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The effect of temperature on the corrosion rate of iron-carbon alloys

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ABSTRACT

Temperature has a significant effect on the progress of corrosion processes on the surface of metals and alloys. The corrosion behavior of iron-carbon alloys in a 0.1 N solution of sulfuric acid at various temperatures was studied. The parameters of the corrosion rate for the investigated system «iron-carbon alloy – 0.1 N solution of sulfuric acid» at different temperatures were determined. It was found that when the temperature increases by 10 °C, the dissolution of the iron-carbon alloy accelerates by an average of 2.3 times. The values of the activation energy of the corrosion process for the investigated iron-carbon alloys are determined, which indicate that the corrosion processes in a solution of sulfuric acid proceed by an electrochemical mechanism. It is established that when the carbon content in the alloy increases, the energy of corrosion activation increases, which means that the beginning of corrosion processes on the surface of iron-carbon alloys occurs later. After the beginning of corrosion, the dissolution of metal under the influence of an aggressive environment occurs faster on the surface of alloys with a high carbon content. Large mass losses of iron-carbon alloys with a high carbon content are caused by the presence on their surface of a greater number of «iron – carbon» galvanic couples. The more such pairs, the more likely and stronger corrosion.

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1. Introduction

Many factors influence the rate of development of corrosion of metals and alloys, for example, the composition of the alloy [1–7] and the aggressive environment [8–10], the operating conditions of the product [11–14], the degree of aggressiveness of the environment [12–17], the presence of protective measures [18–20], the service life of the product [21,22]. Temperature change plays a major role in the development of corrosion processes of metal products, equipment and structures, since it affects the rate of all chemical reactions [23,24].

Machines and equipment in production work under non-stationary conditions, so the rate of development of corrosion processes will not be constant. Experimental studies of the processes of corrosion of metals and alloys under non-stationary conditions and the mass transfer mechanism of the electrolyte supply to the surface of metals help in determining the aspects of the development of corrosion damage [25,26]. Data on the corrosion rate of metal surfaces make it possible to conclude that it is necessary to provide additional protection against corrosion when exposed to aggressive environments [27].

Currently, many studies are devoted to the study of corrosion processes of various metals and alloys [28–31], to the establishment of patterns of occurrence and development of corrosion destruction of metals in environments of varying degrees of aggressiveness [32,33], to the development of methods for protecting equipment, apparatus and machines of various industries from corrosion damage [34,35].

The importance of corrosion research is determined by three aspects: economic, increasing the reliability of equipment and structures, and the safety of the metal stock. The study of the causes and the development of new methods to prevent corrosion damage can reduce the cost of restoration and repair of products and structures, and also ensures the durability of their work.

Basically, metal corrosion proceeds by the electrochemical mechanism [22,36]. Electrochemical corrosion is the result of the work of many microscopic short-circuited galvanic cells that occur on the surface of a metal or alloy in contact with an electrolyte. In this case, the metal dissolves on the anode sections of the surface, and the dissolution rate increases in the presence of heterogeneous inclusions and impurities [22,37].

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Temperature has a great influence on the rate of electrochemical corrosion of metals, since it changes the rate of diffusion, the overvoltage of electrode processes, and the solubility of corrosion products [38]. The temperature dependence of the corrosion rate of iron-carbon alloys in mineral acids is exponential and can be approximately expressed by the exponential equation [39]:

$$K_m^- = Ae^{\frac{Q}{RT}}, \tag{1}$$

here: K_m^- is the negative indicator of change of mass, g/(m^2·h); A is constant equal to K_m^- at $T = \infty$ or $1/T = 0$; Q is the effective activation energy of the process, kal/mol; R is the gas constant (1.99 kal/(deg·mol)); T is the absolute temperature, °K.

This equation in coordinates lgK_m^--$1/T$ is converted to the equation of the line:

$$lgK_m^- = lgA - \frac{Q}{2.303RT}. \tag{2}$$

This dependence is very convenient for graphically finding the missing values of K_m^- at any temperatures.

The unequal temperature of individual sections of the metal surface leads to the appearance of thermovoltaic corrosion couples in which the more heated part of the surface is usually the anode and is subjected to increased corrosion [40].

