The effects of operational thermal cycling on mechanical and magnetic properties of structural steels

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Abstract. This article shows the experimental results of the operational thermal cycling modeling of structural carbon steels with temperature range from the point of phase transition of type II cementite to the beginning of phase transformations of steel. In this study the influence of temperature that the number of thermal cycles and the histogram of temperature loading on the magnetic and mechanical properties of the steels were investigated. The possibilities of controlling the residual life of the elements, which are subjected to thermal cycling on changing the magnetic properties of metal, were determined. The functional dependence of the coercive force and hardness on the number of thermal cycles at a given temperature is obtained.

Keywords: coercive force, hardness, carbon steels, operational thermal cycling, phase transformations.

1. Introduction

The investigated temperature range is located near the Curie point of cementite, where cementite undergoes magnetic transformation (phase transition of II kind), in which it is considered as an Invar system [1]. Near the Curie point of cementite, there is an abnormal behavior of its elastic modulus and an increase in diffusion mobility [2]. In the Fe-Fe3C system, cementite is a metastable phase accordingly cementite near its Curie point which at 210°C must be highly sensitive to external influences [3]. The study of the properties of cementite is devoted to the work [4-9]. It is shown that within the framework of the orthorhombic lattice, variants of the cementite structure with different arrangement of iron and carbon atoms relative to each other can arise, so the cementite will be dependent on the initial heat treatment in two or more structural states. On this subject, experiments proved that high-carbon steels can be graphitized by thermal cycling near the Curie point of cementite [10]. However, there is low data in the literature review about the dependence of the magnetic and mechanical characteristics of low-carbon and medium-carbon steels in thermal cycling, which is especially important in the technical diagnosis of basic parts of machines designed for the system "specified life". Therefore, the topic of the study is relevant.

Thermal cycling above the line PSK in diagram Fe-Fe3C, the temperature of the eutectoid transformation in a metastable system – 727°C, has several applications in the mechanical engineering such as: grinding grain, thermal insulation and concentration of harmful impurities in isolated areas of ferrite relief. Because it causes improvements in the mechanical characteristics of steels due to the partial α→γ transformation. In the manufacture of devices, thermo cycling is used as quick test life in order to identify hidden defects manufacturing process.

However, a number of equipment parts when proceeding technological operations are subjected to temperature insolation in the temperature that ranges significantly below the eutectoid transformation temperature, for example, the frame and shafts of crank hot forging presses are subjected to cyclic temperature loads in the range from the workshop temperature to 150°C – 550°C. That thermal loading is proposed in order to introduce the term operational thermal cycling. So that the impact assessment
of such action is possible, accurate prediction of large basic parts resource is a difficult task because it requires multi-factor tests for its solution. This task is particularly relevant in the technical diagnostics of machines designed for a given durability. This paper aimed to investigate the effect of thermal cycling on the magnetic and mechanical properties of structural carbon steels and to obtain studies basis of the functional dependence of structural carbon steels characteristics on the number of thermal cycles at a given temperature.

2. Materials, equipment and methods
In the experiment, certified and verified devices were used as part of the control and measuring system – Portable pulse coercimeter KIM-2M and hardness taster TKM-459M. Furnace PKE-25.1 was used for heating samples. For the experiment, special samples were made of structural quality steel 25 according to GOST 1050-88 (carbon content 0.22-0.30%). The procedure of the experiments was as follows: the samples were placed in a furnace with a predetermined temperature, kept in the furnace for 3-5 minutes (the temperature of the sample was monitored by a pyrometer Testo 835-T2) and cooling in calm air. This work-cycle is repeated. During the experiment, the coercive force $H_c$, the value of the magnetic field strength necessary for the complete demagnetization of a ferromagnetic or ferrimagnetic substance. A/m, and the hardness HRB on a scale in Rockwell in conventional units were measured. For monitoring the microstructure, an inverted microscope CKX41 was used and for obtaining the fractograms, 3D scanner Range Vision Spectrum was used.

3. Results and Discussions
Figure 1 shows the diffractogram of destroyed sample as a result of operational thermal cycling (temperature from 20°C to 250°C). Obviously, the fracture occurred along the grain boundaries as a result of embrittlement. Therefore, with this type of loading, it is possible to control the value of the residual resource by the degradation of the structure. However, for operational control and technical diagnostics of critical parts, the use of structure-dependent material characteristics is more effective. It is demonstrated that a characteristic is the coercive force, which has a correlation with mechanical characteristics and structure.

