Electrothermal Devices for Gas-Thermal Processing of Structural Metals and Alloys

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Abstract. The provided designs of cylindrical electric resistance furnaces were designed to strengthen the heat treatment of a wide range of metal products with various applications. Special-purpose electric furnaces allow carrying out strengthening heat treatment of metal and alloy surfaces in reaction process medium comprising air, superheated water vapour, a mixture of inert and oxidising gases with the formation of thermal oxide coatings with increased indicators of both wear and corrosion resistance.

1. Introduction
The application of resource-saving and low-waste strengthening technologies is one of the promising directions for the creation of high-quality machine-building metal and metallurgical products. These technologies include gas-heat oxidation which allows one without the use of additional materials, complex equipment and tooling to obtain mechanically strong and corrosion resistant thermal oxide coatings on the functional surface of metal products. These coatings significantly increase reliability and service life of critical components of various components of machines along with technology and quality indicators of rolling products, etc [1-5].

2. Urgency
Thermal oxide coatings are of great practical importance when used on steel bearing rings [6-7]. These coatings strengthen steel surface, give it increased hardness and wear resistance, and provide high corrosion resistance when interacting with chemically aggressive environments. With a certain morphological structure, thermal oxide coatings contribute to the retention of a thin film of lubricant on the metal surface, significantly improving the performance of bearings and increasing their wear resistance.

In the majority of cases, oxide coatings are formed on steel products in order to improve the protective properties and mechanical characteristics of the surface, which are mainly influenced by the thickness and phase-structural condition of the thermal oxide layers. In rolling production, these thermal oxide layers can be formed on the surface of products comprising pipes of different diameters and cross-sectional shapes; corners; fittings; etc. Moreover, the applied technological coating based on thermal metal oxides ensures not only a better hold of lubricant layer on metal, but also significantly enhances their durability and functional reliability, which is achieved by making the surface thermally modified with the necessary structural, morphological, mechanical and anticorrosive characteristics [8-12].
Thermal strengthening modification of metal surfaces of products with the help of oxidation makes it possible to give them higher hardness and wear resistance due to the formation of a thin layer of the metal oxides on the surface, which are part of the chemical composition of the metal base. Metal oxide compounds in the form of a coating formed on the surface differ from the metal of a base as they have increased mechanical, thermal and anticorrosive characteristics, along with the ability to maintain their functional properties for a long time under friction without destroying the metal oxide matrix [13-20].

3. Problem Statement
The most widespread methods for the creation of functional oxide coatings on metal products are: air-thermal and steam-thermal oxidation, as well as oxidation in mixtures of inert and reaction gases, characterized by high technical and economic efficiency. These technological methods allow you to give the oxidised surface a range of performance characteristics and to change the parameters of modes and indicators of physical, chemical and mechanical properties of the coatings in a wide range.

Therefore, the aim of the study is to develop highly efficient heating equipment in the form of cylindrical electric resistance furnaces for modifying the surfaces of structural metals and alloys with metal oxide compounds.

4. Theoretical Part
When air-thermally oxidised, coating formation occurs due to the physical and chemical interaction of the metal matrix with the air oxygen, resulting in the formation of their own metal oxide compounds on the surface, causing nonstoichiometric phase composition of the coating.

Air-thermal oxidation of metal products is carried out in heating devices, i.e. electric resistance furnaces with free air access to the working space of the furnace (Fig. 1).

![Figure 1. Block diagram of electric furnace for air-thermal oxidation of metals and alloys: HC is the furnace heating chamber, TR is the temperature regulator.](image_url)

The formation of the coating is due to the interaction of the metal base with air oxygen at a certain temperature in the furnace. As a result of such reactionary interaction, metal oxide compounds are formed on the treated surface, which give it a complex of increased physical, chemical and mechanical properties different from those of the base metal. Thermal strengthening of the modified surface layers of the product occurs while maintaining the chemical composition and properties of the basic metal matrix. Due to the thermochemical processes of phase formation, the formation of an air-thermal metal oxide coating on the surface is carried out without the use of additional materials to obtain the coating.

When steam-thermally oxidised, the metal surface is treated with an oxygen-depleted medium representing superheated water vapour. This allows you to avoid or minimize the formation of undesirable phases (e.g., nitrides) in the coating as they have a negative impact on the corrosion and mechanical properties of the oxidised products.