Therefore, it is important to find out the causes of metal corrosion, to study the factors that have a significant impact on the acceleration of the development of corrosion processes, and to develop measures to prevent corrosion destruction, for which it is necessary to conduct research on the mechanisms of corrosion processes.

2. Materials and methods

To study the influence of temperature on the rate of corrosion, samples of the same size were made from iron-carbon alloys (Table 1).

Before the experiment, the samples were cleaned, measured with a caliper and weighed on analytical scales. Then 3 samples of an alloy of the same grade were hung in a container with 0.1 N sulfuric acid solution (Fig. 1). The samples were kept in solution at a constant temperature for 2 h. Studies were conducted at 20, 35, 45, 55 and 65 °C.

After removal from the vessel, the samples were washed with distilled water, wiped dry with filter paper, and weighed to determine the change in mass. The calculations used the average value change in the mass of samples at a given temperature.

The calculation of the corrosion rate of samples was carried out using the following formulas:

$$K_m^- = \frac{\Delta m}{S \cdot \tau}, \tag{3}$$

$$K_n = K_m^- \cdot \frac{8.76}{\rho_{me}}, \tag{4}$$

here: K_m^- is the negative mass change index, g/(m^2·h); Δm is the change in mass of the sample, g; S is the surface area of the sample, m^2; τ is corrosion time, h; K_n is the depth index of corrosion, mm/year; ρ_{me} is the metal density, g/sm^3.

Table 1
Investigated iron-carbon alloys.

Alloy grade	Carbon content, %
Steel 0.8kp	0.08
Steel 10	0.1
Steel 20	0.2
Steel St3ps	0.14–0.22
Steel 45	0.45
Steel U7	0.7
Grey cast iron SCH20	3.3–3.5

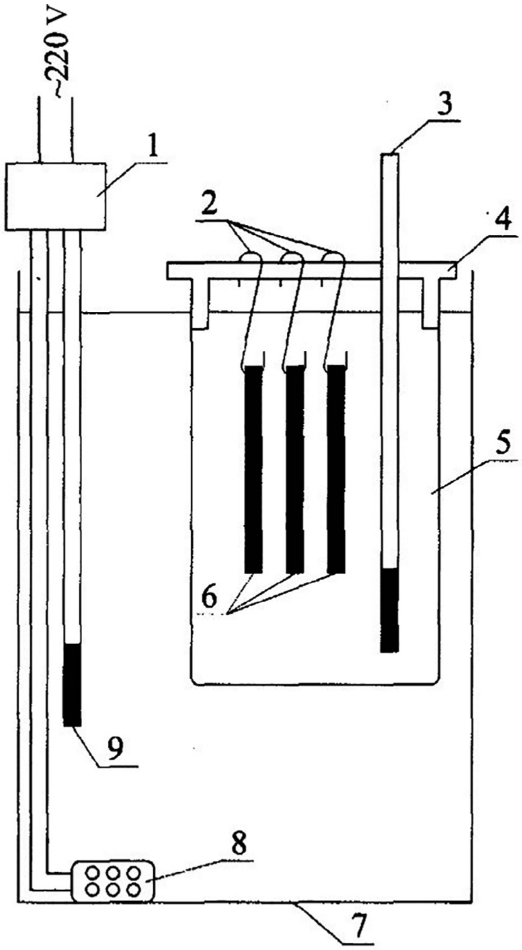

Fig. 1. Installation diagram for the study of acid corrosion of metals: 1 – electronic relay; 2 – glass hooks for hanging samples; 3 – thermometer; 4 – rod; 5 – glass vessel with electrolyte (0.1 N H_2SO_4 solution); 6 – test samples; 7 – water thermostat; 8 – electric heater; 9 – contact thermometer.

3. Result and discussion

The results of calculating the values of the mass change index of samples from iron-carbon alloys at different temperatures are shown in Fig. 2, and the values of the depth index of corrosion are presented in Fig. 3. The data obtained during the experiment show that the increase in temperature accelerates the corrosion processes on the metal surface. It is obvious that with an increase in the carbon content of the alloy, the dissolution of the metal occurs more intensively. However, for grey cast iron of the SCH20 grade, in which the carbon content is 3.3–3.5%, the mass change is not the maximum of all the studied samples. This may be due to structural and phase features of the alloy structure [41,42].

