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HARDENED LAYER FORMING DURING NONEQUILIBRIUM PLASMA TREATMENT OF CARBON STEELS

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Results of experimental studies of changes in the mechanical and structural characteristics of the steel surface by treatment in a nonequilibrium plasma are presented. Plasma generator with liquid electrode was used as a source of nonequilibrium plasma. There are described results for the surface after the local thermal exposure accompanied by phase transformations. These data show that surface hardness after treatment in a nonequilibrium plasma may be greater of the hardness value after any other processing method. The high energy efficiency of the described material processing method is showed.

INTRODUCTION

Methods of surface hardening of steel products make it possible to greatly improve the quality of products and to achieve the specified parameters of the surface without affecting the deeper layers of the product. It causes the saving of energy resources in result. These methods include the use of plasma generators with liquid cathode.

This technological solution improves the hardness and wears resistance of the steel products at a relatively low energy costs and organizes the entire process using existing equipment with minimal changes without the applying of complex technical solutions [1, 2].

However, it is impossible to speak of a real application of a treatment method without the ability to accurately select mode for each specific case. The best solution in this case would be to create a theoretical model, which accurately describes the discharge in the metal anode and electrolyte cathode system. However, for multi-channel discharge between the surface of the electrolyte and the metal anode at atmospheric pressure, this model is not currently developed [3].

In this situation, the problem may be solved by experimental methods applying. In particular, it is important to study the pattern of the hardened layer formation with time. Study of this question is the aim of this article.

Actuality of the theme is to develop an energy-efficient method of surface treatment of steel products.

Scientific novelty lies in the fact that the patterns of the hardened layer formation in such a system are described for the first time.

THE ORETICAL ESTIMATES

The aim of this work is the thermodynamic analysis of the processes occurring in the discharge gap of nonequilibrium electron plasma generators of the type described and the study of the steel surface layer modifying possibility by the method described.

In the treated sample variation of the phase composition of the sample is due to the extreme heat and cooling of the surface layers. There may occur surface hardening or tempering layer depending of the treatment mode. The temperature distribution in the sample allows estimating the thickness of the hardened layer. The temperature distribution can be obtained by solving the heat conduction problem. It’s possible to use a uniform linear heat equation for the semi-infinite body in the context of a short duration of intense surface heat source that corresponds to the method of nonequilibrium plasma surface treatment [3],

$$c_p \rho \frac{\partial T}{\partial t} - \vec{\nabla}\left(\lambda \vec{\nabla} T\right) = 0 , \qquad (1)$$

c_p – heat capacity; ρ – density; λ – heat conductivity of material.

Initial and boundary conditions, as well as thermal properties of the sample, are required to solve this problem. It is reasonable to use the requirement of equality of material temperature to the room temperature as the initial condition. Boundary conditions must take into account the stationary heat flux from the plasma layer, convection and radiative heat transfer from the heated sample to the surrounding space.

Level of convective and radiative factors reducing of the surface temperature can be estimated as follows. In the first approximation, energy losses due to convection may be described by Newton-Richman law

$$\frac{d}{dt}\frac{\partial}{\partial S} q_{conv} = h \Delta T , \qquad (2)$$

q_{conv} – convective heat flux; h – heat transfer coefficient from the metal to the environment; for gases h = 10…100 W/(m^2·K); ΔT – temperature difference between the surface element dS and the ambient air.

Thermal radiation losses are determined by the Stefan-Boltzmann law

$$\frac{d}{dt}\frac{\partial}{\partial S} q_{rad} = \sigma T^4 , \qquad (3)$$

q_{rad} – energy radiation from the element dS; σ – the Stefan-Boltzmann constant; T – temperature of the surface.

It is known that the surface temperature reaches values up to the material melting temperature during the plasma heating process of the sample. A quotient of equations (2) and (3) estimates the degree of convection and radiation losses influence on the establishment of the sample surface temperature

$$\frac{q_{rad}}{q_{conv}} = \frac{\sigma T^4}{h\Delta T} = 2...10 \quad (4)$$

for surface temperature limit values.

Thus, the estimate (4) shows that the quantities q_{rad} and q_{conv} are comparable, and should be considered when forming the boundary conditions for the not plasma covered surface area.

Then boundary conditions take the next form for the lateral sample surface with a side

$$\left.\frac{\partial}{\partial x}T\right|_{x=\pm\frac{a}{2}} = -h\left(\left.T\right|_{x=\pm\frac{a}{2}} - T_0\right) - \left.\sigma T\right|_{x=\pm\frac{a}{2}} ,$$
$$\left.\frac{\partial}{\partial x}T\right|_{y=\pm\frac{a}{2}} = -h\left(\left.T\right|_{y=\pm\frac{a}{2}} - T_0\right) - \left.\sigma T\right|_{y=\pm\frac{a}{2}} , \quad (5)$$

where T_0 is the ambient temperature.

