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A technique for predicting steel corrosion resistance

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Abstract. Research works were carried out to develop a technique with the aim to increase the lifetime of steel items used in corrosive media. The possibility to monitor corrosion parameters of steel samples is analyzed on the basis of magnetic properties obtained by means of a magnetic structuroscope DIUS-1.15M designed by the Institute of Metal Physics of the Ural Branch of the Russian Academy of Sciences (IMP UB RAS).

1. Introduction
There are many modern metal corrosion inspection and monitoring techniques, such as weight loss analysis, metallographic evaluation, ultrasonic testing and radiography (metal thickness measurements); magnetic sensing (magnetic field measurements); optical sensing (light intensity measurements) and others. Corrosion prediction is normally based on determining the corrosion rate of coupons by means of direct or indirect methods [1, 2]. This approach is destructive, time-consuming and does not provide 100 per cent efficiency of monitoring. New monitoring parameters should be stated to assure high reliability of corrosion rate prediction by means of nondestructive accelerated techniques [3].

2. Experimental procedures
In magnetic structuroscopy, magnetic hysteresis loops are generated to monitor strength properties of steels. The loops involve many experimental points, but only some of these points are used for nondestructive monitoring. Among them we can name coercive force, magnetic permeability, relaxation coercive force, differential permeability, etc. An objective of this research was representing a quasi-static magnetic hysteresis loop as a periodic signal and calculating harmonics of this signal.

Quasi-static hysteresis loops for ferromagnetics were generated by means of a modern structuroscope (and a hardware/software module DIUS-1.15M designed and produced at the Institute of Metal Physics, Ekaterinburg).

The material under investigation was 45KH (45X) steel which was temperature (950ºC) quenched with the sequence of tempering procedures that followed.

Magnetic hysteresis loops for 45KH (45X) steel generated by means of the hardware/software module DIUS-1.15M are shown in Figure 1.

To enhance possibilities of the entire hysteresis loop we designed and applied the harmonic analysis for a quasi-static hysteresis loop [4].

For this, time parameter in the harmonic analysis was replaced with the magnetic field strength

$$t = H/k, \quad (1)$$

since magnetizing and demagnetizing current in the device used and, therefore, magnetic field strength, are described by a ramp function. To form a periodic function, we imaged the descending (upper) branch of the loop symmetrically with respect to the vertical line going through the H_{max} point (Figure 2).

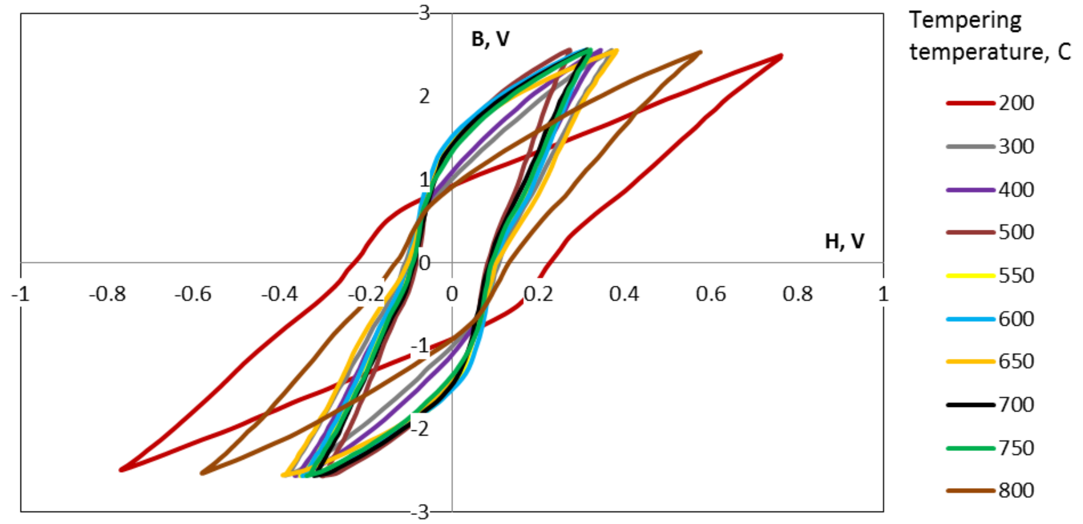


Figure 1. Hysteresis loops of 45KH (45X) steel tempered at various temperatures.

