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Influence of Heat Treatment Technologies on the Structure and Properties of the Corrosion-Resistant Martensitic Steel Type AISI 420

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Abstract. One of the methods for increasing the complexity of chromium steel properties of martensitic class AISI 420 is the use of an optimal heat treatment mode. The steel of martensitic class AISI 420 has high resistance in atmospheric conditions (except for the sea atmosphere), in the river, and tap water. It is widely used in power engineering, in cracking units with a long service life at temperatures up to 500 °C, for furnace parts. Additionally, it is used in the following fields: the production of turbine blades, working in conditions of high temperatures and parts of increased plasticity, subject to shock loads, for products exposed to atmospheric precipitation, solutions of organic salts and other slightly aggressive environments; production of fasteners; production of parts for compressor machines operating with inert gas; production of parts operating at low temperatures in corrosive environments; production of parts for aviation purposes. It is shown that the optimal mode of heat treatment for a maximum hardness of 40 HRC is quenching at a temperature of 980 °C with cooling in oil and tempering at a temperature of 200 °C with air cooling. With an increase in the tempering temperature from 200 °C to 450–500°C, the impact strength does not change much. Tempering at higher temperatures leads to the intense weakening of the steel. Simultaneously, a decrease in the impact strength is observed, the minimum value is reached at a tempering temperature of 550 °C. With an increase in the tempering temperature to 700 °C, the impact toughness increases, but the steel's hardness sharply decreases at such temperatures.

Keywords: hardening, tempering, hardness, toughness, mechanical properties, chromium carbide.

1 Introduction

The active expansion of machine-building activities in Ukraine requires new technologies for obtaining the necessary properties for products operating in an aggressive

need for the development of materials is required, particularly steels with a unique combination of mechanical properties, including strength, ductility, cold resistance, resistance to various types of corrosion, and corrosion-erosion destruction, wear resistance. This combination of properties should ensure the high operational reliability of equipment, structures for multiple purposes in the conditions under consideration and is also essential for other types of equipment, including loaded parts used in aviation, mechanical engineering, and other industries.

Analysis of world experience shows that corrosion-resistant chromium steels of the martensitic and/or martensitic-austenitic class with a low carbon content, for which specific heat treatment modes were used, are promising for achieving the specified set of properties. …igh hardness, strength, …al corrosion [1].

Martensitic stainless steels play a huge and often invisible part in our modern world due to their combination of strength, toughness, and good corrosion resistance. They have good strength after quenching and tempering, like simple carbon steel, and therefore find application mainly in the manufacture of cutting tools [2], cutlery, and others [3–5].

Martensitic stainless steels are widely used as a material in the manufacture of products for work in mildly aggressive environments: atmospheric conditions, except for sea; aqueous solutions of salts of organic acids at room temperature; solutions of nitric acid of low and medium concentration at moderate temperatures, etc. parts of oil and gas equipment, which are prone to corrosion, high contact loads and temperatures during operation. These critical parts' precision surfaces are subject to increased requirements for the cleanliness of processing, strength, and wear resistance.

The most widely used martensitic steel grades are AISI 420, AISI 420F, and AISI 420S [3, 5].

The steel of martensitic class AISI 420 has high resistance in atmospheric conditions (except for the sea atmosphere), river, and tap water. It is used in power engineering, in cracking units with a long service life at temperatures up to 500 °C for furnace parts. Due to its heat-resistant and other characteristics, chromium steel AISI 420 is widely used in the following areas: mechanical engineering; manufacture of furnaces and turbine blades operating at high temperatures; production of parts with increased ductility, subject to shock loads, for example, valves of hydraulic presses; production of products that are susceptible to the effects of atmospheric precipitation, solutions of organic salts and other slightly aggressive environments; production of fasteners; production of parts for compressor machines operating with inert gas; production of parts operating at low temperatures in corrosive environments; production of parts for aviation purposes.

One of the main directions of increasing the complex properties of modern high-strength chromium steels of martensite class with chromium content at the 13–16 % level is heat treatment, which consists of hardening and tempering to a given hardness [1, 3].

Different types and modes of heat treatment affect the properties of materials in different ways. Quenching and tempering temperatures depend on the level of required mechanical properties. Based on the above, the selected topic for research is relevant and modern. Therefore, the choice of appropriate heat treatment modes is an important task to achieve a given level of strength in combination with the necessary resistance to brittle fracture at various temperatures. This solution will allow you to master the production of products that work in any operating conditions.

