Structural transformations on the surface of 1.3343 tool steel and 12Cr18Ni10Ti stainless steel after induction heat treatment and quenching

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Abstract. The article describes the use of induction heat treatment for products made of 1.3343 tool steel (analogue R6M5) and 12Cr18Ni10Ti chromium-nickel steel. The changes in the surface morphology parameters as well as in hardness after strengthening heat treatment were studied. The hardness of tool steel after quenching (from 1150–1200 °C) reached 940–1080 HV (9.2–10.8 GPa). During induction treatment (temperature 800 °C and duration not less than 120 s) of 12Cr18Ni10Ti steel, a metal oxide coating with a hardness of at least 9.55±1.97 GPa was formed.

1. Introduction

In machinery and instrumentation, as well as medicine, stainless steels and tool materials are often used, e.g. 12Cr18Ni9Ti, 12Cr18Ni10Ti, 316L, AISI 1.2361, 1.3343, etc. They are used for the manufacture of tools, including the surgical ones, as well as various orthopedic designs [1], implants, functional sensor elements, metal or metal-ceramic tips of indentors for various purposes [2,3]. The surface of these products must have a special combination of physical, chemical and mechanical characteristics. The metal substrate ensures resistance to mechanical loads of a distributed type, however, when interacting with hard tissues (bone), large concentrated mechanical stresses appear. Under these conditions, the main characteristics of the surface layer are hardness and wear resistance [4-7]. In addition, the functional coating on metal implants should also have certain indicators of roughness, porosity, micro- and nanocrystalline structure. As a rule, modification of the surface of metal products is performed by vacuum-condensation or electrochemical methods, as well as by gas-thermal oxidation. In this paper, the study results of structural changes in the surface and hardness of steel samples subjected to induction heat treatment (IHT) are presented.

2. Methodology

The samples were disks with a diameter of 10–15 mm and length of 2–3 mm fabricated from 12Cr18Ni10Ti chromium-nickel stainless steel and 1.3343 tool steel (Figure 1a). Their surface was subjected to the texturing air-abrasive (corundum with an average fineness of 150–500 μm) treatment. The surface of 1.334 tool steel was modified by fine grinding and polishing in order to obtain the necessary roughness parameter $Ra = 0.08–0.16$. The resulting metal substrates of samples were also subjected to ultrasonic cleaning in an ethanol solution.

Induction heating was performed in the temperature range from 800–850 to 1200–1300 °C. The samples of carbon steel were treated with paste and since their size was small, cooling of the samples in the air with shell residues was considered to be the quenching process (Figure 1b).
Figure 1(a, b). Samples of 1.3343 tool steel: 1 – a sample; 2 – a ceramic holder; 3 – a quartz chamber; 4 – a protective shell; 5 – a copper inductor (a); as well as quenching with HFC (b).

Scanning electron microscopy (SEM) with energy-dispersive X-ray analysis (EDX) was used to study the surface morphology and chemical element composition. To test hardness, the Vickers method was used.

3. Results

SEM results of the surface of stainless steel samples showed the presence of metal oxide coatings (Figure 2a). At the IHT temperature of 800 °C, grains with an average size of 180–450 nm were formed on the protrusions of the steel surface, and those of 80–150 nm were observed in the cavities (Figure 2b). Increasing the temperature to 1000–1200 °C lead to the formation of coatings with a loose structure and low adhesion.

Figure 2(a, b). Morphology of the steel surface after IHT (a); nanostructure of the metal oxide coating (b).
The conducted chemical EDX analysis showed that in the coated samples, the main elements were Ni (42–67 at.%), Cr (29–37 at.%) and O (18–19 at.%). There were also impurities of Mn (1.2–3.4%), Fe (0.52–0.95%) and traces of Ti, Si, Al – less than 1.5 at.%.