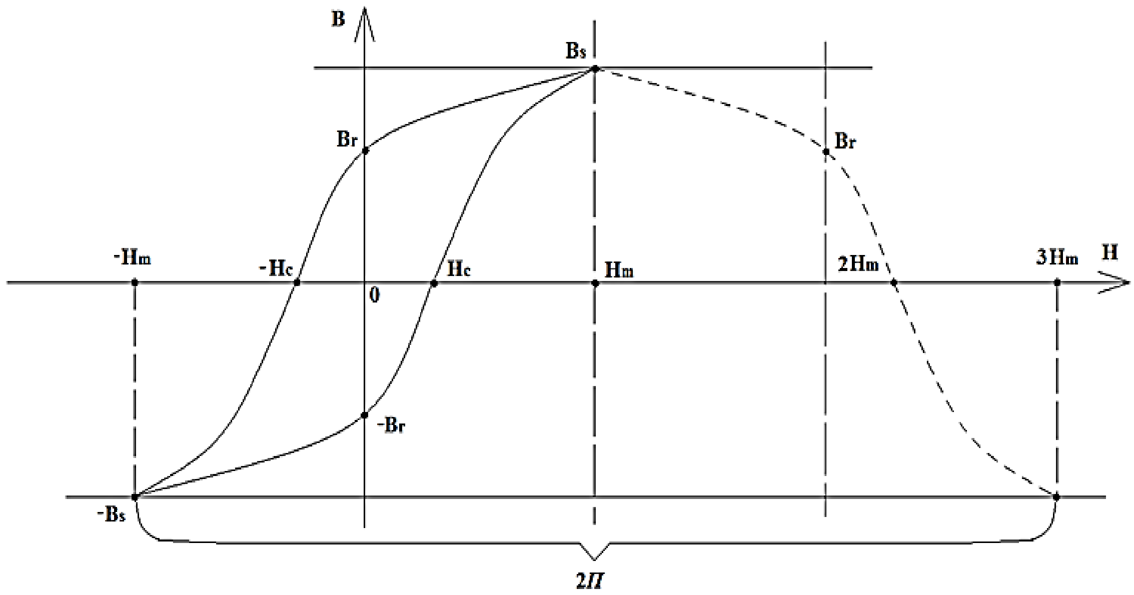


Figure 2. Imaging an involute of the magnetic hysteresis loop.

As a result, we obtained the representation of the hysteresis loop as a periodic function

$$f(H) = f(kt) \quad (2)$$

3. Results and discussion

For this function, the discrete Fourier transform can be applied [5, 6]. With the discrete Fourier transform, the amplitudes of the 1st, the 3rd, the 5th and the 7th harmonics of the hysteresis loops were calculated for 45KH (45X) steel, depending on tempering temperatures given in Figure 3. In this chart, A constitutes dimensionless amplitudes of Fourier spectrum harmonics. As one can note, the peak values of harmonic components endure a non-monotonic change all through the temperature range, what is connected to the structural changes taking place in the test steel.

