Coercivity of Metal as a Measure of its Damage at Micro Level in Assessing Fatigue, as well as in Problems of Restoration of Mechanical Properties

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Abstract. Coercimetry today is the most effective method both informationally and practically (instrumentally and methodically) for assessing fatigue-type damage of metal at micro level in bench tests and during actual operation. Equally effective and useful it is in solving a specific inverse problem when attempts are made to restore the properties of fatigue-affected metal by different types of effects on it to obtain a kind of “healing” of micro fatigue accumulated in the metal. Depending on the mode of loading operation or during the tests performed recovery of desired properties in the surface layers or in the whole volume of the sample or item can be carried out. Properly executed (methodically and instrumentally) coercimetry here too very effectively monitors both qualitatively and quantitatively the degree of recovery in case of micro fatigue type degradation. On the example of cyclic mechanical bench testing of samples of alloy steel used for the manufacture of high-strength mechanical parts, 40X (C, 0.36–0.44; Si, 0.17–0.37; Mn, 0.5–0.8; Cr, 0.8–1.10), is shown such efficiency of coercimetry in assessing degradation of metal under cyclic loading in multicycle fatigue mode, as well as in various technologies of recovery of micro-level damage of metal accumulated during cyclic testing.

The problem of determining current state of the mechanical properties of metal products in the course of their operation was, is and will be relevant. To solve it, always is needed a simple, inexpensive and quite informative method of nondestructive testing of metal. This method can now safely be named: it is magnetic coercive force method; coercive force is a very structurally sensitive characteristic reflecting the degradation of material of product following the development and accumulation of fatigue micro-damage therein. The effectiveness of such magnetometric method for evaluating the fatigue micro-damage has been fairly well tested both in bench tests as well as during actual operation. No less effective and useful is coercimetry in solving of a kind of inverse problem, when there is a need of controlling when trying to recover the properties of fatigued metal by a kind of “healing” of accumulated fatigue micro-damages, by acting on it in various ways.

In this paper, such employment of coercimetry is demonstrated through the example of medium alloy steel 40X (chemical composition: C (0.36–0.44); Si (0.17–0.37); Mn (0.5–0.8); Cr (0.8–1.10), which is widely used in mechanical engineering for the manufacture of high strength parts.
The aim of the work was to determine regularities in changing coercive force after mechanical cyclic loading of steel samples both in their initial state and after surface plastic deformation (strain hardening). Work hardening procedure was used as a method of "healing" of micro-damages.

Cyclic tensile testing was carried out in air at room temperature on a universal testing machine with a hydraulic pulsator. Test pattern provided tensile load applied along the axis of the sample. Frequency of cycling was 11.4 Hz, while the amplitude was varied from 420 to 600 MPa. The criterion for terminating the test was reaching of a predetermined number of loading cycles (5 \cdot 10^6 cycles) or complete fracture of the sample. On all samples at all stages of the experiment was carried out measurement of the coercive force using coercimeter MC-04H-2 of own design.

Two batches of cylindrical samples of steel 40X in as delivered condition were used for cyclic testing. Samples of both batches were tested at the same stress amplitudes. Samples of the first batch were tested till their fracture.

For the second batch the tests was carried out in two stages with an intermediate surface treatment. The first stage came to an end after the sample sustained at certain stress amplitude about 40% of the total number of cycles determined by the results of testing on the first batch of samples. After the first stage the sample was unloaded, removed from the testing machine and the coercive force was measured. Also at this stage we determined relative elongation (deformation) of the samples. After that, surfaces of the samples were subjected to plastic deformation (work hardening) by mechanical impact treatment of their working surfaces using a striking tool with electromechanical drive. On the thus treated specimens was measured coercivity, then the samples were again installed in the test machine and the tests were continued with corresponding to each sample level of stress until fracture or until the number of cycles reached 5 \cdot 10^6.

With all samples of the first batch after the tests in the investigated range of amplitudes was observed growth of the coercive force value $H_c$. This growth in the amplitudes for different loads ranged from 60 to 110%.

As for fatigue testing is typical some scatter of results, it can be assumed that the fracture of samples took place at about the same level of increase in the coercive force. It increased as compared with the original value at all amplitudes of loading, on the average 1.8–2 times. This value of coercive force characterizes energetically such degree of fatigue accumulation of micro-structure in the material, at which the metal begins to break down.

With Samples of both the first and the second batch cyclic loading already at an early stage leads to a significant increment of coercive force $\Delta H_c$: from 0 to 4.8–5.5 A/cm, which is from 54 to 67% of its value in test samples before the testing. The magnitude of deformation of samples in so doing was varied from 1 to 1.5%. At deformations $\varepsilon > 1.5\%$ is observed a point of inflexion, and further $\Delta H_c$ growth occurs at a slower rate. Here $\Delta H_c$ increase was from 5.5 to 7.9 A/cm.

In the physical sense, this curve reflects change in the rate of accumulation of defects in the metal. The high growth rate of $\Delta H_c$ at the initial stage of deformation indicates fairly rapid accumulation of damage at the initial stages of loading. The flow of these processes at this stage of sample loading was the same for samples of both batches. After that samples of the first batch were brought to fracture through continued trials, while samples of the second batch were subjected to restoring surface work hardening.

In all samples of the second batch after the first loading stage there was an increase in the coercive force by 4.8–7.6 A/cm. The percentage of increase at this stage of tests was 54–96%.

As a result of surface treatment of the second batch of samples after the first loading step, the coercive force decreased in the value of $H_c$ by 1.2 to 2.6 A/cm, which made up 9
to 17%, respectively. A more significant decrease in $H_c$ after the surface treatment was observed in samples tested at higher amplitudes of loading.

After mechanical surface hardening treatment samples of the second batch again were subjected to cyclic loading at the same respective amplitudes with subsequent measuring the $H_c$ after the tests.

After the tests were finished, increase of the coercive force compared to reference value over the entire range of the examined stresses was from 4.4 to 7.4 A/cm, which ranged from 49 to 94% (samples of the 2nd party).

Comparison of the values of the coercive force after tests showed that its increase over the initial (pre-test) values for both batches of samples was on the average 50 to 100%. The resulting increase in coercive force values characterizes the increase in the degree of fatigue damage accumulation in the structure of metal, leading ultimately to its fracture.

The decrease of the coercive force after the surface plastic deformation can be associated with healing of micro-defects of the metal structure, accumulated as a result of cyclic loading at the first testing stage. Comparison of results of cyclic tests on reinforced and unreinforced samples indicate that the surface treatments carried out

On the second batch of samples allowed increasing their endurance by 2.8–3.4 times (depending on the number of loading cycles to fracture).

Thus, the results clearly demonstrate the high sensitivity of the coercive force to changes in the structural state of the metal both as a result of both fatigue damage accumulation under elastoplastic strain, and at partial restoration of the structure and properties of the fatigued metal due to the partial "healing" in it of fatigue micro-damage in carrying out mechanical surface treatment by impact plastic deformation.