2 Literature Review

Heat treatment technology assumes the choice of operations and modes of heat treatment according to the conditions of processing and operation of machine parts, structures, tools, and the requirements for the structure and properties of materials standards and technical conditions [3, 5]. The influence of various types and modes of HT on the properties of steel AISI 420 was investigated by the authors of [1–12].

A right combination of AISI 420 steel's mechanical properties can be achieved by optimizing the heat treatment process (temperature and time of austenitizing and tempering). The authors of [3] have shown that the corrosive properties of this type of steel do not affect the optimization of heat treatment conditions, and the maximum value of hardness (~ 50 RC), strength (about 1900 MPa), and impact strength (~ 30 J) are due to the processes during austenitization at a temperature of 1050 °C.

The authors of [4] considered austenitizing heat treatment on the microstructure and hardness of martensitic stainless steel AISI 420. Steel samples were austenitized at temperatures from 1000 to 1200 °C, followed by quenching in oil. It was found that after such heat treatment, the microstructures of the samples change from almost entirely martensitic to martensitic with the presence of austenite up to 35 % and different amounts of carbides after quenching.

In [5], when studying the effect of heat treatment on the mechanical properties and microstructure of martensitic stainless steel AISI 422, the following results were obtained: with an increase in the austenitizing temperature from 1040 °C to 1070 °C, the impact energy decreases, and the hardness and yield strength increase, which is due to an increase in the size austenite grains; secondary hardness occurs at a tempering temperature in the range of 400–500 °C, that is, after tempering, an increase in hardness and strength and a decrease in toughness occurred in the samples; with an increase in the hardening time from 2 to 5 hours at a temperature of 700 °C, the toughness increased, and the hardness and strength decreased due to the deposition of carbides.

The authors of the work [6] studied the mechanical properties of welded martensitic stainless steel (AISI 420) under various heat treatment. The best results from the side appearance of the microstructure of epitaxial grains, which were observed along the boundary of the weld metal section, is the obtained maximum hardness of 414 HV in conventional heat-treated samples that were quenched at 200 °C. The deposition of fine carbides was also observed, which is responsible for improving the material's mechanical properties. The microhardness was highest in the melting zone.

When studying the effect of rapid quenching on the microstructure, mechanical and corrosion properties of martensitic stainless steel AISI 420 in [7], all samples were austenised 1050 °C for 1 hour and quenched at 200 °C for 1 hour. The samples were quickly heated with a salt bath oven in the temperature range from 300 to 1050 °C for 2 min and cooled in air. Tensile, impact, hardness, and galvanic corrosion tests on reheated specimens showed that minimum properties such as tensile strength, impact energy, hardness, and corrosion resistance were obtained at a reheating temperature of 700 °C. Carbides were observed at this temperature along with the grain boundaries. The secondary solidification phenomenon occurred at a heating temperature of 500 °C.

In [8], experiments were carried out with low-energy irradiation of AISI 420 stainless steel samples with protons of different energies, preliminarily annealed or quenched at temperatures of 600 or 700 °C. The results obtained show that the microstructure's dislocation density near the surface of AISI 420 stainless steel increases with increasing energy irradiation with protons.

The authors of [9] investigated the effect of heat treatment on the microstructure and corrosion resistance of martensitic stainless steel. The results obtained show a strong dependence of the corrosion behavior on heat treatment, the regimes of which influence the corrosion mechanism in different ways.

The authors investigated the effect of austenitizing heat treatment on the microstructure and hardness of martensitic stainless steel AISI 420 [10–12]. These attemnpts were done for providing users with heat treatment recommendations that will offer a martensitic structure with a minimum austenite content, uniform carbides in fineness, and a hardness of 610 to 740 HV after quenching and tempering. It has been established that hardened microstructures have hardness values in the hardening mode from 700 to 270 HV, depending on the amount of retained austenite.

In [13], the influence of various cyclic treatments on the structure and properties of AISI 410 steel is considered. The microstructure and mechanical properties of martensitic stainless steel AICI 410 after different heat treatments were studied to restore hardness and improve the grain structure during material processing. The results show that the steel structure after HT at a temperature of 1020 °C has lamellar martensite mixed with a small retained austenite. The result indicates that quenching and tempering according to the schemes (500, 600, and 700 °C) improve the hardness and grain refinement, which leads to the existence of finely distributed carbides in the AICI 410 steel.