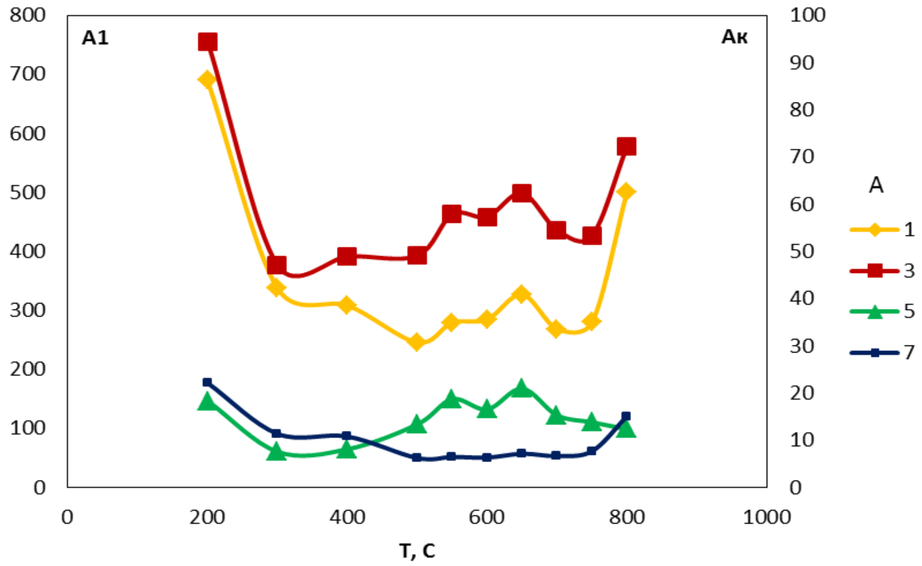


Figure 3. Tempering temperature dependence of A_1, A_k amplitudes (k=3, 5, 7) of the odd Fourier spectrum harmonics in the hysteresis loops for 45KH (45X) steel.

To define the reliability of the readings taken by means of the hardware/software module DIUS-1.15M, the comparison of the readings coercive force was carried out by means of the coercitimeter KRM-Ts-K2M (Figure 4).

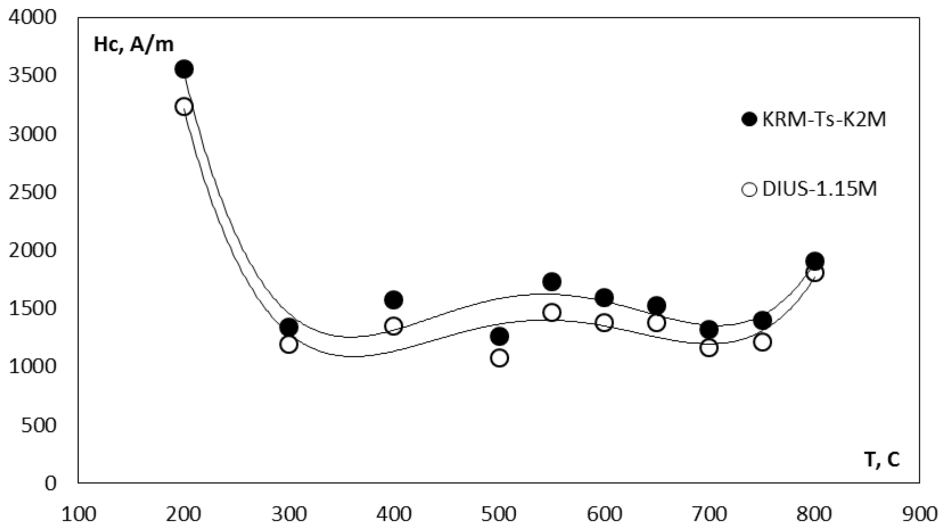


Figure 4. Tempering temperature dependences of the coercive force Hc for 45KH (45X) steel, which were generated by means of the coercitimeter KRM-Ts-K2M and the hardware/software module DIUS-1.15M.

The test steel samples tempered at various temperatures were subjected to corrosion testing in the 5% solutions of hydrochloric and sulfuric acids at room temperature (Figure 5).

