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The technology of thermal cyclic electrolytic plasma hardening of steels

This work describes the technology of thermal cyclic electrolytic plasma hardening, as well as describes the design features of the electrolytic plasma heater. There are presented the results of the research of medium-carbon steel hardness treated by thermal cyclic electrolytic plasma hardening under different conditions. An industrial installation for thermal cyclic electrolytic plasma hardening of materials was developed to carry out thermal cyclic electrolytic plasma hardening of steels in an automated mode. Tempered layers were obtained on the surface of the samples with average thickness values from 0.5 to 10 mm and hardness up to 750 HV. Experimentally that the alternation of switching on the electric potential at a voltage of U1 = 320 V and U2 = 200 V provides heating of the product surface to a depth of 10 mm. In this case, the maximum hardness of the surface layer (750 HV) practically does not depend on the thickness of the hardened layer. The hardness of the hardened layer of the product gradually decreases from the maximum (750 HV) to the hardness of the base (280-300 HV). The developed installation allows to vary the electrophysical parameters within a wide range: to set the voltage, the duration of processing, the time of switching on and off the voltage.

Keywords: plasma, electrolyte, technology, structure, hardening, thermocyclic quenching.

Introduction

One of the most important problems of modern mechanical engineering is to ensure maximum wear resistance of machine parts and tools. Machine parts and tools during operation are exposed to large contact loads, abrasive wear, and various types of friction. Therefore, an effective increase in the service characteristics of parts and tools is largely associated with the need to increase their wear resistance. In addition, the durability of parts depends not only on the properties of the material determined by the manufacturing technology and volumetric hardening, but largely, on the surface properties. Its role in ensuring the operational properties of products is constantly increasing, which has contributed to the emergence and development of a new direction - surface engineering by methods of energy and physicochemical effects along with the widespread use of traditional methods of chemical and thermal treatment. The implementation of this concept under choosing a material will improve the performance properties of parts, and in some cases reduce the consumption of expensive materials. Therefore, recently, low-alloy structural and tool steels are increasingly used and produced due to the use of protective coatings and surface hardening, which made it possible to reduce the cost of expensive high-alloy steels and alloys. At the same time, an important role in the use of protective coatings and surface hardening is played using resource-saving technologies that help to reduce the cost of resources and energy, increase labor productivity [1].

Surface treatment of steel parts with the use of heating by concentrated energy flows (electron beam, laser radiation, plasma arc) is a significant reserve for saving material, labor and energy costs [2]. Experience shows that a plasma source of surface heating in many cases can be used along with sources such as laser and electron beam, providing high technical and economic indicators of the process [3]. There are two directions of using plasma heating. The first area should include the technology of ion-plasma [4] and electrolyte-plasma processing [5]. Moreover, the second direction of plasma heating application is based on the use of a compressed arc of direct or indirect action generated by a special plasmatron [6]. The first direction has particular interest among them, specifically the technology of electrolytic plasma treatment, due to which it is possible to achieve sufficiently high operational properties. Electrolytic plasma treatment is one of the methods of high-speed heating, in which the workpiece is the cathode or anode relative to the aqueous electrolyte [5, 7]. The electrical circuit between the electrodes is closed through an electrolyte (aqueous salt solution). Conversion of electrical energy into heat occurs mainly in the layer adjacent to the product. As a result of heating, this layer turns into a vapor-gas state, in which micro-arcs are excited under the influence of the applied voltage. The power density reaches up to $3 \cdot 10^3$ W/cm^2 [1]. The technology allows varying the rate of heating and cooling and the thickness of the hardened layer within a wide range. By regulating the temperature and speed modes of plasma surface heating and cooling, as well as the use of various electrolytes, it is possible to carry out the processes of nitriding, carburizing, nitrocarburizing, boriding, sulfating and surface hardening [8-10].

In connection with the above, the purpose of this work is to develop a technology for thermal cyclic electrolytic plasma hardening of machine parts and tools, which will increase the wear resistance and hardness of their surface layer, as well as to establish the main regularities of structural-phase transformations in structural and tool steels during electrolytic plasma hardening by the way of surface hardening.