3 Research Methodology

3.1 Research objectives

Steel AISI 420 is the corrosion-resistant heat-resistant steel, refers to chromium stainless steels of the martensitic class and is used in cases where products must have sufficiently high strength, as well as high ductility and toughness: power engineering and furnace construction; turbine blades, bolts, nuts, fittings of cracking units with a long service life at temperatures up to 500 °C. Steel AISI 420 is included in steels of type AISI 410 – AISI 422. It occupies its own range in terms of carbon content – from 0.16 to 0.25 %, the amount of other alloying elements and impurities - the same as in other steels of AISI 420 type [14] (Table 1).

Table 1 – Chemical composition of steel AISI 420, %

C	Mn	Si	Cr	Ni	Mo	P	S
0.16–0.25	≤ 0.6	≤ 0.6	12–14	≤ 0.6	0.15–0.30	≤ 0.030	≤ 0.025

The main alloying element of this type of steel is chromium. It is thanks to him that it is resistant to corrosion when working in an oxidizing environment. Corrosion resistance is also due to the presence of a very dense protective film on the steel. The highest degree of corrosion resistance of AISI 420 steel is achieved through heat treatment. Steel AISI 420 has good workability in hot plastic deformation.

Steel AISI 420 belongs to martensitic steels; after hardening, the steel's microstructure contains martensite and carbides. When using annealing, the steel structure changes to a mixture of high-chromium ferrite and carbide of the $M_{23}C_6$ type.

3.2 Methods of research

The values of the mechanical properties, hardness, and structure of the studied samples from steel AISI 420 were obtained using standard methods using a metallographic microscope MIM-7, a Rockwell hardness tester, and a magnetic tester.

When carrying out microscopic analysis of samples made of steel AISI 420, a metallographic microscope a microscope MIM 7 was used, intended for observing and photographing the microstructure of metals in ordinary light in a bright and dark field and in polarized light in a bright field.

The hardness tester for measuring hardness TP-5006 is designed to measure the hardness of metals and alloys by the Rockwell method, plastics, graphite and metallographite, plywood, pressed wood, and other materials. The depth of penetration determines Rockwell hardness into a diamond cone's test material with an apex angle of 120°. The method for determining a metal's impact toughness is based on the destruction of a sample with a notch with one blow of a pendulum impact machine MK-30A.

Technological processes for the heat treatment of steel (selection of operations and modes) are based on the theory of phase transformations during heating and cooling. Heat treatment modes for specific materials are selected based on operating conditions and required properties. Martensitic steels containing 13 % chromium are usually used in the state after quenching and tempering [3–5, 11, 12, 14].

Therefore, for AISI 420 steel, heat treatment in order to improve the structure and increase the properties also consists of quenching and tempering. Heat treatment is carried out considering the following points [3, 5, 14, 15]:

1. Due to the high heat resistance, hardening is carried out at a temperature of about 980–1100 °C.

2. Forging is carried out at a temperature of 780 °C. In this case, heating is performed gradually, which eliminates the possibility of structural deformation during plastic deformation.

3. Annealing is considered a softening type of metal processing.

4. After quenching, cooling is carried out in various environments (air, oil, or water).

5. With an increase in the tempering temperature to 450 °C, the plasticity can be significantly increased, but the hardness of the surface layer decreases. However, this effect leads to a decrease in corrosion resistance.

In order to study the effect of different tempering temperatures on the structure and hardness of AISI 420 steel, the samples were hardened at a temperature of 980 °C with cooling in oil or in air. Then, tempering was carried out at various temperatures, followed by cooling in air.

When carrying out experiments to study the effect of heating temperature during quenching on mechanical properties, specimens of steel AISI 420 were heated in a shaft electric furnace in the temperature range from 930 to 1040 °C, followed by cooling in air or water. Vacation lasting 1.0–1.5 hours was carried out in the range from 500 °C to the temperature of austenite formation (A_{C1}). After tempering, cooling was carried out in the air.