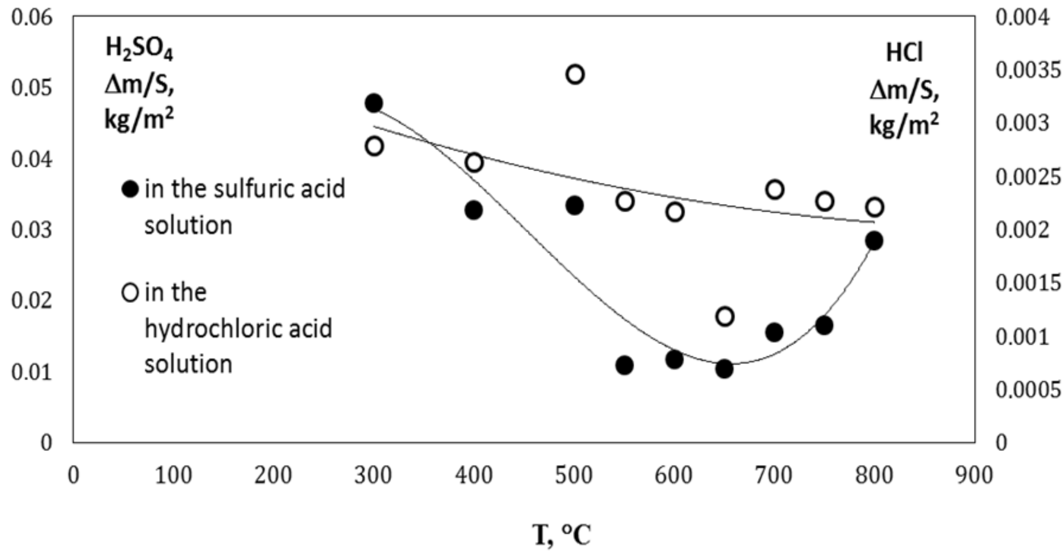


Figure 5. Tempering temperature dependence of the samples weight loss for 45KH (45X) steel in the 5% solutions of hydrochloric and sulfuric acids.

According to the inclusion theory of coercive force, the increased contents of carbide components of carbon lead to the increased coercive force. The structure dispersion results in the increased number of micro-galvano pairs and, therefore, in the increased rate of corrosion processes.

The work [7] shows that at the temperatures over 200ºC the retained austenite transforms to the tempered martensite, and internal strains decrease, leading to the decreased coercive force.

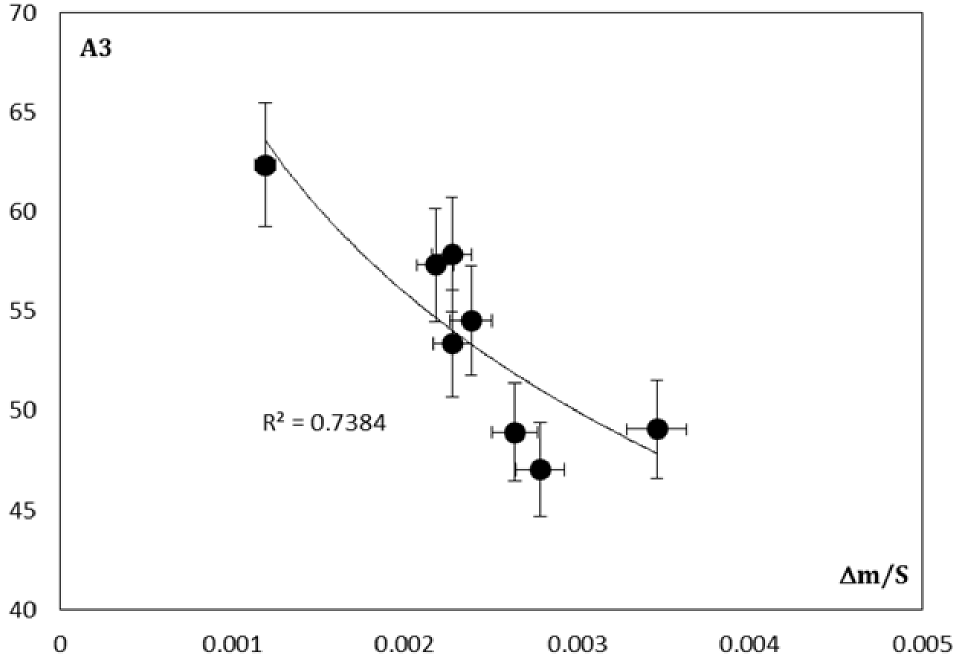
At tempering within the temperature range of 300…450ºC, carbon is completely released from the supersaturated solid solution, and the martensite transforms to the ferrite. The carbide Fe_2C transforms to the cementite Fe_3C [8]. A structure is formed, which is called the tempered troostite and consists of the ferrite with small cementite particles regularly distributed. All these processes reduce the corrosion susceptibility of steel (Figure 4). As the magnetic hysteresis loops correlate directly with the magnetic parameters of steel, the changes of magnetization harmonic spectra on their basis will also be susceptible to the changes of the steel structure and phase composition. In Figure 3 the amplitudes of the 3rd, the 5th and the 9th magnetization harmonics increase, while those of the 1st and the 7th decrease.

