conditions of cyclic loads application. Experimental studies are based on inextricable relationship between the dislocations density and the magnitude of SMSF intensity in local zones of the metal, which allows to monitor remotely, using the metal magnetic memory method, the dislocation processes kinetics and the staged accumulation of fatigue damages in the specimens metal with the increase of load cycles. As a result of the carried out studies, it was established that when the samples are subjected to both static and cyclic tensile loads not exceeding the stress proportional limit, variation of the specimen's self-magnetic stray field is reversible. When the load amplitude is increased above the proportional limit, appearance of the plastic (relaxation) component, which increases with load increase, was recorded. It was also established that as the number of load cycles increases, the growth of the specimen's metal resistivity increases. The metal resistance to strain will grow until the internal energy of the specimen becomes equal to the external effect energy. A point is identified on the fatigue curve, which can be considered as a point of stability loss corresponding to the limiting strain state of the specimen under given cyclic loading parameters, after which irreversible fatigue failure with a macrocrack formation occurs. The performed tests on cyclic tensile loading of specimens made of various grades of steels allow stating the possibility to estimate the equipment life and to monitor variation of its state by metal magnetic memory parameters in stress concentration zones.

1. Introduction

It is known that metal fatigue is a process of gradual degradation of the material strength due to occurrence and development of cracks in it under the effect of long-acting cyclic loads. At the structural level the fatigue failure process is associated with generation, movement and localization of dislocations. Durability in the low-cycle fatigue area with constant total strain amplitude per cycle depends on the elastic and plastic components (1). Study of such processes is difficult even at static research, and especially under cyclic loads. Currently, these components can be determined using the parameters of the mechanical loop of load cycle.

Features of the metal magnetic memory (MMM) method, which are based on close relation between the dislocation density and the value of the self-magnetic leakage field

(SMLF) intensity in local areas of the metal (2), allow remote monitoring of the kinetics of dislocation processes under cyclic loading, as well as accumulation of fatigue damages in metals.

In paper (3), during testing of steel specimens for cyclic tensile loading, the possibility to apply the MMM method for studying the processes that occur in the specimens metal at the physical level was shown. The same study on variation of specimens SMLF, which is the main diagnostic parameter of the MMM method, for the first time recorded the effect of abrupt drop and instant increase of resistance to strain at the applied load maximum. It was demonstrated that this effect, which is probably associated with stress relaxation and accumulation of residual strain, gradually increases as the number of load cycles increases and reaches its maximum value just before the specimen failure.

In order to further study the identified effect mechanism and staged accumulation of damage occurring in the specimens metal under cyclic loads, steel specimens were tested with application of cyclic tensile loads of different amplitude and frequency values.

The article presents the results of said tests of specimens of steel 20 using the MMM method.

2. Results of testing of steel specimens

Testing of specimens was carried out at room temperature under cyclic tensile loads on the BiSS “The Nano Plug'n'Play” servohydraulic testing machine with the force measurement error of <0.5%.

Figure 1 shows the general view of fatigue testing specimens. It can be seen in the photograph that there is an oval-shaped concentrator in the test portion of the 100 mm long specimen. The specimen cross section in the test portion is 10.0×1.5 mm, and in the middle area of concentrator – 4.0×1.5 mm.

Figure 1. General view of a static and fatigue test specimen

Measurement of the specimens SMLF was carried out in the middle area of the concentrator using a special instrument-computer complex consisting of flux-gate sensors, a transducer and a TSC-10M type instrument-recorder with installed information recording and processing program.