Material and methods of research

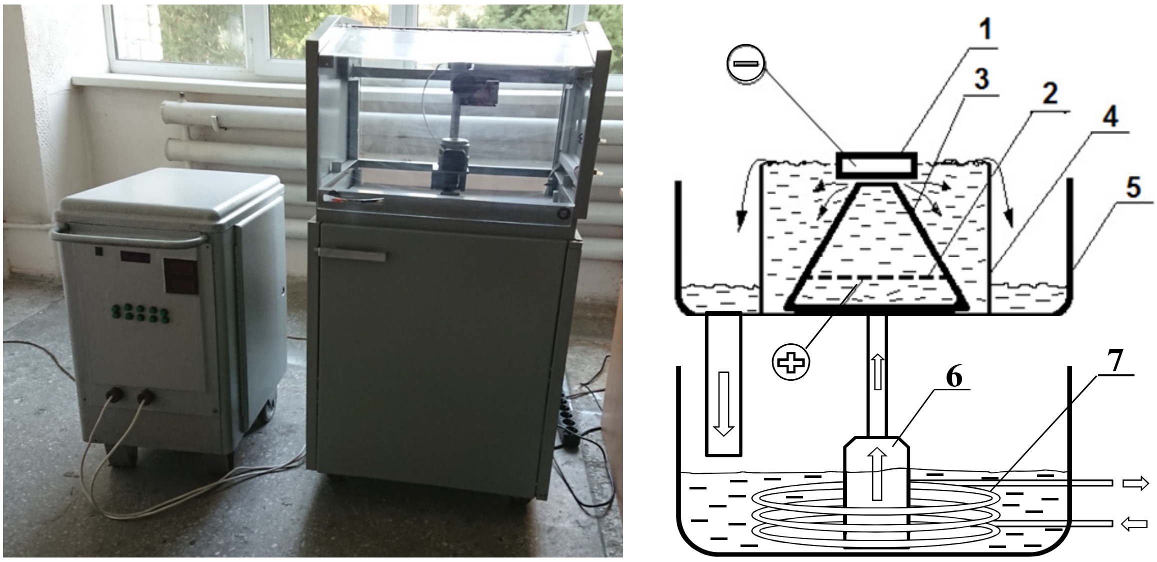
0.34CrNi1Mn medium-carbon steel was chosen as the object of research in accordance with the tasks set. The choice of research material is justified by the fact that 0.34CrNi1Mn structural alloy steel is used for the manufacture of highly loaded critical parts with high requirements for mechanical properties operating at temperatures not exceeding 500 °C - shafts, disks, rotors of compressor machines and turbines, excavator shafts, gear wheels, couplings, gear shafts, half couplings, power pins, bolts, other products. The chemical composition of 0.34CrNi1Mn steel is presented in Table 1.

Table 1

The chemical composition of 0.34CrNi1Mn steel

Steel	C	Si	Mn	Ni	S	P	Cr	Mo
0.34CrNi1Mn	0.3 - 0.4	0.17 - 0.37	0.5 - 0.8	1.3 - 1.7	up to 0.035	up to 0.03	1.3 - 1.7	0.2 - 0.3

Electrolytic plasma hardening of steel samples was carried out in a laboratory setup at the Scientific Research Center «Surface Engineering and Tribology». General view and diagram of the installation for electrolytic plasma treatment is shown in Figure 1. The installation structurally consists of a power source, a chamber for electrolytic plasma processing of materials.



1- treated sample (cathode), 2- stainless steel anode with holes, 3- cone-shaped partition, 4- working chamber of bath with electrolyte, 5- pallet, 6- pump, 7- heat exchanger