Under standard conditions, steels with a carbon content of 0.08 to 0.1% corrode at approximately the same rate, the mass change index is in the range of 0.74–0.81 g/m^{2}h. Steel grade St3 corrodes 2.5 times faster than steel grade 0.8kp. Steel grade 45 corrodes 2.3 times faster, and steel grade U7 3 times faster than steel grade St3.

When the temperature rises to 65 °C, the dissolution of steel grade St3 is 14 times faster than steel grade 0.8kp, 5 times faster

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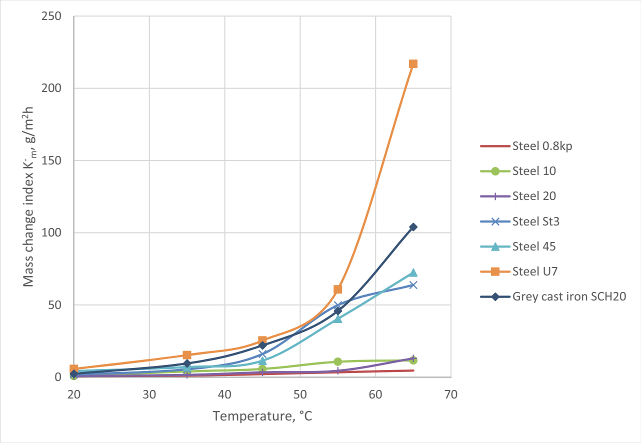

Fig. 2. Change in the values of a negative mass change index of samples of iron-carbon alloys during corrosion in a 0.1 N H_2SO_4 solution with increasing temperature.

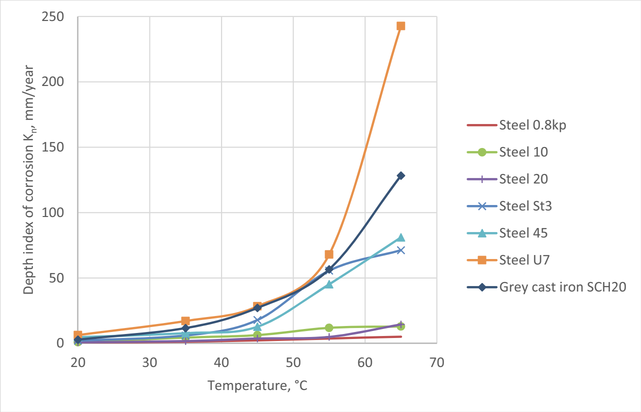

Fig. 3. Change in the values of the depth index during corrosion in a 0.1 N H_2SO_4 solution of samples from iron-carbon alloys with increasing temperature.

than steel grades 10 and 20, and steel grade U7 corrodes 3.4 times faster than steel grade St3. At 65 °C, steel grades St3 and 45 corrode at approximately the same rate.

When the temperature increases from 20 to 35 °C, the rate of dissolution of steel grade 0.8kp increases by 1.5 times, when increasing from 20 to 45 °C increases by 2.9 times, when increasing from 20 to 55 °C increases by 4.6 times, and when increasing from 20 to 65 °C increases by 6.2 times. On average, when the temperature increases by 10 °C, the rate of corrosion of steel grade 0.8kp in 0.1 N H_2SO_4 solution increases by 1.6 times.

When the temperature increases from 20 to 35 °C, the rate of dissolution of steel grade 10 increases by 4.9 times, when increasing from 20 to 45 °C increases by 7 times, when increasing from 20 to 55 °C increases by 13.2 times, and when increasing from 20 to 65 °C increases by 14.3 times. On average, when the temperature increases by 10 °C, the rate of corrosion of steel grade 10 in 0.1 N H_2SO_4 solution increases by 2.3 times.

When the temperature increases from 20 to 35 °C, the rate of dissolution of steel grade 20 increases by 2.1 times, when increasing from 20 to 45 °C increases by 4.5 times, when increasing from 20 to 55 °C increases by 6 times, and when increasing from 20 to 65 °C increases by 17.4 times. On average, when the temperature increases by 10 °C, the rate of corrosion of steel grade 20 in 0.1 N H_2SO_4 solution increases by 2.1 times.

