COERCIVITY OF A THERMOSTRENGTHENED STEEL 14X17H2 AFTER FORGING AND REPEATED LOADING

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Introduction

One of the most pressing technical problems of the early XXI century is the problem of assessing the residual life of in-service hardware. Urgency of the problem is explained by substantial wear-out of the fleet of metal structures and the exhaustion of their active operating life.

In solving this problem, 2 main approaches can be identified: use of the computational methods of mechanics of deformed solid bodies and analysis of structural state of the structure material. One of the principal methods for the analysis of structural state of the material, which has proved itself useful in solving specific operational problems, is the coercive force method, which is implemented using the devices developed by Special Scientific Engineering Company (Kharkov) [1]. It is noteworthy that up till now such problems were usually solved with respect to the structures made from as-delivered steels having slightly distorted crystalline structure, low strength and a substantial margin of plasticity. For such materials in their operation is typical significant increase of coercive force, and when reaching a critical value H_c, these materials fail, which, strictly speaking, allows using measurements of H_c of the material of operated parts at the points mostly affected by stress concentration, judge of the degree of degradation of metal and of the need to replace a relevant part and its repair.

It should be noted that the bulk of structures in need of such monitoring are made of highly ductile steels. Therefore, the method based on measuring coercive force has become highly in demand in the solution of a large number of specific problems of reliability and safe operation of power plants, pipelines, pumping stations, ship hulls and other important installations.

To what extent can this method be used in the analysis of structural state of steels in the hardened state, for example, as a result of hardening heat treatment? This question is far from being idle, because there is a need to address these problems for example, in assessing the state of large parts of turbines. To answer this question it is necessary to know how changes the coercive force of such steels under static and cyclic loading. Because getting such information from the literature was not possible, the study of this issue made the objective of this work.

Research Methodology

The study was conducted on steel 14X17H2 (see below its chemical composition), which is a heat-resistant stainless steel of class and is widely used, in particular, for manufacturing working blades of turbines.

Chemical composition of steel 14X17H2 (%)

C	Si	Mn	Ni	S	P	Cr	Ti	Cu
0.11–0.17	up to 0.8	up to 0.8	1.5–2.5	up to 0.025	up to 0.03	16–18	up to 0.2	up to 0.3

The steel was delivered in the form of 6-mm thick sheet, which was split with guillotine shears into rectangular 180x50 mm blanks. From these blanks were made 5 mm thick specimens for testing with the allowance for grinding after heat treatment.

Specimens heat treatment cycle: heating to 1050 °C, holding for 40 minutes, hardening in oil, tempering for two hours at 650 °C with subsequent cooling in water.

After heat treatment the specimens were grinded on all sides to the depth of 0.5 mm. After heat treatment the steel has hardness HB 2000 MPa, $\sigma_{0.2}$ = 635 MPa and $\sigma_в$ = 835 MPa.
Coercive force was measured on structurescope-coercimeter KRM-Ts-K2M manufactured by Special Scientific Engineering Company. This characteristic was measured on the working areas of specimens after their heat treatment, as well as after subsequent deformation by forging and cyclic tension-compression on universal testing machine type MUP-30 with a hydraulic pulser. Loading cycle was of constant sign. Working force was created by high-pressure hydraulic pump. The pulser was a valveless single-plunger hydraulic pump designed for creating variable cyclic loading on the tested specimen. Monitoring of loading was carried out based on readings of a special force-measuring device[1)].
Tests were carried out in accordance with GOST 25.507-79 "Methods of mechanical testing of metals. Fatigue testing methods", and GOST 25.507-85" Fatigue testing methods at operating conditions of loading. General requirements".
Cycle asymmetry coefficient was taken equal to 0.3. The frequency of loading was 5.8 Hz when testing for low-cycle fatigue and 11.4 Hz when testing for multi-cycle fatigue.
Tests were carried out in air at room temperature, mainly at two amplitudes: at amplitude of σ_{max} = 725 MPa (average σ_{av} = 471 MPa, minimum stress σ_{min} = 217 MPa) and amplitude of σ_{max} = 438 MPa (average stress σ_{av} = 284.7 MPa and minimum stress σ_{min} = 131.4 MPa). A number of tests were conducted also at other amplitudes.
We note that in the process of testing the specimens are kept at different tensile stresses of varying, changing with time magnitudes.

Results and discussion
The tests showed that the coercive force measured on the plates cut from sheet steel in as-delivered state, was equal to ~ 13.6 A/cm. After heat treatment *Hc* increases significantly and is in the range 20.5–22 A/cm. In this case there takes place some reduction in Brinell hardness of steel from 2100 MPa in as-delivered state to 2000 MPa after heat treatment.
The spread in values of H_c after heat treatment shows that conditions of heat treatment for the specimens of the lot are somewhat non-identical. In this connection about the change of H_c of heat-treated specimens in subsequent loadings was judged based on measurements carried out on each specimen separately.