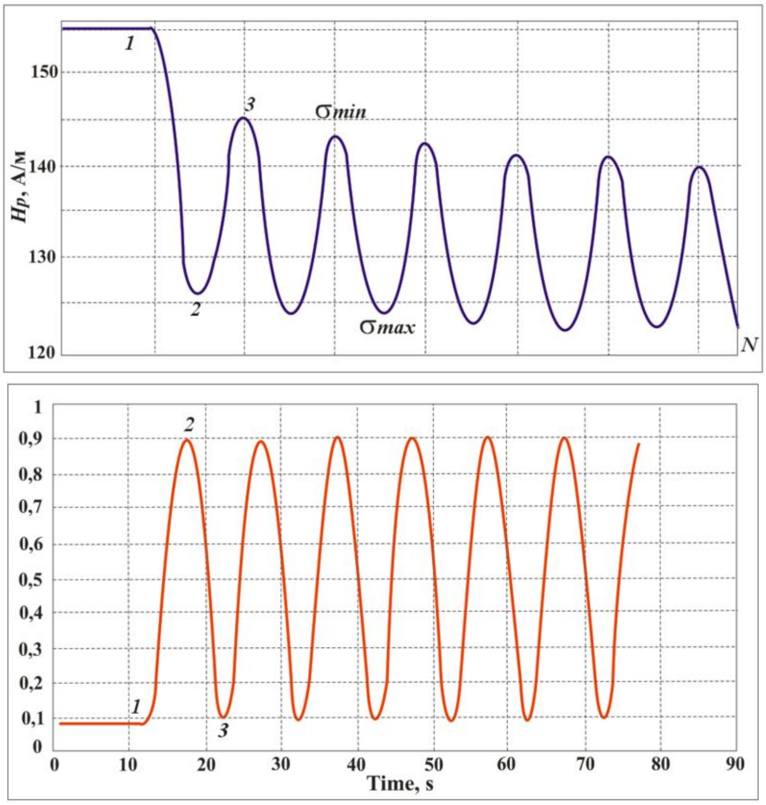
TSC-10M instrument complex allows continuous recording of a large amount of information during the entire time of the cyclic fatigue experiment.

In the course of static testing of one of this type specimens the following was established using the “stress-strain” diagram: proportional limit $\sigma_{p.l.}$ = 101 MPa, yield strength σ_y = 259 MPa and tensile strength σ_t = 335 MPa. The value of $\sigma_{p.l.}$ was established by the $H_p = f(t)$ diagram in comparison with $\sigma = f(t)$ diagram, here H_p – is intensity of self-magnetic field of specimen; f – is frequency of cycling; t – is the test time (duration).

The obtained values of mechanical characteristics were used for selection of cyclic tensile loads range during testing on other similar specimens of steel 20.

In order to study in detail the processes of the specimens’ self-magnetic field variation, depending on different amplitude and frequency values of the applied tensile loads, the following experiments were carried out on one of the specimens.

First the specimen was loaded to the value of 0.3 of the yield strength σ_y, which approximately makes 77 MPa. This value was taken slightly lower than the proportional limit $\sigma_{p.l.}$ recorded on a similar specimen under static load. Then cyclic tensile load at the level of $0.3\sigma_y$ with frequency of 0.1 Hz was applied to this specimen without its removal from the testing machine. Figure 2, *a* presents the magnetogram recorded when the cyclic tensile load is applied in the range from σ_{min}=7.7 MPa to σ_{max}=77 MPa compared to the mechanical curve (figure 2, *b*) in which the load value is presented in relative units. The ordinate axis unit corresponds to the load of approximately 85 MPa.



a) b)

Figure 2. Curve of self-magnetic field H_p intensity variation during cycling with frequency of 0.1 Hz in the tensile loads range from 7.7 MPa to 77 MPa (*a*) vs the mechanical curve (*b*) recorded on the testing machine: *N* – number of cycles

It can be seen in Figure 2, *a* that when the load of 77 MPa was applied, the field intensity changed by the value of $|\Delta H_p| \cong 29$ A/m compared with the initial state (modulus of difference between the points *1* and *2*). Then, in the process of tensile load cycling from 77 MPa to 7.7 MPa the field intensity changes by the value of approximately 19 A/m (modulus of difference between the points *2* and *3*). Further re-application of cyclic tensile loads in the specified range with the frequency of 0.1 Hz hardly changes this value of the $|\Delta H_p|$ field and repeats the H_p field values at loads maximum and minimum. After applying of 7 cycles the machine was stopped, and the load dropped to zero.

