INFLUENCE OF CYCLIC HEATING MODES ON THE WEAR RESISTANCE OF STEEL

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Abstract - The heat treatment technology has been improved, which makes it possible to increase the wear resistance of parts of working parts by 30-40%, operating under conditions of metal-to-metal friction using preliminary cyclic heating and then pulse hardening. When using the cyclic heat treatment method, the intensity of the diffusion transformation mechanism increases due to repeated accelerated heating and cooling in the stage of incomplete austenite recrystallization and grain growth that has not yet been formed. It has been established that during preliminary reheating, this thermally stable dislocation serves as a source that forms a new dislocation at the α - γ - α transition. It was determined that the value of the highest degree of the defect in the crystal structure of steel grade 65G should be preliminarily subjected to three-fold cyclic heating in the temperature range of 450-500°C in the range of 4-5 seconds. As a result of cyclic heating, a lamellar structure was formed in the steel structure and this structure is thermally stable.

Keywords: Heat treatment, Dislocation density, Extreme temperature, Low-alloy steel.

1. Introduction

Agricultural engineering enterprises of the Republic of Uzbekistan are constantly increasing the production of cotton pickers. During the operation of this equipment, as a result of abrasive wear, such parts as gears and gear shafts fail, as a result of which a large amount of metal is consumed annually for the manufacture of spare parts. Every year, machine-building equipment becomes more complex, and a powerful repair base is needed to ensure its effective use.

The performance of gears largely determines the durability of their teeth. Gears are usually made of low carbon steel (carbon content 0.1÷0.25%) and subjected to heat treatment - carburizing, hardening and low tempering. Reducing the processing time provides cementation in a gaseous environment. This consumes a lot of electricity and gaseous hydrocarbons [1].

In subsequent years, researchers have proposed various options for heat treatment of gears, including multiple heating and cooling, mainly above the phase transformation point. This treatment was called thermal cycling [2].

An analysis of published materials in recent years in the field of heat treatment shows [4–7] that cyclic heat treatment is currently widely used to improve the structure and properties of steels. On the basis of cyclic heat treatment of steels, some of their mechanical properties are improved, the result obtained is quite effective in comparison with conventional heat treatment technology [5]. In this work, special attention is paid to increasing the wear resistance of steels after cyclic heat treatment. The possibilities of ensuring the wear resistance of steel parts without changing their chemical composition are considered.

An effective result has been achieved by applying methods that increase the intensity of many physical and chemical processes by using the features of internal structural transformations and the nature of steels.

When using the cyclic heat treatment method, the intensity of the diffusion transformation mechanism increases due to repeated accelerated heating and cooling in the stage of incomplete austenite recrystallization and grain growth that has not yet been formed. The purpose of this method is to obtain stable austenite due to the refinement of structural grains and the redistribution of dislocations using induction heating at high temperatures. As a result of the accumulation of structural transformations, due to phase transformations, it became possible to obtain a structure that cannot be formed by conventional methods of heat treatment of steels.

2. Method

From the point of view of improving properties, the effectiveness of cyclic heat treatment is determined by its order, the number of cycles, the rate of heating and cooling, and the chemical composition of the steel. During cyclic heat treatment, under conditions of polymorphic transformations, and in the absence of such transformations, it was found that during heating and cooling of steels, the regularities of phase transformations act [7].

To solve the problem of an additional increase in the wear resistance of low-alloy steels, it is necessary to improve the technology of heat treatment of steels by studying the features of their structure. Including after determining the structural indicators and the quantitative ratio of the wear resistance index of steels under the conditions of metal-to-metal friction after preliminary cyclic heat treatment, using the method of preliminary cyclic heating and then completed induction heat treatment, which contributes to the maximum use of the nature of steel to increase its wear resistance [6].

The wear resistance of steels, as a rule, largely depends on the hardness and density of dislocations in the bulk of the material [8].

It was found that it is possible to further increase the wear resistance of steels using non-standard heat treatment modes, which consists in creating favorable combinations of structural parameters of the material at the maximum hardness already achieved for them.

According to [5-6, 9-10], cyclic hardening can significantly change the dislocation density in the material, which will increase wear resistance and change other indicators of its mechanical properties.

The object of the study are samples of low-alloy steel grade 65G, obtained in industry by casting, the chemical composition of which is given in Table. 1. A sample of armco iron was used as a reference material.