At tempering within a higher temperature range (500…650ºC), the cementite particles coagulate – small particles merge into bigger ones and, as a result, their number decreases [9]. After such tempering the steel consists of a coarse mixture of the ferrite and cementite, called the granular, or tempered, pearlite. With the tempering temperature increasing, the structure approaches equilibrium to an increasing extent [10, 11]. The properties of steel also change considerably, including corrosion properties (the increased corrosiveness in the sulfuric acid solution). The coercive force has a low peak value within the temperature range of 500…600ºC, which is mostly related to the presence of the alloyed cementite or special carbides with smaller inclusions. The amplitudes of magnetization harmonics increase and the peak values for the amplitudes of the 1st, the 3rd and the 5th harmonics can also be observed due to some concentration of carbide particles and their reaching a “critical size” through the coagulation [8, 10].

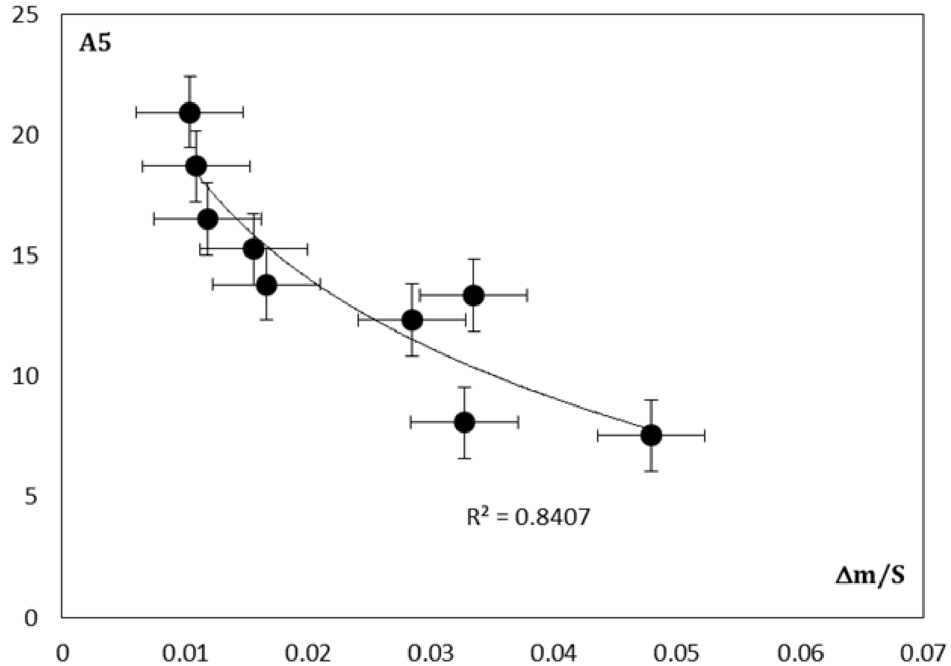
At tempering within a yet higher temperature range (600…800ºC), carbides are released. The amplitudes of the harmonics stay monotonic up to 700ºC, but with a higher temperature the amplitudes of the 1st and the 7th harmonics increase, while the amplitude of the 5th harmonic decreases [12, 13]. The carbide release results in the formation of micro-galvano pairs which lead to the increased corrosiveness.