EXPERIMENTAL RESULTS

The unit from [3] was used for the experimentation. Steel 45 samples with 15 mm^2 cross-section were used as an anode. NaCl water solution (0.1 mass per cent) was used as cathode. The end surface was processed. The current was 2.25 A, and the discharge gap voltage was 940…1000 V during the processing.

After processing the lateral surface of the sample was ground, and then it was etched. The boundary between hardened and nonhardened layers was observed. Visualization of boundary is possible because of difference in etch capability of hardened and nonhardened layers. Then the thickness of hardened layers was measured by eye. Measurements of the hardness in hardened and nonhardened areas were provided to confirm the relationship between the real picture of the hardness distribution and visually observable differences in etching layers.

Group of samples was treated. The processing time varied from 30 to 240 seconds. After the measurements, it was found that the hardened layer is not formed for processing times of less than 1 minute. It is a uniform increase in thickness of the hardened layer for the time range from 60 to 140 seconds. The thickness of the hardened layer is practically unchanged for more treatment duration. Fig. 1 shows the results for the hardened layer thickness vs. the processing time.

The fact that the hardened layer is not formed directly, apparently due to the fact that heating of the sample to a temperature above the critical takes some time. Saturation is observed for more than 150 seconds of processing, due to the establishment of steady state heat distribution when losses through the side surface of the sample completely compensate the heat flow to the sample. To test this hypothesis, we used the model, similar to one shown in [4]. The results are shown in Fig. 2.

There is a qualitative agreement between the experimental data and simulation. In particular, the saturation is observed due to an increase in heat loss as the temperature increases. It should also be noted that the best match the experimental data with the simulation results is carried out between 30…35% efficiency, which is also consistent with earlier results obtained by us.

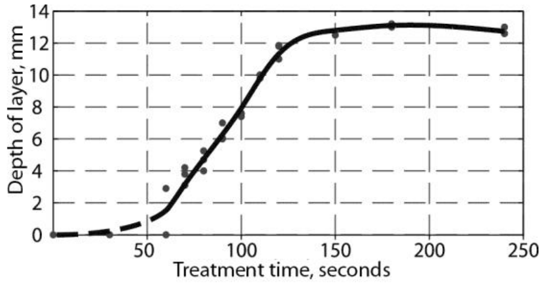


Fig. 1. The hardened layer thickness vs. the processing time

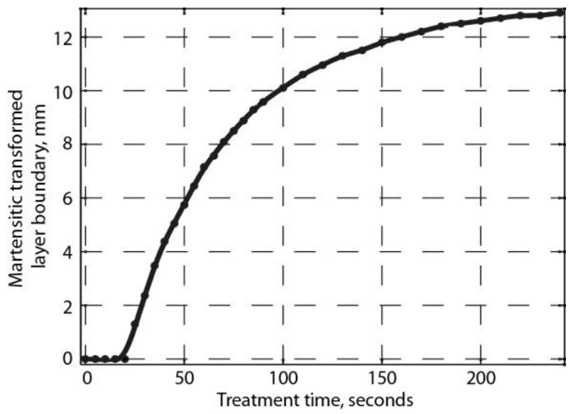
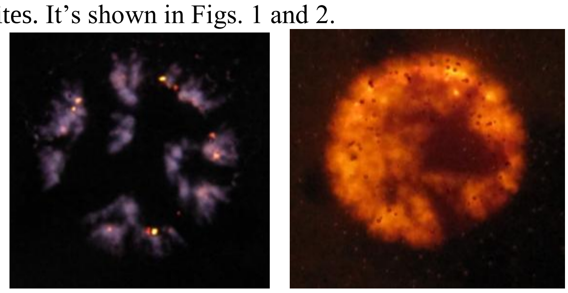


Fig. 2. Martensitic transformed layer depth vs. the processing time

Analyzing the results obtained, we can conclude that the hardened layer forming peculiarities in the steel product, treated with a liquid cathode plasma torch, is associated with nonstationary processes in the metal – liquid electrical discharge system. A typical distribution pattern of discharge channels is shown in Fig. 3.

Microstructure of the material was surveyed after treatment in a nonequilibrium plasma. The results are shown in Figs. 4, 5.

One of the steel structure features after the nonequilibrium plasma treatment is the lack of a clear boundary between the hardened and non-hardened region, as it is observed at laser quenching. Lack of clear boundaries in our case can be attributed to the fact that the heating of the surface is not uniform and reflects the transient nature of the discharge. It is well illustrated with photographs, presented in Fig. 3. This nature of the discharge has a negative property also. It is impossibility to product the micron-sized hardened sites. It's shown in Figs. 1 and 2.



a *b*

Fig. 3. The discharge channels distribution between the metal and a liquid cathode at low current (a) and high current (b)