![Figure 1. Diffractogram of the sample destroyed as a result of thermal cycling in the temperature from 20°C to 250°C.](image)

The results of the experiment are shown in table 1, and illustrated by the graphs in figures 2 and 3. The number 1-5 refer to the numbers of the samples under research. It is obvious hardness and coercive force of the samples increases up to 2 times in that thermal cycling near the Curie point of cementite on the third cycle. Even more with an increase in the temperature load cycles, a monotonic drop in the research values occurs. However, thermal cycling of these steels at temperatures above 300°C (but below the PSK line of the Fe-Fe3C diagram, where austenitic transformation occurs during heating and eutectoid transformation during cooling) did not lead to the same result.
Table 1. Experimental results values of coercive force

| Samples numbers | Initial state | The number of thermal cycles (300°C) |
|-----------------|--------------|-------------------------------------|
|                 | 0            | 2 | 3 | 6 | 12 | 20 |
| 1               | 614          | 633 | 797 | 760 | 737 | 681 |
| 2               | 758          | 753 | 914 | 790 | 745 | 710 |
| 3               | 902          | 820 | 1105 | 1000 | 1015 | 753 |
| 4               | 835          | 844 | 903 | 857 | 805 | 715 |
| 5               | 909          | 894 | 1012 | 919 | 920 | 723 |
| \( \bar{H}_c \) | 804          | 789 | 946 | 865 | 844 | 716 |

Figure 2. Influence of the coercive force of the 5 samples on the number of thermal cycles.

Figure 3. Effect of the average value of the coercive force on the number of thermal cycles.

In addition to the coercive force, hardness of samples was measured. Hardness measurements have a smaller spread of the obtained values due to the fact that the hardness is less structure dependent characteristic than the coercive force. But it has the same kind of dependence of the measured characteristics on the number of thermal cycles as the coercive force.

The graphic depend on the average value of hardness (HRB) with number of thermal cycles as shown in figure 4. Figures 3 and 4 were demonstrated by the following functional equations; the coercive force of the number of loading cycles \( H_c = -1.136 n^2 +17.58 n +814.2 \) (the coefficient of determination is 0.615), hardness HRB= \(-0.271 n^2 +5.7085 n +35.818\) (the coefficient of determination is 0.76). These factors can be used for analyzing technical diagnostics. The measured
values (hardness and/or coercive force) are determined the number of thermal cycles and the residual life of the structure.

![Figure 4](image)

**Figure 4.** Effect of the average hardness of the sample on the number of thermal cycles.

![Figure 5](image)

**Figure 5.** Structure: in the initial state, a – in the initial state; b – after 3 cycles; c – after 7 cycles; d – after 20 cycles; (e, f, g, h the same as a, b, c, d, respectively but with a larger scale).
To investigate the structure of the samples, micro-sections were made in the initial state, and then micro-sections were made from the same sample after thermal Cycling at a temperature of 300°C after 3, 7 and 20 cycles. Photos of structures are shown in figure 5 (a-h). The scale is indicated on each photo. Analysis of micro-sections showed that an increase in hardness and magnetic characteristics, and that can only be partially explained by the transformation of granular perlite into lamellar perlite. In other words, the appearance of temperature stresses in the structure can be an explanation. The relevant micro-sections showed the propagation of inter-crystalline corrosion with increasing of the number of thermal loading cycles. Corrosion continued to increase after the completion of the experiment in a room temperature. The increase in magnetic properties (coercive force) and hardness at the third cycle by temperatures near the Curie point of cementite is confirmed by thermal Cycling of flat samples from steels 20 and 45.

Furthermore, thermal Cycling by loading with 2 temperature blocks (the total number of cycles in each of the histograms 15) was carried out in order to study the magnetic properties and hardness of structural carbon steels. The results are shown in figures 6 and 7 (material of samples is steel 25). Number 1 and 2 — refer to the samples of the loading histogram.

**Figure 6.** The influence of average value of coercive force on the number of loading cycles by two histograms (1 – 7 cycles with 550°C, then 8 cycles with 300°C & 2 – 8 cycles with 550°C, then 7 cycles with 300°C).

**Figure 7.** The influence of hardness average value on the number of loading cycles of two histograms (1 and 2 is the same action as the figure 6).
4. Conclusions

1. The possibility of controlling the residual life of elements subjected to thermal Cycling by changing the magnetic properties of the metal. In order to achieve that task it is required to create a new system which is unclouded control and measuring methods by software system, control and measuring devices and adaptive block for express-analysis of the state of the metal.

2. During the thermal cycling from 20°C to the maximum cycle temperature, it is regarded to the coercive force and hardness behavior on the number of loading cycles and cycle temperature is revealed. It is shown, that thermal Cycling near the Curie point of cementite on the third cycle increases up to twice the hardness and coercive force of structural carbon steels.

3. The analysis of micro-glyphs showed that the sharp peak increase in the hardness and magnetic characteristics can only be partially explained by the transformation of granular perlite into lamellar (figure 5, e and f). This point requires further research.