4 Results

4.1 Preliminary heat treatment of steel AISI 420

Heat pretreatment is necessary to relieve internal stress, refine grain structure, and eliminate other low carbon and alloy steels' defects. Annealing at a temperature of 980 °C followed by cooling in a furnace at a 50 °C/h was used as preliminary heat treatment of AISI 420 steel (Fig. 1).

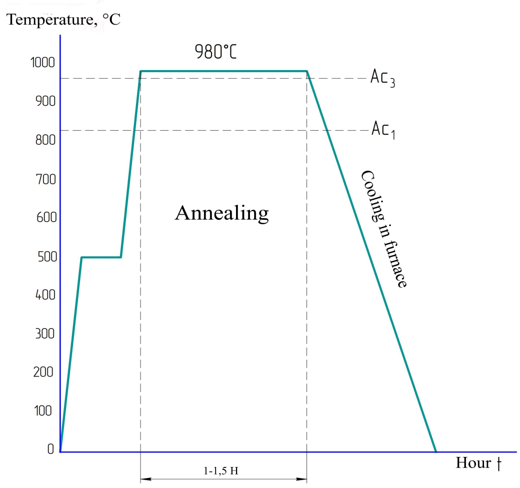

Figure 1 – Schedule of preliminary heat treatment for steel AISI 420

The microstructure of AISI 420 steel after annealing is shown in Figure 2.

Figure 2 - Microstructure of AISI 420 steel in the vertical direction at 980 °C, ×200

In the process of annealing, which consists of heating above A_{C3} by 30–50 °C, followed by slow cooling in a furnace, phase recrystallization occurs.

Upon annealing, the state of steel approaches only the equilibrium state; steel structure after annealing: pearlite + ferrite and carbides. Grinding grain was obtained in comparison with the initial state. The uniformity of the metal has improved and, consequently, gives more favorable consequences for further strengthening by further heat and mechanical treatment. The part has a set of corresponding physical and mechanical properties.

4.2 Study of various heat treatment technologies for steel AISI 420

4.2.1 Influence of different tempering temperatures on the structure and hardness of steel AISI 420

In the process of heating for quenching, austenite is formed, and carbides dissolve. Upon cooling, martensite is formed, and in many cases, complex carbides are precipitated [11, 12]. The amount of the carbide phase in the hardened state depends not only on the chemical composition but also on heating and cooling conditions during heat treatment.

For steel AISI 420, when fully hardened for 30 minutes through hardenability is ensured, and a completely martensitic structure is obtained after rapid cooling. To obtain the required ratio of strength and ductility, such an alloy is subjected to additional tempering heat treatment after quenching. As you know, tempering is a heat treatment aimed at reducing internal stresses in alloys after quenching with polymorphic transformation. [3, 5, 14, 15]. Such a restructuring begins with heating. Therefore, tempering was carried out at various temperatures of 700 °C, 650 °C, 600 °C, 550 °C, 500 °C, 400 °C, 300 °C, 200 °C with the holding of 1.5 hours and air cooling.

The applied modes of heat treatment and the results of measuring the hardness are presented in Table 2. They are in good agreement with the literature data [1, 3, 11, 13].

The microstructures of steel grade AISI 420, which are formed as a result of the modes according to table 2 during quenching and various types of tempering with air cooling, are shown in Figure 3.

We conclude that the optimal mode of heat treatment for maximum hardness: hardening at 980 °C with cooling in oil and holding for 30 minutes considering the depth of calcination and tempering at 200 °C and holding 1.5 hours with air cooling.

The results of testing the mechanical properties after different tempering temperatures are shown in Table 3 and show that with an increase in the tempering temperature from 200 °C to 450–500 °C, the impact strength does not change much.

Table 2 – Hardness of samples after various types of heat treatment

Mode No.	Type of HT	Hardness HRC
1	Quenching (980 °C) oil	43
2	Quenching (980 °C) air	40
3	Quenching (980 °C) oil; Tempering (700°C) air	19
4	Quenching (980 °C) oil; Tempering (650°C) air	21
5	Quenching (980 °C) oil; Tempering (600°C) air	22
6	Quenching (980 °C) oil; Tempering (550°C) air	24
7	Quenching (980 °C) oil; Tempering (500°C) air	26
8	Quenching (980 °C) oil; Tempering (400°C) air	37
9	Quenching (980 °C) oil; Tempering (300°C) air	32
10	Quenching (980 °C) oil; Tempering (200°C) air	40