The microstructure of tool steel had its distinctive features (Figure 3). A sample with the original structure was characterized by the presence of inclusions of refractory metal carbides, e.g. carbides of tungsten, molybdenum and chromium (Figure 3a). Their morphology was represented by round and oval formations with the size varying from 0.2–0.4 to 2–4 μm. When exposed to the temperature above 800 °C, carbides coagulated. However, when the temperature reached 1100–1200 °C, the microstructure was transformed (Figure 3b). Increased exposure promoted the formation of a carbide mesh and alloyed martensite. The chemical composition fully corresponded to that of 1.3343 tool steel (Figure 3b). The main elements were: W – 5.5–6 wt.%, Mo – 4–5 wt.%, Cr – 3.5–4 wt.%, V – 1–1.5 wt.%, C – 6.1–7.2 wt.% (elevated content typical for carbides), Fe – balance.

![Figure 3(a, b). Microstructure of 1.3343 tool steel without heat treatment (a); after high-temperature quenching with HFC (treatment temperature of 1300 °C) (b).](image)

During IHT (the temperature of 800 °C and exposure of about 90–120 s) of 12Cr18Ni10Ti steel, a metal oxide coating with a hardness of at least 9.55±1.97 GPa was formed. The hardness of 12Cr18Ni10Ti steel surface increased due to the formation of oxides of a complex composition. It is known that iron oxides are characterized by moderate hardness (5–6 levels according to the Mohs scale of hardness). Thus, high hardness values can be ensured by the oxides of alloying elements, e.g. chromium, nickel and titanium.

In the course of quenching of 1.3343 tool steel, the hardness also grew to 68–72 HRC (Figure 4). High hardness was achieved at a lower HFC quenching temperature. Thus, at T = 600 °C the steel hardness was maintained at the initial value of about 35 HRC. However, with an increase in the quenching temperature to T = 800 °C the hardness equaled 42–44 HRC. These hardness values do not show that steel could be used for a metalworking tool. Therefore, the quenching temperature must be above the phase transition, i.e. it must be at least T = 1000 °C. At this temperature the hardness reached 66–67 HRC, which is typical for high-speed tool steels of the tungsten-molybdenum group. However, due to quenching with HFC higher hardness values can be achieved, so at the temperature T = 1200 °C the hardness of steel reached 70–72 HRC. At the same time, an increase in the exposure duration at a given temperature did not contribute to an increase in hardness. Thus, it is possible to limit the duration of heat treatment with HFC to one cycle of heating and quiescent cooling.
Figure 4. Dependency of hardness HRC of tool steel on the temperature $T$ and exposure time $t$ of the quenching with HFC.

At the high temperature induction treatment (quenching) of 1.3343 tool steel, the microstructure changed (carbides were allocated along the grain boundaries and martensite appeared). This was accompanied by an increase in hardness to 940–1080 HV (equivalent to 9.2–10.8 GPa).

4. Conclusions
Thus, the use of strengthening induction treatment of steel products ensured the formation of the required micro- and nanostructure of the surface and the near-surface layer. As a result of IHT the hardness of tool steel grew, however, to increase the hardness of stainless steel, it is necessary to provide the conditions for the formation of a metal oxide coating (gas-thermal oxidation).

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References
[1] Rodionov I V, Fomin A A, Fomina M A, Poshivalova E Yu and Zakharevich A M 2015 Proc. SPIE Microtechnologies 2015 (Barcelona, Spain), 9519 p 951917
[2] Aman S, Aman A and Morgen W 2013 Comp. Sci. Technol. 84 58
[3] Majcherek S, Aman A, Hirsch S and Schmidt B 2015 Sensors and Actuators A. 233 267
[4] Koshuro V A, Nechaev G G and Lyasnikova A V 2014 Tech. Phys. 59 1570
[5] Xiong J, Guo Z, Yang M, Wan W and Dong G. 2013 Ceram. Int. 39 337
[6] Wang B. and Liu Z. 2016 Int. J. Refract. Met. Hard Mater. 55 24
[7] Brzhovskii B, Martynov V, Žinina E and Brovkova M. 2016 IOP Conf. Series: Mater. Sci. Eng. 116 012007