Samples with dimensions of 20×20×7 mm were processed using different thermal regimes. The control sample was the one that underwent traditional induction heating to a temperature of 900°C, cooling in oil, and tempering at a temperature of 180°C. The samples under study were heated to temperatures T = 450, 570, and 700°C; the largest number of cycles reached 7. The heating temperature was chosen based on the existing modes of thermal cycling. After each heating, cooling was performed in air under a fume hood (the traditional method of cooling in industrial plants). After the last heating to a temperature of 950°C, the sample was quenched in oil and tempered at a temperature of 180°C. To register structural changes during processing, some of the samples did not undergo final hardening and tempering. For heat treatment, a modern VCHG2-100/066 installation for induction heating was used.

Table 1. Chemical compositions of the investigated steel 65G and control 18XGT

Steel	Chemical element, % wt.						
	C	Si	Mn	Cr	Ti	S	P
65G	0,68	0,25	1,15	–	–	0,03	0,03
18XGT (control sample)	0,31	0,29	1,00	0,98	0,1	0,02	0,02

For uniform heating of the samples, the temperature change was 110–120 °C/s. To assess the temperature-time factor during cyclic hardening, a thermocouple was soldered to the sample, connected to a fast-acting potentiometer for temperature recording.

To compare production data at Agregatny Zavod JSC, selected samples of 18KhGT steel (see Table 1) were subjected to carburizing in shaft furnaces together with a cage of gears. Carburizing of gear teeth was carried out at a temperature T = 900–950 °C for 8–10 h.

To study the structure, metallographic and X-ray diffraction analyzes were used. Metallographic analysis was carried out on a Metrochm 850 Professional IC (SEM-EDX) ion chromatograph, as well as Zeiss EVO MA 10 / AztecEnergyAdvanced X-Act scanning electron microscopes with a magnification of 100 × 1000 times [11].

The state of the soft structure was studied using X-ray diffraction [12]. X-ray patterns were obtained on a Shimadzu X-ray spectrum analyzer using the same steel standards. The radiation of an iron anode was used. The physical width of X-ray lines was determined from graphs corrected by the approximation method. The physical width βav of the x-ray line (220) was determined, which was taken as a measure of the imperfection of the crystal lattice. The dislocation density was calculated from the physical broadening of X-ray interferences.

3. Results and Discussion

Wear tests were performed by sliding friction over loose abrasive material on a PV-7 unit [7]. The abrasive material was pulverized quartz sand, which was fed in portions using a dispenser to the surface of the sample and a polyurethane screw. The choice of installation and method for testing for abrasive wear was due to previous studies, which showed that wear resistance tests on the PV-7 machine are close to field wear of the coulter compactor of a cotton seeder in the fields of Uzbekistan - the location of materials and the values of relative wear resistance coincided [13]. The latter was determined by comparing the weight loss (mass Q wear) of the control sample, which was weighed before and after testing on an analytical balance VLA-200M (accuracy up to 0.1 mg); the repeatability of the experiments was.

As studies have shown, the wear resistance of the primary structure of steels is mainly influenced by lamellar structures. At the same time, technological measures aimed at increasing wear resistance were aimed at creating primary structures that are little transformed during friction.

Hardening of the metal to the expected depth by heating the steel with high-frequency current, high productivity and high mechanical properties of the products obtained, the absence of scale on the surface of the product and the possibility of hardening the surface of the product of any shape are the basis for the use of cyclic heat treatment in the heat treatment of steels.

The technology of heat treatment by induction heating using high-frequency current is proposed, resulting in a structure that is convenient for further processing.

The completed cooling of cyclically heat-treated steels by supplying cooling air contributes to the formation of the initial structure in the form of a lamellar one [13]. A complete lamellar structure was formed as a result of cyclic heating of steel 65G at a temperature of 450 °C. In the modes of other heating temperatures, such a fully formed structure was not observed.

As analyzes of the state of the structure of the pre-heat-treated steel using complete induction heating at different temperatures show, after preliminary cyclic heat treatment of steel 65G within the subcritical temperature, the level of defectiveness of the crystalline structure of steel depends little on temperature and the number of cycles [10]. It was found that when heated in the zone above the critical temperature Ac_1 and cooled with the help of cooling air, a structure was formed with slight changes, and the level of defectiveness of the crystal structure turned out to be different in comparison. Accurate results were observed after completion of induction hardening and tempering at low temperatures (Table 2).