Figure 1. General view and scheme of the electrolyte-plasma treatment

Electrolytic plasma hardening of steel samples is carried out as follows. The working bath is filled with electrolyte before starting work. Then the electrolyte is supplied to the electrolytic cell by means of a pump installed at the bottom of the working bath. In this case, the electrolyte flows out through the opening of the cone-shaped partition in the form of a jet and fills the electrolytic cell. Then the electrolyte is drained over the edge of the electrolytic cell into the sump and then back into the working bath. Thus, the electrolyte is in circulation mode. The feed rate of electrolyte 2 (flow rate) is 4-7 l/min. The flow rate of cooling running water into the heat exchanger is 3-6 l/min. The adopted parameters of electrolyte cooling make it possible to maintain the temperature within 40-70 °C when heating the samples to 800-900 °C. With the help of a device for fixing the workpieces, the workpiece is immersed in the electrolyte so that the workpiece area to be treated is at a distance of 2-3 mm from the opening of the tapered partition. In this case, through the opening of the cone-shaped partition, which is 10-15 mm lower than the height of the electrolytic cell, an electrolyte stream is fed to the treated area. Then the anode is connected to the positive pole of the power supply, and the work piece is connected to the cathode to its negative pole. For heating to the hardening temperature, a voltage of 320 V is applied between the electrodes and the current density is 25-30 A/cm^2. At such voltages, an intensely glowing plasma layer is formed in the near-cathode region, and the product is heated at a rate of 300-400 ° C/sec. In this case, an abnormal arc discharge is formed between the electrodes, due to which the workpiece is rapidly heated [11].

An optical microscope NEOPHOT-21 of the National Scientific Laboratory for Collective Use of Sarsen Amanzholov EKU to study the general nature of the structure. The preparation of metallographic sections of steel samples was carried out according to the methods described in [12]. It should be noted that for metallographic microanalysis, thin sections after polishing, using a paste of chromium dioxide, were etched with a 4 % alcohol solution of nitric acid. The microhardness of steel samples was measured at the National Scientific Laboratory for Collective Use of Sarsen Amanzholov EKU on the device PMT-3 in accordance with GOST 9450–76, with loads on the indenter P=1 N and holding time at this load 10 sec [13, 14].

Results and discussions

Currently, heating by radiation from a technological laser, electron guns or high-frequency currents is used for hardening heat treatment of the surface of tools and machine parts. The electrolytic plasma technology of product surface heating and quenching has been known for 50 years [15]. This technology is unique in its ability to change the surface properties of products. In electrolytic plasma technology, the transfer of electrical energy to the product-cathode is carried out from the metal anode through the electrolyte and plasma layer. The plasma layer is formed from the electrolyte material in the gap between the liquid electrode and the electrically conductive surface of the products [15-20].

A water-based electrolyte is used as a liquid electrode. An appropriate choice of the electrolyte composition and electrical modes provides a wide variety of processing technologies [19]. The main reason for the limitation when used in technology is the low reliability and stability of the heating technology. This is primarily due to the instability of the formation of an electrically conductive (plasma) layer between the liquid electrode and the surface of the product. The development of special heaters made it possible to stabilize the technology and increase the conductivity of the electrolyte jet, which, in turn, ensured the efficiency of heating and obtaining an energy density on the heated surface comparable in power density with the energy of a laser plasma.

Special heaters for electrolytic plasma treatment provided control of the power density on the heated surface in the range of $10^2 \ldots 10^4$ W/cm^2, which expands the scope of the technology. The electrical discharges in the plasma layer create local zones of high pressure and temperature on the metal surface underperforming electrolyte-plasma treatment, in which the processes of brittle destruction of non-metallic and organic films and exfoliation of loose contaminants take place. This makes it possible to combine the processes of cleaning the surface of the product and heating it to the required temperature. Experimental work shows that up to 80 % of the consumed electrical energy is introduced into the product in the form of heat when the electrolyte-plasma treatment is heated, and the cost of equipment for the electrolyte-plasma treatment is lower than, for example, at the same processing capacity for HFC in 5 ... 10. In addition, electrolyte-plasma treatment provides a wide range of control over the heating rate, which allows heating and hardening thick layers of the product surface (up to 10 mm). The principal features of the heater for electrolyte-plasma treatment are presented in the diagram, Figure 2. The heater contains a metal anode with a characteristic size D_a and through holes for electrolyte flow. The electrolyte in the heater is compressed by dielectric walls at a distance H to the diameter of the outlet nozzle D_k. The electrolyte speed increases in proportion to the ratio of the area of the holes in the anode and the area of the nozzle. In the volume of the electrolyte, between the electrodes, cross effects take place. On the one hand, an electric field acts on the medium. On the other hand, the hydrodynamic flows of a medium charged with electricity with a density j carry electric currents of convection.