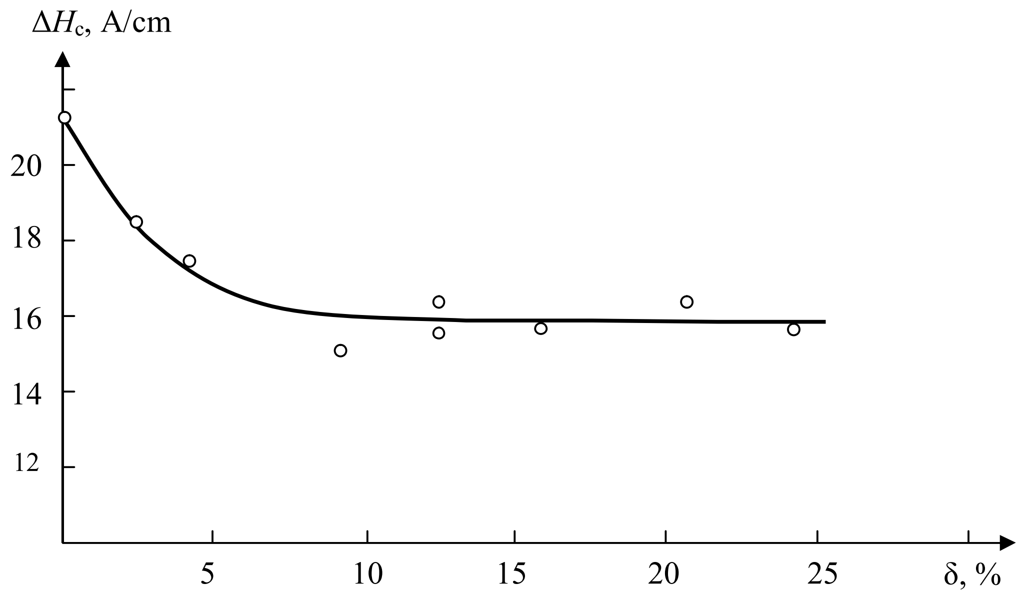

Figure 1. Dependence of H_c of steel 14X17H2 after heat treatment on the degree of subsequent deformation by forging at room temperature.

[1)] Testing machine MUP-30 enables creating maximum static loading of 300 kN and maximum cyclic loading of 150 kN with an error of ± 1%.

Several specimens after heat treatment were forged on an anvil at room temperature, there thicknesses reduced from 4 mm to several smaller thicknesses, and then H_c values of specimens were measured and the influence of forging deformation degree on H_c was analyzed (Fig. 1). As is shown in Figure 1, the coercive force of steel after forging quite sharply decreases at low degrees of deformation, then the rate of reduction of H_c decreases and at deformations of > 8% the coercive force remains about at the same level (~ 16 A/cm).

Maximum decrease in H_c as a result of forging is 5 A/cm, while micro hardness of steel as a result of forging remains virtually unchanged.

Figure 2 shows the curves of coercive force growth dependence on the number of loading cycles at two amplitudes: σ_{max} = 725 MPa (curve 1) and σ_{max} = 438 MPa (curve 2). The former amplitude is taken above the yield point of steel, and the latter one below that. This circumstance, as well as the number of cycles till failure, endured by the specimens at these amplitudes, shows that the former amplitude allows for low-cycle fatigue, and the latter one, for multi-cycle fatigue.

As is seen from Figure 2, cyclic loading at σ = 725 MPa leads to rapid increase of H_c by about 5 A/cm, which is ~ 25% of H_c value after heat treatment. This increase occurs in the range from 1 to 10^3–10^4 cycles, after which as tests continue, ΔH_c decreases and failure of the specimens occurs at lower values of H_c (ΔH level at the time of failure is 3.5–4 A/cm).

At low loading amplitude (σ_{max} = 438 MPa) also takes place an increase of the coercive force, but by a smaller amount (maximum increase of σ_{max} in this case reaches ΔH_c = 3 A/cm). This growth occurs rapidly at first, and then with an increase in the number of loading cycles from 10^4 to 10^5 – at a lower rate. With further increase in the number of cycles there occurs a slight decrease of ΔH_c, and failure of the specimens can take place at values of ΔH_c ~ 2.0 A/cm.