Table 2. Change in the level of defectiveness of the crystal structure of steel 65G after preliminary cyclic heating, hardening by completed induction heating and tempering at a temperature of 180 °C (physical width of the x-ray line 220)

№	The number of cycles	Physical X-ray line width, $\beta\cdot 10^{-3}$ rad	Average value, $\beta\cdot 10^{-3}$ rad	Hardness, HRC
Heating at temperature 450 °C				
1	1 cycle	63,4; 64,45	66,42	59,5
2	3 cycles	64,5; 71,68; 70,36	68,91	60
3	5 cycles	73,9; 69,0; 69,5	70,8	59,5
Heating at temperature 700 °C				
1	1 cycle	71,69; 69,0	70,0	59,5
2	3 cycles	63,66; 64,0	63,87	60
3	5 cycles	63,0	63,0	59
Heating at temperature 800 °C				
1	1 cycle	60,5	60,5	59
2	3 cycles	63,9	63,9	59
3	5 cycles	60,76; 62,99	61,87	59,5
4	Hardening + tempering at a temperature of 180°C of the primary sample	64,98	64,98	59,5

Somewhat different results occurred with final induction hardening and low tempering. With different variants of heat treatment, the samples had the same microstructure, grain size and hardness (600÷620 HB), they differed in the degree of crystalline imperfection. A positive effect is observed after 3-5 cycles of heating the samples to a temperature of 450°C (Fig. 1). At temperatures of 550 and 700 °C, the crystal imperfection is or lower, or this effect is not stable. This can be explained by microplastic deformation as a result of significant temperature differences. The presence of the second phase also contributes to microplastic deformation due to the difference in thermal expansion of the phases.

The effective results obtained can be explained by the fact that conditions are created for microplastic deformation due to rapid heat transfer using cyclic heating. The formation of the second phase contributes to the formation of microplastic deformation by expanding the possibilities of the heat treatment phases. As a result, a dislocation structure develops, and an increase in temperature leads to polygonization. In a polygonized structure, it provides stability at high temperatures, although the crystal structure does not have a high degree of defectiveness.

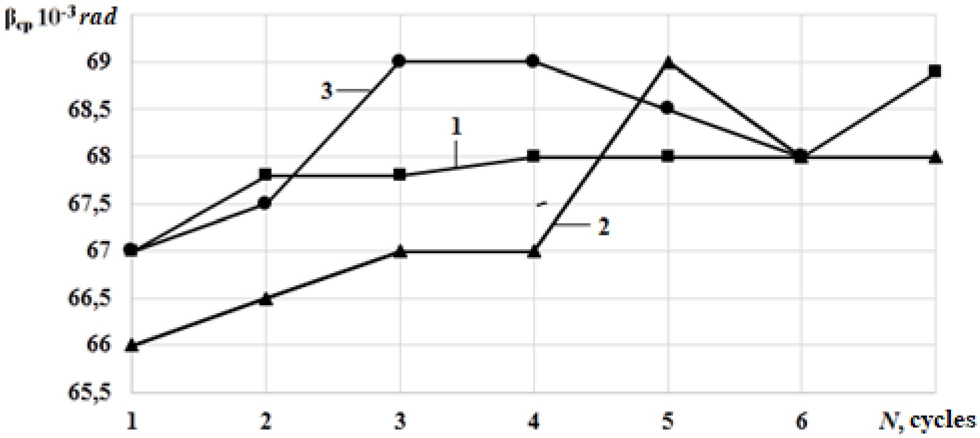


Figure 1: Dependences of the change in the physical width β_{av} of the X-ray line on the number N of thermal cycles and the heating temperature T = 450 (1); 570(2); 700 (3) °C

Reheating in the zone above the point of formation of a disposable polygon structure at a high density of dislocations ensures the formation of the desired structure.

During the preliminary cyclic heat treatment of steels at temperatures up to 450 °C, an intensive recrystallization of the structure occurs, while a polygonal structure is not formed.

However, when comparing the results of preliminary cyclic heating at a temperature of 450 °C and quenching by completed induction heating with the results of conventional quenching by induction heating, it was found that the dislocation density increased slightly. With the same level of hardness 59-60 HRC, the difference in the physical width of the X-ray line is $5 \cdot 10^{-3}$ rad.