At the next stage static tensile load up to the level of $0.6\sigma_y$ equal to 156 MPa was applied to this specimen. And then cyclic tensile load with the frequency of 0.1 Hz in the range from σ_{min} = 15.6 MPa to σ_{max} = 156 MPa was applied to the specimen without its removal from the machine. Figure 3 shows the magnetogram recorded on the specimen at the time of the said cyclic load application and relief.

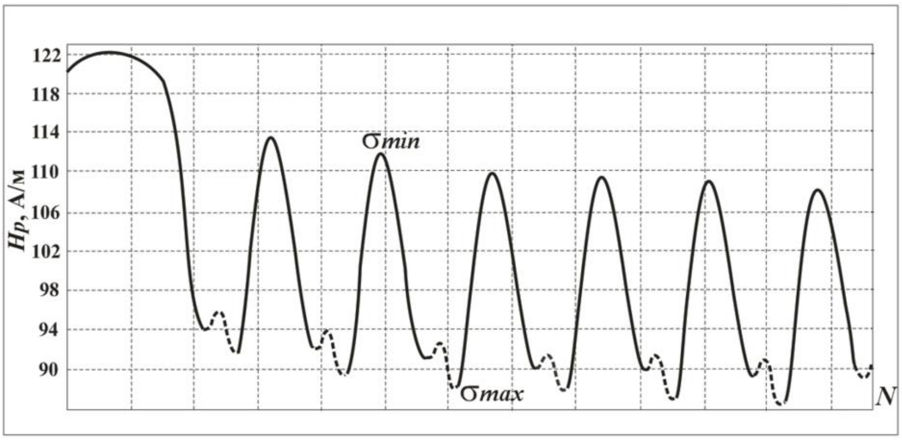


Figure 3. Curve of the specimen's self-magnetic field intensity variation during cycling with the frequency of 0.1 Hz and maximum load of 156 MPa

It can be seen in Figure 3 that cyclic variation of the field intensity of the same value $|\Delta H_p| \cong 22$ A/m repeats with the frequency of 0.1 Hz. At the same time at the load maximum of $0.6\sigma_y$, being significantly higher than the proportional limit for this specimen, the effect of abrupt drop and instant growth of the $|\Delta H_p|$ value, identified earlier in paper (3), was recorded. This effect is obviously related to stress relaxation in the specimen. Here it should be noted that at the load of $0.3\sigma_y$, not exceeding $\sigma_{p.l.}$, such effect was not detected (Figure 2, *a*). This indicates that in the load range up to $\sigma_{p.l.}$ there is practically no effect of stress relaxation and residual plastic strain in the specimen.

In order to investigate the mechanism of SMLF relaxation component occurrence and its development during the process of metal fatigue, studies have been performed on similar specimens under their cyclic straining to failure. Two specimens of steel 20 were tested for cyclic tensile loading in the range from 0.1 to $0.9\sigma_y$ (from 23 to 233 MPa) with the frequency of 1 Hz.

Let us consider the results of the said testing on one of the specimens.

Figure 4 presents the SMLF variation magnetogram of a specimen of steel 20, recorded during the continuous cyclic tensile loading with the frequency of 1 Hz (after 100000 cycles) in the range from 0.1 to 0.9 of the yield strength. It can be seen in Figure 4 that two SMLF variation amplitudes appear at the load maximum (σ_{max}). One amplitude $|\Delta H_a|$ indicates elastic strain due to the external amplitude load, and another $|\Delta H_{rel}|$ – relaxation – characterizes the internal energy of resistance to strain and the process of plastic strain accumulation in the specimen.