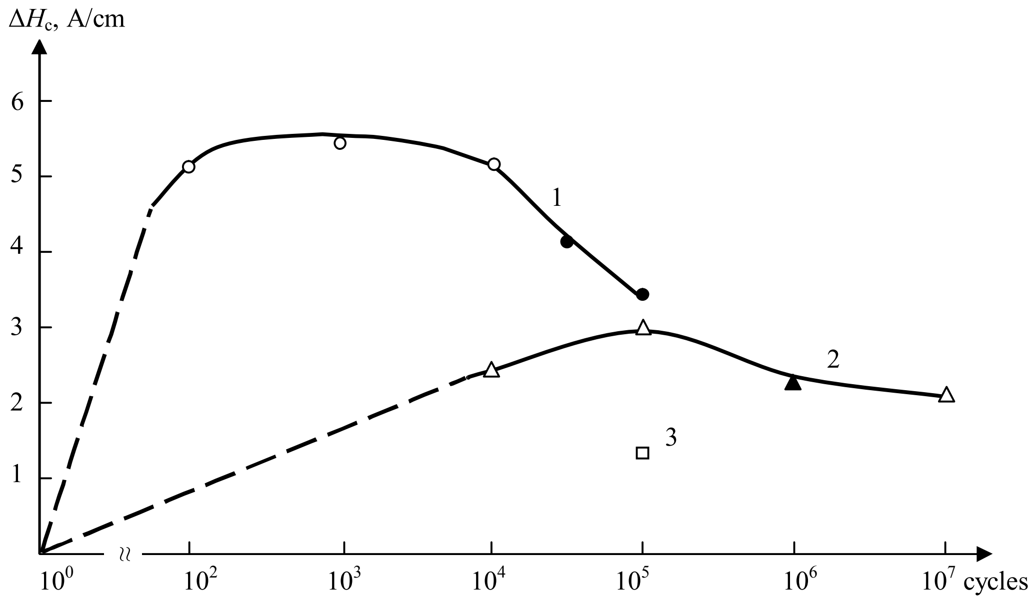

Figure 2. Dependence of the coercive force increase on the number of loading cycles (shaded points correspond to failed specimens).

As high-amplitudes tests were performed at 5.8 Hz frequency and low-amplitude ones at 11.4 Hz, we would have to determine which of these two factors (amplitude or frequency) more strongly influences the rate of H_c of increase with growing number of cycles. To answer this question, were tested a few specimens, also at the amplitude of 438 MPa, but at loading frequency of 5.8 Hz. It turned out that at this frequency increase of coercive force is even slower (the respective point is marked by figure 3 and corresponds to 10^5 cycles). Thus, more rapid increase in H_c with increasing number of cycles at high amplitudes (compared to low ones) is due to the magnitude of the amplitude itself.

Based on the position of point 3 it can also be assumed that at the same amplitude of loading, the higher the frequency of loading, the faster is the growth of the coercive force.

Figure 3 shows the increase of the coercive force reached after 10^5–10^6 cycles, depending on the amplitude of loading σ_{max}.

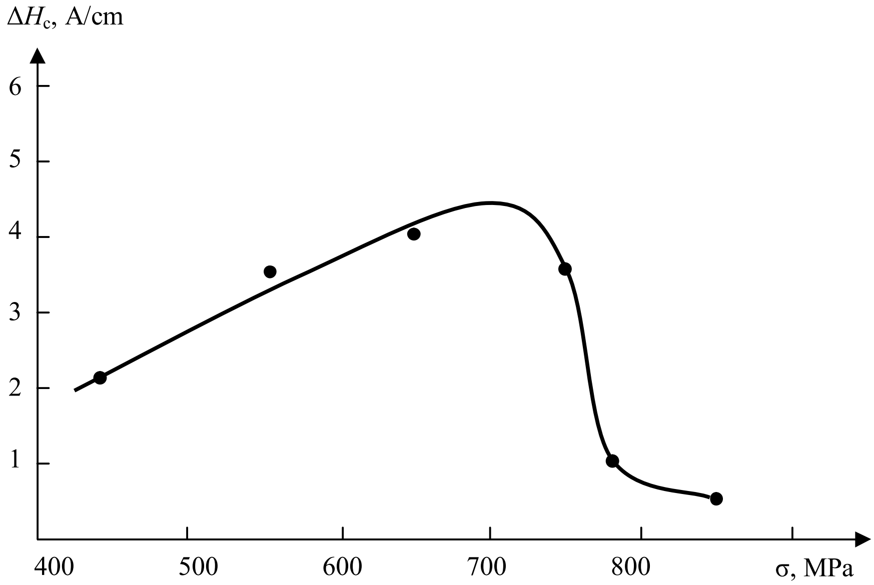

Figure 3. Dependence of growth of the coercive force of the failed specimens on the amplitude of loading.

It is seen that with increasing amplitude, ΔHc initially grows (up to σ_{max} = 725 MPa), whereas at higher σ_{max} it is sharply reduced.