Steam-thermal oxidation is implemented in more complex electric heating devices equipped with a steam generator (process unit for obtaining and supplying superheated water vapour) and a unit for power supply and control of the treatment process (Fig. 2). The steam reaction medium is fed into the oxidation chamber of the furnace under a certain pressure, which is maintained throughout the duration of oxidation.
Figure 2. Block diagram of the installation for steam-thermal oxidation: CF is the chamber furnace, SG is the steam generator, PCU is the power and control unit.

The formation of thermal oxide coating occurs under the conditions of interaction of the metal surface with the reaction components of the vapour-gas medium, resulting in the formation of surface metal oxide systems with a certain thickness and structure [6]. In this case, by changing the thickness of the coating, its properties and morphology also change. Thus, as the coating grows in thickness, its porosity, the degree of roughness and morphological heterogeneity of the surface increases, which leads to deterioration of mechanical strength and reduction of corrosion resistance of metal oxides. Therefore, in order to create thermal oxide coatings with high hardness and protective ability, it is necessary to form thin-layer metal oxide systems with minimal porosity and roughness, along with morphological homogeneity of the surface.

Mixtures of inert (Ar, Ne, He) and oxidising (O\textsubscript{2}, CO\textsubscript{2}) gases are used for oxidation in inert-reaction controlled media. To create strengthening coatings, the two-component gas mixture is directly fed into the resistance electric furnace (Fig. 3). At the same time, firstly, the furnace is heated with the help of a temperature regulator, and then a gas mixture is passed through it, which is formed in a gas mixer connected by rubber hoses to the reducers of the corresponding gas cylinders.

Figure 3. Block diagram of electric furnace for high-temperature oxidation of metal products in gas mixtures: GM is the gas-mixer, TF is the tube furnace, TR is the temperature regulator.

The formation of functional thermal oxide coatings on metal products is carried out in specialised industrial heating devices with the use of various reacting oxidising media. Depending on the metal material of the products used, one or another technological medium of oxidation, processing modes and physical and technical parameters of the electric heating equipment used are selected.

5. Practical Part
For high-efficiency heat treatment of products made of various metal materials, specialized electric furnace equipment has been developed which allows performing group surface strengthening of metal products when using various gases and their mixtures as working reaction media.

To obtain strengthening thermal oxide coatings by air-thermal oxidation, a single-chamber cylindrical electric resistance furnace has been developed, the design of which provides free access of air to its working space (Fig. 4).

This electric furnace consists of a cylindrical chamber 1, open on the one side for the air flow into the working space and closed on the other opposite side with a lid 2 using a latch 3. Inside the chamber 1 a thermocouple 4 is located, and on the housing there is heating system in the form of a heating element 5 which is connected to isolated electric terminals 6 of the power source and closed
from the outer side of the casing 7 with washers made of thermo-insulating material and cooling system in the form of two cooling loops 8 with fittings for circulation of a liquid medium.

The design of the oxidation chamber, open on the one side and closed with the lid on the other, creates the possibility of filling the entire volume of the chamber with air oxidising medium necessary for the product oxidation. In this case, the chamber must be closed with a lid on the one side to prevent heat dissipation and the occurrence of errors in the set temperature regime in the chamber.

![Cylindrical single-chamber electric furnace for air-thermal oxidation of metal products.](image)

Figure 4. Cylindrical single-chamber electric furnace for air-thermal oxidation of metal products.

Equipping the cover 2 with the latch 3 makes it possible to open the camera 1 on the other side, and when open from two opposite sides of the camera one can carry out the required technical training of its entire inner surface by removing the formed carbon deposit from the walls.

When using this electric furnace, the products under treatment are first loaded into the cylindrical chamber 1 through an open, lidless part, and the heating element 5 is turned on to ensure a predetermined temperature in the chamber 1, using a thermocouple 4. When a certain temperature is reached in the chamber with an air-oxidising medium, the oxidation process is carried out during the required treatment time. Having completed the air-thermal oxidation, the heating element 5 is disconnected from the power supply, the coolant is pumped through the circuits 8 and the chamber 1 is cooled with simultaneous cooling of the products under treatment when the heating of the device is turned off. When the chamber and oxidised products are cooled, they are removed from the device.

The developed furnace for air-thermal oxidation is characterised by simplicity of design, reliability of operation and technical efficiency of application, while the formed thermal oxide coatings are characterised by increased indicators of functional qualities. At the same time, depending on the type and size of the products under treatment, the size of the electric furnace can vary in a wide range.