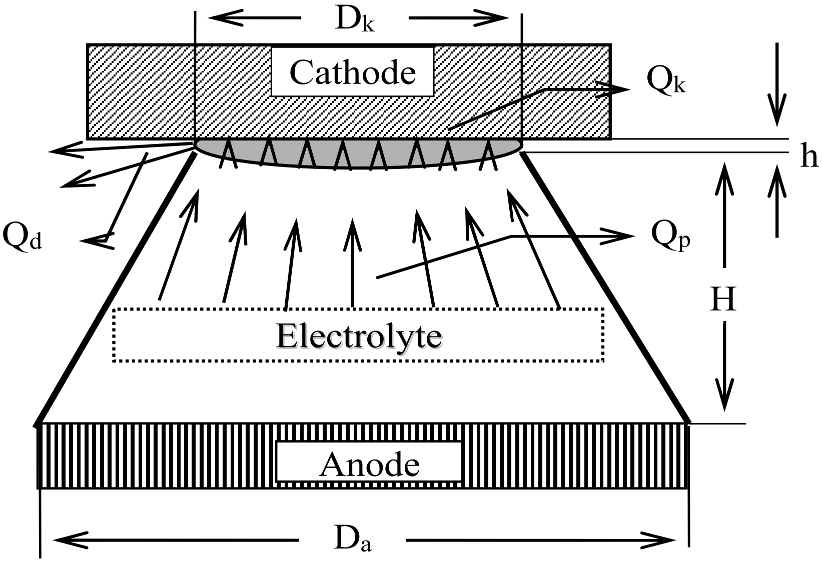


Figure 2. Electrolyte-plasma heater scheme

Heating of the electrolyte is a consequence of the action of the current, as well as radiation. The main energy costs are spent on the evaporation and heating of the electrolyte (formation of a plasma layer) and heating the surface of the product with electric discharges. The discharges are in the form of micro-arc discharges evenly distributed over the processing area.

A periodic increase and decrease in the heating rate is observed with periodic switching on of high voltage electric potential (320V) and low (180V), which makes it possible to increase the time and obtain a thicker heated layer. Connecting an electric potential at the time of cooling the surface of the product allows to reduce the cooling rate and creates the ability to harden products that are made of an alloy with a high carbon content.

Hardened layers can be obtained with a thickness of 0.5 mm, 2 mm, 4 mm, 7 mm, 8 mm and 10 mm by periodically changing the heating power density. As can be seen from Figure 3, heating at a high voltage of 320V without switching the low voltage makes it possible to obtain a hardened layer with a thickness of 0.5-0.6 µm. In order to obtain a hardened layer with a thickness of 4 mm, it is necessary to heat for 25 seconds with periodic switching on of high voltage U1 = 320V for 1 second and low voltage U2 = 180V for 4 seconds. Total heating for 50 seconds provides a hardened layer thickness of 10 mm. The experiment was carried out on a flat sample of 0.34CrNi1Mn steel, which had a thickness of 50 mm. Heating and cooling was carried out with a heater having an outlet nozzle diameter of 20 mm. The electrolyte used was an electrolyte from an aqueous solution containing 20 % sodium carbonate and 10 % carbamide. The microhardness of the hardened layer was measured with a PMT-3 microhardness tester.