The results indicate that the coercive force of steel is a complex function of amplitude, frequency and number of loading cycles.

Let us try to explain some of the results.

First of all, consider the reduction of the coercive force of heat-treated steel as a result of its forging. Forging is known to be one of the methods of plastic deformation of metal, which is widely used in manufacturing practice. Depending on the state of the metal before forging, one can obtain different degrees of hardening (cold work hardening); in the case of heavily hardened condition (due to prior plastic deformation or heat treatment) the result of forging can be loss of metal strength. In our case, we find absence of hardening as a result of forging (micro hardness of steel remained virtually unchanged), but we note a significant decrease in the coercive force. This effect is an evidence of higher structural sensitivity of the coercive force compared to the hardness. With regard to the physical reasons of such behavior of the coercive force, at least two can be assumed. First, it is further disintegration of martensite, which has not been completed at a high tempering of hardened steel. Passage of dislocations while forging in such martensite may contribute to further withdrawal of carbon from the α-solid solution. Second, the reduction in coercive force during forging may be associated with some decrease in the density of dislocations due to the dynamic relaxation, and curing of submicrocracks, formed earlier during hardening. Deformation by forging, in which high dynamic stresses, with significant hydrostatic component beneath the surface of steel in the center of forging blows are developed, can participate in curing of submicrocracks**;** in these conditions, as a result of dislocations annihilation, as well as the elimination of submicrocracks should increase the concentration of vacancies in the adjacent volumes of metal (as a result of dissolution of voids). This leads to increased self-diffusion coefficient, which ensures rapid creep of dislocations (even at room temperature) and promotes the formation of new borders and dispersing the structure.

With cyclic loading scheme used in the present study, the hydrostatic component in the metal is not present. Perhaps that is why we observe an increase in the coercive force, which is fairly intense (relative to the number of loading cycles). This increase can be reasonably related both to further increase of the density of dislocations, as well as to the growing concentration of noncontinuities (submicrocracks), the more so because, as shown in several studies [see, for instance, 2–3], the

major change in the flaw structure in the state of fatigue is taking place just at the initial stage of loading (after reaching ~ 5% of the total deformation of the metal from the beginning till its complete failure). Further on, as the accumulation of dislocations and discontinuities in the metal, there begin to dominate the processes of softening (dynamic relaxation), which integrally leads to reduction of internal stresses and coercive force, after which also rapidly develops macro-failure.
It is important to note here that the higher the amplitude of oscillations, the faster is growing H_c, it faster reaches its saturation and begins to decline earlier. If the amplitude of stresses reaches a critical value (in our experiments with σ_{max} = 700–725 MPa), then a further increase in amplitude leads to a drastic reduction of the coercive force and rapid failure of metal.
At low amplitudes the process of hardening and accumulation of elements of failure is very slow and occurs at a much smaller scale: as a consequence, the growth of the coercive force is small. At these amplitudes failure can happen either with very large number of cycles, or not happen at all (the rates of hardening and loss of metal strength are equal).
In general, given the magnitude of change in coercive force at cyclic loading, we can say that estimation of the critical state of the metal structures of steel 14X17H2 after hardening, high tempering and subsequent cyclic loading at high and low amplitudes is possible in principle, subject to mandatory periodic performing of reasonably accurate measurements of H_c during the entire period of operation of hardware. Development of methodology for such monitoring is a separate problem to be addressed in relation to a specific hardware with regard for its alleged operation conditions.

Conclusion
The effect of forging and cyclic loading on the coercive force of specimens of steel 14X17H2 after hardening and high tempering was studied. The following results were obtained.
1. It was found that the coercive force of steel after forging is significantly reduced. It has been suggested that this effect is associated with curing submicro-noncontinuities and development of dynamic relaxation processes.
2. It was established that under cyclic loading of steel after heat treatment, H_c is a complex function of amplitude, frequency and number of loading cycles.
3. It was shown that under cyclic loading of steel after heat treatment, the coercive force is growing rapidly, and the higher the amplitude, the faster the growth. In further tests the coercive force reaches a maximum and then decreases. At high amplitudes this results in failure, while at low amplitudes failure can occur after 10^6 and 10^7 cycles, or may not occur at all.
4. It was conjectured that the increase in H_c during cyclic loading of steel after heat treatment is due to the accumulation of submicrocracks as well as hardening of the metal areas free from elements of failure. Subsequent drop in H_c (after a maximum) is associated with the development of dynamic relaxation and microfractures.
5. The observed patterns of change in coercive force under the influence of cyclic loading indicate the fundamental possibility of the use of precision coercimetry in analyzing the state of the metal structures made of steel 14X17H2.

References
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