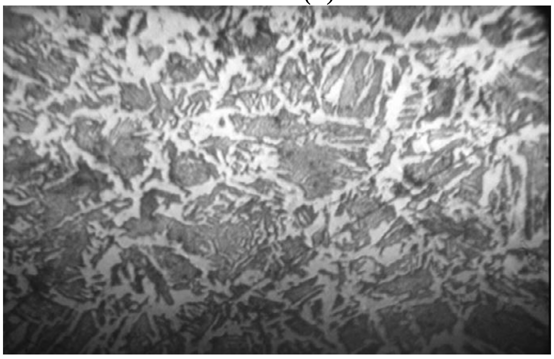


Fig. 4. Microstructure of untreated steel

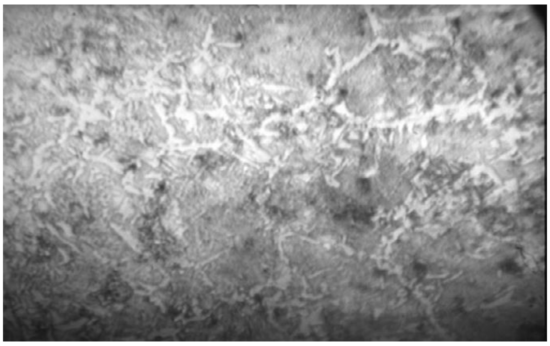


Fig. 5. Boundary layer between hardened and raw areas

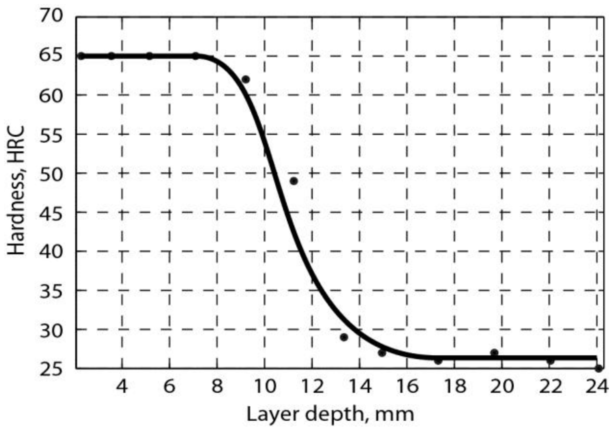


Fig. 6. Hardness of the treated sample

Estimation of the sample hardness was made by the Rockwell method. In Fig. 6 there are shown measurement data corresponding to treatment for 180 seconds.

Hardness value in this case is higher of conventional heat treatment or laser treatment ones. The treatment time, including preconditioning, is significantly reduced. Investigation of the material structure after processing in a plasma torch with a liquid electrode showed that there is no strict boundary between hardened layer and raw metal. Transition is longer in this situation. It is noticeable in Figs. 1, 2.

CONCLUSIONS

The paper analyzes the features of formation of the hardened layer in steel products during heat treatment in the plasma torch with a liquid cathode.

This processing method allows the achieving of high surface hardness, while avoiding the formation of a sharp boundary that adversely affects the properties of the product. This property of the heating parts in a nonequilibrium plasma reduces residual stresses in the hardened area.

The processing in a nonequilibrium plasma, which source is the plasma torch with a liquid electrode, is characterized by the formation of hardened layer with a thickness of 0.5 mm. It is due to the uneven heating of the surface by the discharge in the streamer.

In general, the method of surface hardening using a plasma torch with a liquid cathode shows itself suitable for industrial use.

Future research should be aimed at getting the equilibrium structure of the hardened layer in the processing of parts with a liquid electrode plasma torches.

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ФОРМИРОВАНИЕ УПРОЧНЁННОГО СЛОЯ ПРИ ОБРАБОТКЕ УГЛЕРОДИСТЫХ СТАЛЕЙ В НЕРАВНОВЕСНОЙ ПЛАЗМЕ

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Представлены результаты экспериментальных исследований изменения механических и структурных характеристик поверхности стали при обработке в неравновесной плазме. В качестве источника неравновесной плазмы рассматривается плазмотрон с жидким электродом. Проведен анализ состояния поверхности после локального теплового воздействия, сопровождающегося фазовыми превращениями. Представленные данные показывают, что твердость поверхности после обработки в неравновесной плазме может превышать значения твердости, полученные при любом другом способе обработки. Показана высокая энергетическая эффективность описанного способа обработки материалов.

ФОРМУВАННЯ ЗМІЦНЕНОГО ШАРУ ПРИ ОБРОБЦІ ВУГЛЕЦЕВИХ СТАЛЕЙ В НЕРІВНОВАЖНІЙ ПЛАЗМІ

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Представлено результати експериментальних досліджень зміни механічних і структурних характеристик поверхні сталі при обробці в нерівноважній плазмі. Як джерело нерівноважної плазми розглядається плазмотрон з рідким електродом. Проведено аналіз стану поверхні після локального теплового впливу, що супроводжується фазовими перетвореннями. Представлені дані показують, що твердість поверхні після обробки в нерівноважній плазмі може перевищувати значення твердості, що отримані при будь-якому іншому способі обробки. Показана висока енергетична ефективність описаного способу обробки матеріалів.