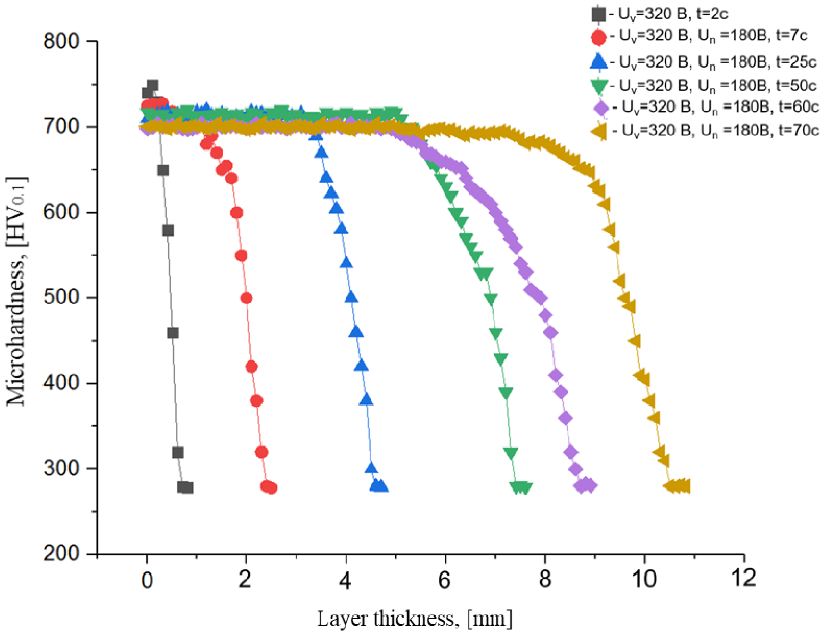


Figure 3. Microhardness of the tempered layer on the surface of steel 0.34CrNi1Mn depending on the heating time t and the voltage of the electric potential

Analysis of the experiment results (Figure 3) shows that the alternation of switching on the electric potential at a voltage of U_1 = 320 V and U_2 = 200 V provides heating of the product surface to a depth of 10 mm. In this case, the maximum hardness of the surface layer (750 HV) practically does not depend on the thickness of the hardened layer. The hardness of the hardened layer of the product gradually decreases from the maximum (750 HV) to the hardness of the base (280-300 HV) and, as a rule, does not depend on the heating time. A periodic change in the electric field strength between the surfaces of the liquid electrode and the product changes the power density of the surface heating, which ensures the control of the electrolyte-plasma heating and the creation of the necessary thermal conditions for the formation of quenching structures.

The heating power density was calculated from the experimentally measured values of current, voltage, and heating area. The heater had an outlet nozzle diameter of 30 mm. The current value varied in the range of 30 - 45A when the voltage of the electric current was changed from 200 to 300V. Accordingly, the heating power density varied from $1x10^3$ to $3x10^3$ W/cm^2. In addition, the ability to control the power density of electrical discharges will ensure the use of electrolytic plasma treatment in cleaning, melting and soldering technologies.

Experimental work has shown that it is possible to obtain hardened layers on the surface of the product depending on the technological conditions, which have a thickness of 0.5 to 10 mm and a hardness of up to 750 HV. The placement of thermally treated layers on the surface of the product depends on the speed, the trajectory of movement of the electrolyte heaters relative to the surface to be hardened and the design features of the heaters themselves.

The research results carried out show the wide possibilities of using the electrolytic plasma hardening technology to improve the service characteristics of alloy steels. In addition, this technology makes it possible to bend the product in the hardened state, weld the product and save energy by hardening only the wearable areas of the surface.

The regulation of the structural-phase state and thickness of the modified layer by varying the heating time and temperature makes it possible to implement optimal technological modes for obtaining various options for the physical-mechanical properties of steel.

The task was set to develop an installation for thermal cyclic electrolytic plasma hardening to carry out the thermal cyclic electrolytic plasma hardening of steels in an automated mode. For this, there were developed an electrolytic plasma treatment chamber and a direct current of power supply. An installation for thermal cyclic electrolytic plasma hardening of materials was created, which allows the processing of samples and steel products in an automated mode. The general view of the installation is shown in Figure 4.

Figure 4. The general view of the installation thermal cyclic electrolytic plasma hardening

The developed direct current of power supply allows varying electric-physical parameters within a wide range: setting voltages, processing duration, voltage on and off times. The power supply provides periodic high and low voltage switching. The power supply is equipped with software to control the operation of the power supply using a personal computer. The power supply specifications are shown in Table 2.