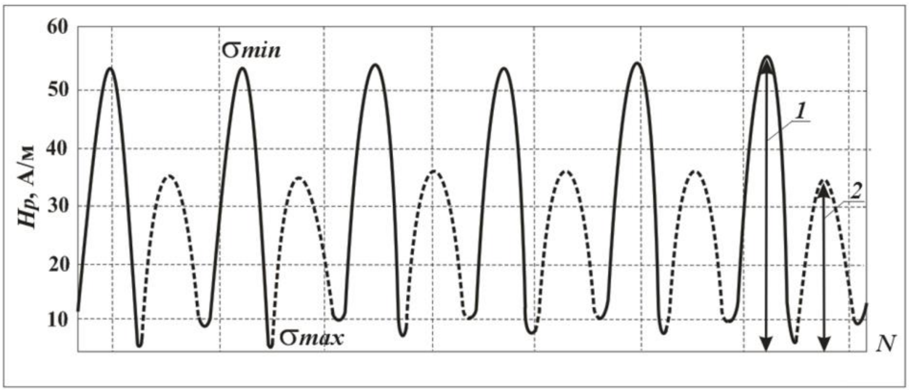


Figure 4. Dependence of the longitudinal magnetic component on the time at the initial stage of the specimen loading (before 100000 cycles): *N* – number of load cycles; *1* – $|\Delta H_a|$; *2* – $|\Delta H_{rel}|$

Figure 5 presents the magnetogram of the specimen's self-magnetic field components $|\Delta H_a|$ and $|\Delta H_{rel}|$ variation recorded after 226900 load cycles. It can be seen in Figure 5 that after the said number of load cycles SMLF amplitudes $|\Delta H_a|$ and $|\Delta H_{rel}|$ have practically the same values.

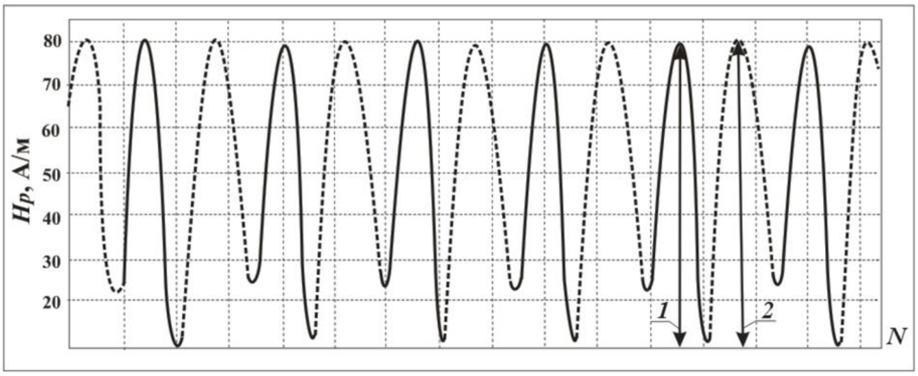


Figure 5. Magnetogram of the specimen's self-magnetic field components $|\Delta H_a|$ (*1*) and $|\Delta H_{rel}|$ (*2*) variation recorded after 226900 load cycles

Figure 6 presents the magnetogram of SMLF components $|\Delta H_a|$ and $|\Delta H_{rel}|$ variation at the final stage of the specimen failure. It can be seen in Figure 6 that at this stage at this stage, with almost constant amplitude component of the field $|\Delta H_a|$ = 80 A/m, the value of $|\Delta H_{rel}|$ increases sharply to 590 A/m.

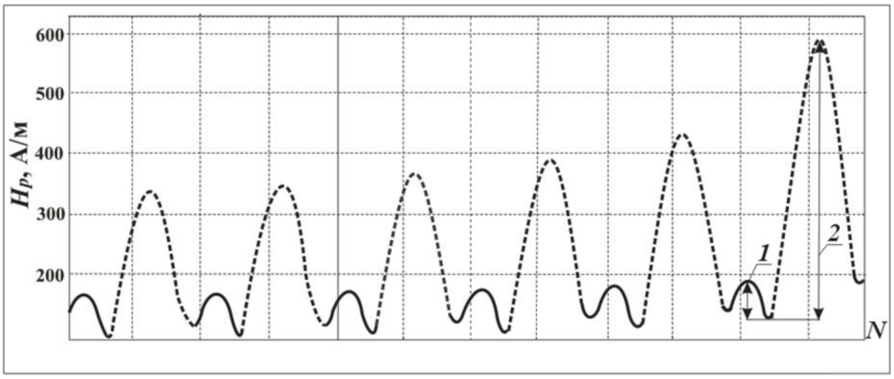


Figure 6. Magnetogram of the specimen's self-magnetic field components |Δ*H*a| (*1*) and |Δ*H*rel| (*2*) variation recorded after 226900 load cycles at the final stage of the specimen failure

Figure 7 shows the graph of the magnetic field components $|\Delta H_a|$ and $|\Delta H_{rel}|$ variation depending on the number of tensile load cycles, plotted based on the results of the specimen testing.