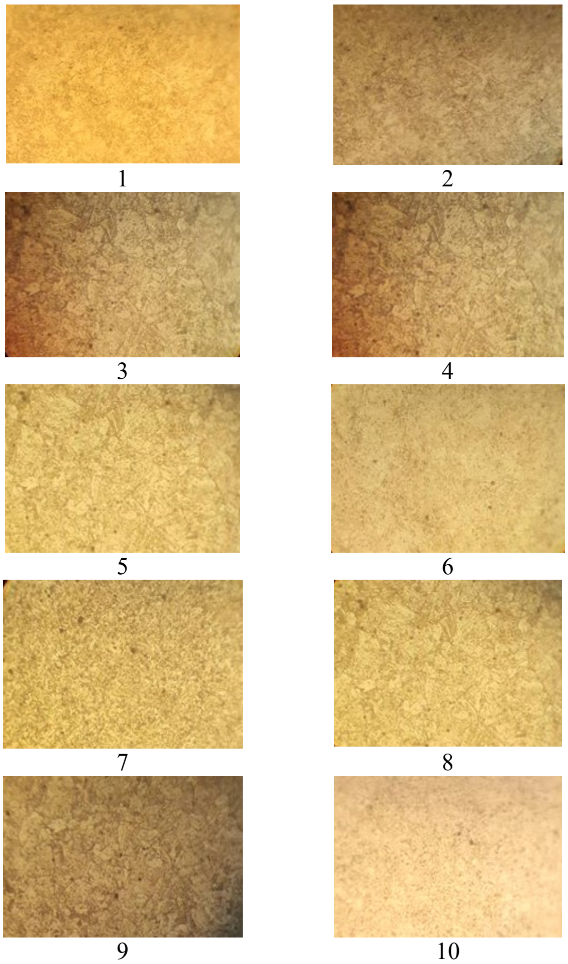

Figure 3 – Microstructures of steel grade AISI 420, which are formed as a result of modes according to Table 3 during quenching and various types of tempering with air cooling (×500)

Tempering at higher temperatures leads to intense softening of the steel. Simultaneously, a decrease in impact toughness is observed, reaching a minimum value at a tempering temperature of 550 °C.

Table 3 – Impact toughness of hardened AISI 420 steel samples after tempering at different temperatures

Tempering temperature, °C							
200	300	400	500	550	600	650	700
KCU, kJ/cm^2							
96	98	79	73	67	72	95	104

The macrostructure of the specimens after impact testing is shown in Figure 4.

Figure 4 – Macrostructure of a specimen tested for impact toughness after quenching and high tempering

A decrease in toughness is observed after tempering at 500–600 °C, which is caused by the phenomenon of secondary hardness. In steel at these temperatures, carbides precipitate mainly along the grain boundaries (Fig. 5 a). At higher tempering, the steel structure is sorbitol, with carbides evenly distributed over the entire intersection (Fig. 5 b). In this case, the impact strength increases, but at such temperatures, the steel's hardness decreases sharply.

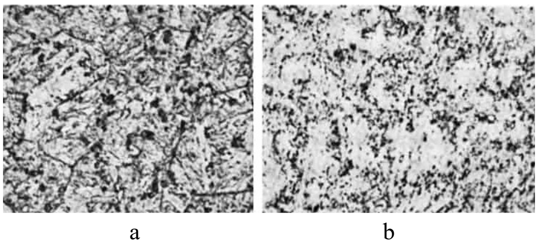

Figure 5 – Microstructure of steel AISI 420 after quenching from 980 °C (×500): tempering at 500 °C (a) and 550 °C (b)

4.2.2 Study of the effect of heat treatment modes on phase transformations and mechanical properties of steel AISI 420

Figure 6 shows the effect of the heating temperature for quenching on the investigated steel's hardness after cooling in air and water. It can be seen that an increase in temperature from 920 to 1020 °C after cooling in the air is accompanied by a regular increase in hardness (from 42 to 49 HRC) associated with a solution of chromium carbides $Cr_{23}C_6$.

Thus, under certain treatment conditions after air and water quenching cooling, the same hardness is achieved, which has a value of 48 HRC. This indicates the formation in both cases of the martensitic structure shown in Figure 7 and is confirmed by the literature [2, 10–12, 14].