4. After the third cycle, there is a monotonic drop in the magnetic properties and hardness of the material with an avalanche-like increase in intergranular corrosion, which must be considered when carrying out technical diagnostics of parts subjected to thermal Cycling. For machines designed and manufactured according to the "specified life" system, which will be subjected to operational thermal Cycling during operation, we recommend the use of chromium and titanium alloying to eliminate the phenomenon of intergranular corrosion. However, thermal Cycling with 3 cycles from 20 °C to 300 °C can be used to strengthen small and medium - carbon steels in structures that will not be subjected to thermal cycles during operation.

5. References

[1] Medvedev N I, Karkina L E and Ivanovskaya A L 2006 Electronic structure and magnetic properties of α-, γ-phases of iron, their solid solutions with carbon and cementite Physics of Metals and Metallography 101(5) pp 479-484

[2] Drapkin B M and Fokin B V 1980 On the young module of cementite Physics of metals and materials science 49(3) pp. 649-651

[3] Titorov D B 2007 Simulation of various possible cementite structures Physics of Metals and Metallography 103(4) pp 413-419

[4] Schastlivtsev V M, Yakovleva I L, Mirzaev D A and Okishev K Yu 2003 On the Possible Positions of Carbon Atoms in the Cementite Lattice Physics of Metals and Metallography 96(3) pp 75-82

[5] Medvedeva N I, Ivanovskii A L and Kar'kina L E 2003 Effects of Atomic Disordering and Nonstoichiometry in the Carbon Sublattice on the Energy-Band Structure of Cementite Physics of Metals and Metallography 96(5) pp 16-20

[6] Bunin K P and Baranov A A 1970 Metallography (Moscow: Metallurgy) p 256

[7] Tikhonova I V, Kuzovlev O V, Starikov N E and Gvozdev A E 2008 Dissolution of cementite in carbon steels by thermal Cycling Production of Rolled Products 8 pp 36-37

[8] Tikhonova I V, Malyarov A V, Kuzovlev O V, Gvozdev A E and Starikov N E 2009 The influence of carbon content on the dissolution of cementite in carbon steels under cyclic thermal processing Production of Rolled Products 5 pp 29-31

[9] Lomov S B, Sokolova T V, Mal'kova M S and Balakirev E V 2015 The dependence structure of the 40X steel cold deformation from the original structure and cyclic heat treatment Metallurgy Engineering 2 pp 21-24

[10] Malyarov A V 2009 Graphitization of carbon steels under cyclic thermal treatment near the Curie point of cementite Proc. X Int. Sc. and Tech. Ural School-Seminar of Metallurgists-Young Scientists pp 79-81

[11] Collins D A, Barkley E L, Lach T G and Byun T S 2019 Effects of thermal aging on the fracture toughness of cast stainless steel CF8 International Journal of Pressure Vessels and Piping 173 pp 45-54
[12] Yeddu H K, Shaw B A and Somersb M A J 2017 Effect of thermal cycling on martensitic transformation and mechanical strengthening of stainless steels – A phase-field study  
  *Materials Science and Engineering: A* **690** pp 1-5

[13] Shao Y, et al 2019 Thermal simulation on double-pass welding of a high Cr ferritic steel  
  *Journal of Manufacturing Processes* **43(A)** pp 9-16

[14] Baxter D J and Fordnam R J 2000 The Oxidation and Corrosion Behavior of Nonoxide Ceramic Matrix Composites  
  *Comprehensive Composite Materials* **4** pp 221-264

[15] Li S, Ren X, Hou H 2015 The effect of thermal cycling in superplastic diffusion bonding of 2205 duplex stainless steel  
  *Materials & Design* **86** pp 582-586

[16] Qu H, Hou H, Li P, Li S and Ren X 2016 The effect of thermal cycling in superplastic diffusion bonding of heterogeneous duplex stainless steel  
  *Materials & Design* **96** pp 499-505

[17] Park S-J and Seo M-K 2011 Chapter 8 - Composite Characterization  
  *Interface Science and Technology* **18** pp 631-738

[18] Elaieb M, Shuaeib F M, Saied R O and Almalki M G 2013 The Influence of Thermal Cycling on the Corrosion and Hardness of the Low Carbon Steel  
  *Libya for Applied and Technical Science* **2** pp 24-28

[19] Ilyin A M, Tazhibaeva I L and Borisov B A 2002 Effect of thermal cycling on impurity grain boundary segregation in maraging steel  
  *Journal of Nuclear Materials* **307(311)** pp 475-478

[20] Tataurova E V 2002 Effect of thermocycling on structure and properties of carbon steels  
  *Russian Metallurgy (Metally)* **1** pp 67-71