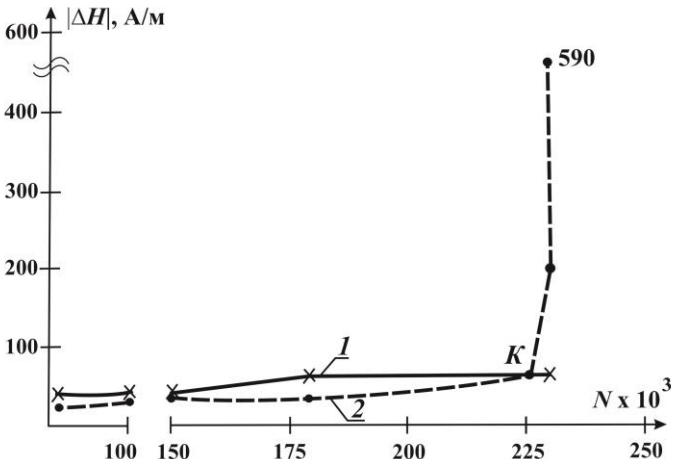


Figure 7. Variation of self-magnetic field components |Δ*H*a| (*1*) and |Δ*H*rel| (*2*) depending on the number of tensile load cycles *N*: *K* – point of |Δ*H*a| and |Δ*H*rel| components intersection (equity of values) at *N*=227350

It can be seen in Figure 7 that in the graph section up to 227x10^3 cycles the magnetic field components $|\Delta H_a|$ and $|\Delta H_{rel}|$ increase smoothly and insignificantly and intersect in the point *K*, in which the values of $|\Delta H_a|$ and $|\Delta H_{rel}|$ become equal and make 68 A/m. After the point *K* the value of $|\Delta H_a|$ remains practically unchanged, and the relaxation component $|\Delta H_{rel}|$ increases sharply right up to the specimen failure.

The total testing duration of the considered specimen of steel 20 at continuous application of the cyclic tensile load with the frequency of 1 Hz in the range from 23 to 233 MPa was 62 hours. With the total of 230000 load cycles, the number of cycles from the point *K* to complete specimen failure destruction was 3000 times or 48 min with respect to time.

Similar fatigue curves plotted by SMLF variation were obtained as a result of testing of other samples of steel 20 during their cyclic loading.

3. Conclusions

3.1 As a result of the performed studies, it was found that in specimens exposed to both static and cyclic tensile load not exceeding the proportional limit $\sigma_{p.l.}$, variation of the specimen's SMLF is reversible and indicates that at the applied load maximum there is practically no plastic component of SMLF. When the specimens are exposed to static and cyclic load higher than $\sigma_{p.l.}$, the curves of SMLF variation at the load maximum recorded the appearance of the plastic (relaxation) component, which increases with the load increase.

3.2 Point *K*, shown on the fatigue curve (Figure 7), can be considered the point of stability loss corresponding to the specimen's limiting state at specific cyclic loading parameters with a macrocrack formation begins. In the theory of mesomechanics (4) this stage of the "strain-failure" process is called the stage of global loss of stability, at which mesostructures permeating the entire specimen volume occur.

3.3 The completed cyclic tensile load testing of specimens of steel 20 versus similar test results of specimens of steels 3 and 10CrCNiCu allow stating the possibility to assess the equipment life and to monitor variation of its state by metal magnetic memory parameters in SCZs.

Given that diagnostic parameters of the MMM method are not influenced by different kinds of noise, and application of this method does not require artificial magnetization and special additional loading, the TSC-type instruments and the appropriate sensors (not requiring direct contact with the inspection object) have obvious practical advantages for monitoring of the equipment's technical state.

References and footnotes

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