### Table 1. Physical and technical characteristics of cylindrical electric resistance furnaces for thermal oxidation in air and superheated water vapour.

| Supply voltage U, [V] | Current type | Frequency of the supply current $f$, [Hz] | Maximum duration of heat treatment, [h] | Cooling medium | Heating range, [$^\circ$C] | Overall dimensions Length $l$, [mm] | Diameter $d$ of the oxidation chamber, [mm] |
|----------------------|--------------|------------------------------------------|----------------------------------------|----------------|--------------------------|-----------------------------------|------------------------------------------|
| 220-230              | ~            | 50                                       | 8.5-9                                   | process water | 50-1200                  | 1000-3000                         | 300-700                                  |

In addition to thermal oxidation in the air atmosphere, in modern industrial production there is widely used the method of oxidation in the medium of superheated water vapour, which is widely used in the creation of wear-resistant, protective, insulating, decorative and other types of oxide coatings [5, 6]. This method of oxidation can be used with high efficiency in the production of strengthening and corrosion-resistant functional coatings, e.g., on steel bearing rings or rolling products.

To implement the process of steam-thermal oxidation, an electric furnace has been developed, the design of which consists of a cylindrical chamber 1 closed on both sides by lids 2 and 3, which is
equipped with a thermocouple 4 and a heating system in the form of a heating element 5 located on the housing, connected to the insulated electric terminals 6 of the power source (Fig. 5, table). On the outside, the heating element 5 is closed by a casing 7 with washers made of insulating material. The lid 2 is equipped with a fitting 8 for supply of superheated water vapour from the steam generator (not shown on Fig. 5) for the implementation of the oxidation process and the cooling gas supply fitting 9 for accelerated cooling of the treated metal products. To remove exhaust gases after oxidation and cooling of products, the housing of the chamber 1 is equipped with the gas outlet fitting 10. At the same time, this electric furnace has a cooling system of the chamber 1 in the form of cooling circuits 11 with fittings, which provide circulation of the liquid medium. Cooling circuits 11 are located on the housing of the chamber 1 on both sides of the heating element 5 at an equal distance from it. Lids 2 and 3 are equipped with sealing rings, in addition to it, lid 3 is equipped with a latch 12 for opening and closing the chamber 1.

**Figure 5.** Cylindrical single-chamber electric furnace for steam-thermal oxidation of metal products.

The technological process of treatment in the electric furnace begins with the lid 3 being open, when a group of products is loaded into the chamber 1. Having closed the lid 3 with the latch 12, the power supply of the heating element 5 is turned on to ensure the desired temperature in the chamber 1, using the thermocouple 4. Through the gas outlet fitting 8, superheated water vapour is fed into the chamber 1 and the oxidation process of the products is carried out. Having completed steam-thermal oxidation, the steam supply is stopped, the heating element 5 is disconnected from the power source and the treated products are cooled in the chamber 1 with the flow of cooling inert gas (Ar, Ne, He) through the fittings 9 and 10. At the same time, the oxidation chamber 1 is being cooled to normal temperature, enabling the circulation of the cooling liquid medium through the circuits 11. When the thermo-oxidised products are cooled, the lid 3 is opened and they are removed from the chamber 1.

Oxidised metal products can be cooled in chamber 1 when steam supply is stopped and the furnace heating is switched off (inertial cooling).

The presence of a cooling system in the form of circulation circuits 11 with a cooling liquid medium in the oxidation chamber ensures rapid reduction of temperature in the chamber to the required level in order to load and oxidise the next batch of certain products.

The developed device for steam-thermal oxidation is characterised by simple design and reliability, while the obtained thermal oxide coatings strengthen the metal surface, giving it increased hardness, wear resistance, and corrosion resistance.

Performance characteristics of cylindrical electric resistance furnaces for air-thermal oxidation and steam-thermal treatment include several basic physical and technical parameters: the supply voltage of the furnace – 220-230 V, current type – AC, Frequency of the supply current – 50 Hz, adjustable temperature range of the heating furnace – from 50 to 1200°C, the recommended maximum heating time – 8.5-9 hours.
6. Conclusions

1. There was developed original design of cylindrical electric resistance furnaces, allowing one to obtain strengthening thermal coatings on various metal products under conditions of their treatment (oxidation) in reaction oxidising environments.

2. The characteristics of structural elements and technological parameters of electric resistance furnaces are given. There is also shown the possibility of group gas-heat oxidation of products and their subsequent cooling in inert gases in one working chamber of a cylindrical electric furnace.

7. References

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