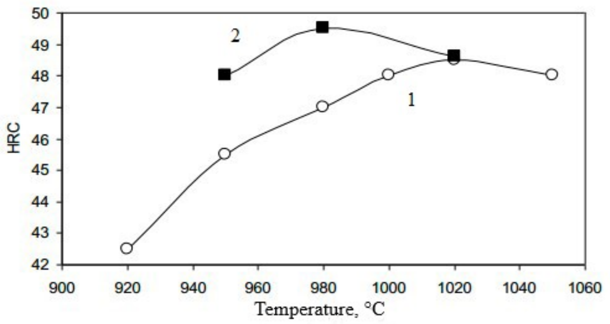

Figure 6 – Influence of the heating temperature for quenching on the hardness of steel AISI 420 after cooling in the air (1) and in water (2)

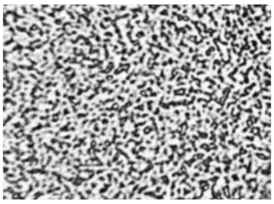

Figure 7 – Microstructure of steel AISI 420 after quenching at 1000 ° C (×500)

During isothermal holding or slow cooling in the range 800–550 °C after austenitization, the steel undergoes austenite decomposition into a ferrite-carbide mixture, which consists of high-chromium ferrite and $Cr_{23}C_6$ type carbides.

For steel AISI 420, an increase in hardness is characteristic, increasing the hardening temperature to 1020 °C. When quenched from temperatures above 1020 °C, the amount of retained austenite increases markedly. At temperatures above 1100 °C, no further increase in retained austenite is observed.

The microstructure of AISI 420 steel, which is formed as a result of quenching upon cooling in air, is structureless martensite. A certain amount of particles are present, do not dissolve during austenitization of the carbide phase.

For reducing the grain size of the investigated steel, further heat treatment was carried out using a lower heating temperature for hardening (960 °C). This led to a slight increase in the dispersion of the structural components. The average grain size decreased from 50 μm to 15 μm.

With a decrease in the quenching temperature from 1000 °C to 960–940 °C, the strength properties of steel AISI 420 slightly decrease, associated with the incomplete dissolution of chromium carbides during austenitization (Table 4). A more significant effect of lowering the hardening temperature is made on the value of impact toughness. A decrease in the hardening temperature from 1000 °C to 960–940 °C led to an increase in the values of impact strength at room temperature, compared with the previously used mode.

Table 4 – Mechanical properties of steel grade AISI 420 after heat treatment in laboratory conditions

Heat treatment	Mechanical properties			
	$[\sigma]$, MPa	$[\sigma]_{0.5}$, MPa	δ %	KCU, J/cm^2
Quenching 1000 °C; Tempering 700 °C	751	572	24.0	53
Quenching 960 °C; Tempering 700 °C	761	595	23.0	95
Quenching 940°C; Tempering 700 °C	750	578	22.0	101

When tempering high-chromium steel AISI 420, hardened from 950 or 1000 °C, there is a small secondary hardening temperature of 500 °C.

A further drop in hardness is probably since the Cr_7C_3 carbide is transformed into the $Cr_{23}C_6$ carbide [3–5, 12, 14–16].

5 Conclusions

Optimum heat treatment for maximum hardness 40 HRC: hardening 980 °C with cooling in oil and holding for 30 minutes considering the depth of hardenability and tempering at 200 °C and holding 1.5 h with air cooling.

Testing the mechanical properties after different tempering temperatures shows that with an increase in the tempering temperature from 200 to 450–500 °C, the mechanical properties do not change much. Tempering at higher temperatures leads to the intense weakening of the steel. Simultaneously, a decrease in impact strength is observed, reaching a minimum value at a tempering temperature of 550 °C.

It is shown that with an increase in temperature from 920 to 1020 °C after cooling in air, a regular increase in hardness (from 42 to 49 HRC) is observed, associated with the dissolution of chromium carbides $Cr_{23}C_6$.

Under specific processing modes, after air and water quenching cooling, the same hardness is achieved, equal to 48 HRC, which indicates the formation of a martensite structure in both cases.

A decrease in the hardening temperature from 1000 °C to 960–940 °C led to increased values of impact strength at room temperature.

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