As it is shown in Figure 4, the minimal corrosiveness of 45KH (45X) steel can be observed within the tempering temperature range of 450–600ºC. This arises from the decreased structure heterogeneity, the material reaching equilibrium.

The comparison of the harmonic spectrum components and the weight loss in the abovementioned corrosive media allowed to obtain the dependences given in Figure 6.



a)



b)

Figure 6. Dependences of the harmonic amplitudes A_3 and A_5 on the relative corrosion weight loss m/S of the heat-treated 45KH (45X) steel samples: (*a*) dependence of the 3rd harmonic amplitude on the weight loss in the hydrochloric acid solution; (*b*) dependence of the 5th harmonic amplitude on the weight loss in the sulfuric acid solution.

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4. Conclusions

Thus, we obtained the dependences for the harmonic spectrum and the relative weight loss, described by the logarithmic function with 74% and 84% reliability.

To sum up, the research work resulted in the following conclusions:

1. The correlation between the corrosion weight loss and the changes of the harmonic spectrum amplitudes for quenched and tempered 45KH (45X) steel samples is determined with 75% and 80% rate.

2. The coercive force for 45KH (45X) steel is proved not to correlate with the corrosion in the solutions of hydrochloric and sulfuric acids.

3. The dependence obtained with the use of the harmonic analysis constitutes a promising research direction to develop a technique for predicting 45KH (45X) steel corrosion resistance.

References

[1] Klyuev V V 2003 *Nondestructive Monitoring and Diagnostics* (Moscow: Mashinostroyeniye)

[2] 2004 *GOST 9.008-85.YeSZKS. Metals and Alloys. Techniques to Define Corrosion and Corrosion Resistance Indicators* (Moscow:Izdatelstvo Standartov)

[3] Novikov V F, Ustinov V P, Radchenko A V, Yevko V P 2015 Method and device to monitor excessive corrosion of steel Patent RU 2570704

[4] Novikov V F, Neradovskiy D F, Sokolov R A 2016 *Herald of Perm National Research Polytechnic University. Machine-Building, Material Science* **18** 38–50 (in Russion).

[5] Belashov V Y, Chernova N M 1997 *Effective Algorithms and Programs of Computational Mathematics* (Magadan: NEISRI)

[6] Ponomaryov Y F 1986 *Russian Journal of Nondestructive Testing* **7** 67–78

[7] Malakhov A I and Zhuko A P 1989 *Bases of Material Science and Theory of Corrosion* (Moscow: Vysshaya Shkola).

[8] Mikheyev M N and Gorkunov E S 1993 *Magnetic Methods of Structural Analysis and Nondestructive Monitoring* (Moscow: Nauka)

[9] Novikov I I 1974 *Theory of Metals Heat Treatment* (Moscow: Metallurgiya)

[10] Mogutnov B M, Tomilin I A, Schwartzman L A 1984 *Thermodynamics of Iron Alloys* (Moscow: Metallurgiya)

[11] Mikheyev M N, Morozova V M, Noskova N I 1981 *Structure and Physical and Mechanical Properties of Steels* (Sverdlovsk: Institute of Metal Physics of Ural Scientific Center of Academy of Sciences Russia)

[12] Bida G V, Nichipuruk A P 2005 *Magnetic Properties of Heat-Treated Steels* (Ekaterinburg: the Ural Branch of the Russian Academy of Sciences)

[13] Kurdyumov V G, Utevskiy L M, Entin R I 1977 *Transformations in Iron and Steel* (Moscow: Nauka)