When the temperature increases from 20 to 35 °C, the rate of dissolution of steel grade St3 increases by 3 times, when increasing from 20 to 45 °C increases by 9 times, when increasing from 20 to 55 °C increases by 27 times, and when increasing from 20 to 65 °C increases by 35 times. On average, when the temperature increases by 10 °C, the rate of corrosion of steel grade St3 in 0.1 N H_2SO_4 solution increases by 2.5 times.

Table 2
Values of the effective activation energy of the corrosion process Q in the investigated system «iron-carbon alloy – 0.1 N solution of H_2SO_4».

Alloy grade	Carbon content, %	Q, kJ/mol
Steel 0.8kp	0.08	37.85
Steel 10	0.1	49.42
Steel 20	0.2	50.41
Steel St3ps	0.14–0.22	70.37
Steel 45	0.45	54.5
Steel U7	0.7	64.17
Grey cast iron SCH20	3.3–3.5	69.63

When the temperature increases from 20 to 35 °C, the rate of dissolution of steel grade 45 increases by 1.7 times, when increasing from 20 to 45 °C increases by 2.7 times, when increasing from 20 to 55 °C increases by 9.6 times, and when increasing from 20 to 65 °C increases by 17.1 times. On average, when the temperature increases by 10 °C, the rate of corrosion of steel grade 45 in 0.1 N H_2SO_4 solution increases by 2.2 times.

When the temperature increases from 20 to 35 °C, the rate of dissolution of steel grade U7 increases by 2.7 times, when increasing from 20 to 45 °C increases by 4.5 times, when increasing from 20 to 55 °C increases by 10.7 times, and when increasing from 20 to 65 °C increases by 38.2 times. On average, when the temperature increases by 10 °C, the rate of corrosion of steel grade U7 in 0.1 N H_2SO_4 solution increases by 2.7 times.

When the temperature increases from 20 to 35 °C, the rate of dissolution of grey cast iron SCH20 increases by 4 times, when increasing from 20 to 45 °C increases by 9.5 times, when increasing from 20 to 55 °C increases by 19.8 times, and when increasing from 20 to 65 °C increases by 44.8 times. On average, when the temperature increases by 10 °C, the rate of corrosion of steel grade 20 in 0.1 N H_2SO_4 solution increases by 2.7 times.

The values of the depth corrosion index indicate that under standard conditions, steel grades St3, 10, 20, 45 and U7 are less resistant to aggressive media, steel grade 0.8kp and cast iron grade SCH20 are little resistant to aggressive media. At elevated temperatures, steel grades 0.8kp, 10, 20, St3 are low-resistant to aggressive media. Steel grades 45 and U7, as well as cast iron SCH20 are unstable to acid corrosion at elevated temperatures.

Table 2 presents the calculated values of the activation energy of the corrosion process Q of the studied iron-carbon alloys in a 0.1 N sulfuric acid solution. The obtained data show that the effective activation energy of the corrosion process increases with an increase in the carbon content of the alloy.

The established values of the effective activation energy indicate the electrochemical nature of corrosion of iron-carbon alloys in an acidic environment, since they are in the range of 37.7–87.9 kJ/mol [43,44]. Electrochemical dissolution of metal on the surface is caused by the appearance of a galvanic couple «iron – carbon», and the more such couples occur, the faster the corrosion processes in the iron-carbon alloy [45].

4. Conclusion

During an experiment to study the influence of temperature on the rate of acid corrosion of iron-carbon alloys, it was found that when the temperature increases, the corrosion processes intensify, and the metal dissolution accelerates. In iron-carbon alloys with a high carbon content corrosion occurs faster. On average, when the

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temperature increases by 10 °C, the rate of corrosion of iron-carbon alloys increases by 2.3 times.

The higher the activation energy value, the longer it takes to start the development of the corrosion process on the alloy surface. However, since high activation energy values correspond to high carbon content in an iron-carbon alloy, after the beginning of corrosion the metal dissolves faster. This is due to the fact that as the carbon content increases, the number of micro-galvanic «iron – carbon» couples on the surface of the alloy increases. Thus, as the carbon content of an iron-carbon alloy increases, its corrosion resistance decreases.

An increase in temperature contributes to an increase in the number of active centers of corrosion on the metal surface and accelerates the development of corrosion processes; therefore, it is necessary to provide the protection of metal products, equipment and structures operating at elevated temperatures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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