Table 2

The main power supply specifications

	Name	Signification
	Input voltage	380 V
	Regulation limit of the constant voltage output	0 to 320 V
	Discreet output voltage, not more than	10 V
	Maximum output current, not less than	100 A
	maximum power supply capacity, not less than	32 kW

Conclusions

Analyzing the experimental results obtained in this work, the following conclusions can be done:

1. Experimental work has shown that, it is possible to obtain hardened layers on the surface of the product depending on the technological conditions, which have a thickness of 0.5 to 10 mm and a hardness of up to 750 HV. The placement of thermally treated layers on the surface of the product depends on the speed, the trajectory of movement of the electrolyte heaters relative to the surface to be hardened and the design features of the heaters themselves.
2. The regulation of the structural-phase state and thickness of the modified layer by varying the heating time and temperature makes it possible to implement optimal technological modes for obtaining various options for the physic-mechanical properties of steel.
3. An installation for thermal cyclic electrolyte-plasma hardening of materials was developed in order to carry out the thermal cyclic electrolytic plasma hardening of steels in an automated mode, which allows processing samples and steel products in an automated mode. The developed installation allows varying the electric-physical parameters within a wide range: to set the voltage, the duration of processing, the time of switching on and off the voltage. The unit is equipped with software for controlling the operation of the power supply using a personal computer.

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Болаттарды термоциклдік электролитті плазмалық беріктендіру технологиясы

Мақалада термоциклдік электролитті плазмалық беріктендіру технология, сонымен қатар электролитті плазмалық қыздырғыштың құрылма ерекшеліктері сипатталған. Термоциклдік электролитті плазмалық әдіспен түрлі режимдерде беріктенген орташа көміртекті болаттың қаттылығын зерттеу нәтижелері келтірілген. Болаттарды термоциклдік электролитті плазмалық беріктендіру үдерісін автоматтандырылған режимде жүзеге асыру мақсатында материалдарды термоциклдік электролитті плазмалық беріктендірудің өнеркәсіптік қондырғысы жетілдірілді. Үлгілердің бетінде шыныққан қабаттар алынды, олардың қалыңдығы орта есеппен 0,5-тен 10 мм-ге дейін, ал қаттылығының шамасы 750 HV. U_1 = 320 В және U_2 = 200 В кернеулерінде электрлік потенциалды алмастырып қосу бетті 10 мм тереңдікке дейін қыздыруға мүмкіндік беретіндігі тәжірибе жүзінде анықталды. Сонымен қатар, беттік қабаттың қаттылығының ең үлкен мәні (750 HV) беріктенген қабаттың қалыңдығына байланысты емес. Заттың беріктенген қабатының қаттылығы ең үлкен шамадан (750 HV) бастапқы күйдегі шамаға (280-300 HV) бірқалыпты өзгеріске ие болады. Жетілдірілген қондырғы электрлік физикалық параметрлерді, яғни кернеулердің шамасын, өңдеу үдерісінің жалпы уақытын, кернеуді қосу мен өшіру уақытын кең ауқымда түрлендіруге мүмкіндік береді.

Кілт сөздер: плазма, электролит, технология, құрылым, қаттылық, термоциклдік шынықтыру.

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Технология термоциклического электролитно-плазменного упрочнения сталей

В статье описаны технология термоциклического электролитно-плазменного упрочнения и особенности конструкции электролитно-плазменного нагревателя. Приведены результаты исследования твердости среднеуглеродистой стали, обработанные термоциклическим электролитно-плазменным упрочнением при разных режимах. Для проведения термоциклического электролитно-плазменного упрочнения сталей в автоматизированном режиме была разработана промышленная установка. Были получены на поверхности образцов закаленные слои со средними значениями толщины от 0,5 до 10 мм и твердости до 750 HV. Экспериментально установлено, что чередование включения электрического потенциала при напряжении U_1 = 320 В и U_2 = 200 В обеспечивает прогрев поверхности изделия на глубине до 10 мм. При этом максимальная твердость поверхностного слоя (750 HV) практически не зависит от толщины упрочненного слоя. Твердость упрочненного слоя изделия плавно понижается от максимальной (750 HV) к твердости основы (280-300 HV). Разработанная установка позволяет в широких пределах варьировать электрофизические параметры: задавать напряжения, продолжительность обработки, время включения и отключения напряжения.

Ключевые слова: плазма, электролит, технология, структура, твердость, термоциклическая закалка.

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