The results of wear resistance tests correspond to the results of the study of the microstructure and fine structure of the samples. During the initial cyclic heating and then induction heating of the samples, the same microstructure, the same grain sizes and the same level of hardness were formed, the difference was observed only in the level of defectiveness of the crystal lattice. This difference was shown in wear resistance tests. The test results are shown in Table 3.

When analyzing the data given in Table 3, it was found that the value of the wear resistance of steel grade 65G, formed after preliminary 3-time cyclic heating at a temperature of 450 ° C, cooling with air, induction hardening at a temperature of 900 ° C and tempering at a temperature of 180 °C within 60 minutes will be 25-30% higher than other types of heat treatment.

Table 3. The results of testing for wear resistance of steel grade 65G after heat treatment at various temperatures

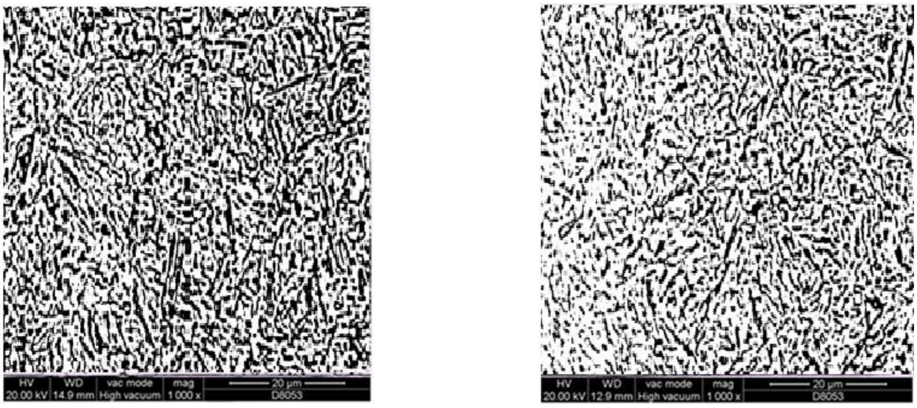
Type of heat treatment and heating temperature, °C	Wear, mg		Hardness, HRC	The average amount of wear of the upper and lower samples, mg	Wear, %
	Upper sample	Down sample			
Induction hardening at 900 °C, tempering at 180 °C	59,07 65,0 61,53 58,36	29,06 28,86 28,78 27,34	53,5-60 53,5 58-69 59	89,37	100
3 cycles at 450°C, induction hardened at 900°C, tempered at 180°C	46,09 49,30 40,02 38,0	22,14 23,09 24,49 24,01	59 59 58 59	66,78	75

Structural analysis of steels showed that in all cases of preliminary cyclic heat treatment and induction hardening of steels, a martensitic structure with a high level of hardness is formed (Figure 2.). It became known that the dimensions of martensitic plates depend on the heating temperature for quenching.

During preliminary cyclic heating at a temperature of 450 °C, no effect of temperature on the sizes of austenite grains and martensite plates was observed. It has been established that a change in the size of austenite grains has a great influence on the results of hardening.

X-ray diffraction analysis of steel samples heat-treated by induction at different temperatures shows that the level of defectiveness of the crystal structure of steel after hardening depends on the duration of cyclic heating (Fig. 3.),

The highest value of the level of defectiveness of the crystal structure is observed with a duration of cyclic heating of 4-5 seconds at all cycling temperatures, but this may vary depending on the size of the article to be heated.



3 cycle heating (×1000) 5 cycle heating, (×1000)

Figure 2: Microstructure of 65G steel after cyclic heating at a temperature of 450°C and cooling with air, completed induction hardening at a temperature of 900°C and tempering at a temperature of 180°C

To conduct comparative tests, steel samples of the 18KhGT grade were used, which had previously simplified the process of nitrocarburizing and heat treatment at Aggregatny Zavod JSC.

When analyzing the control sample, it showed that all samples had a martensitic structure (in steel 18KhGT, areas of lower bainite were observed in the core). With a high hardness of the material, to maintain the required viscosity, a fine austenite grain is required, the presence of which was determined by etching (GOST 5639-65).

Had austenitic grains with average diameter d_{av}= 0.02736÷0.03315 mm (7; 8 points).

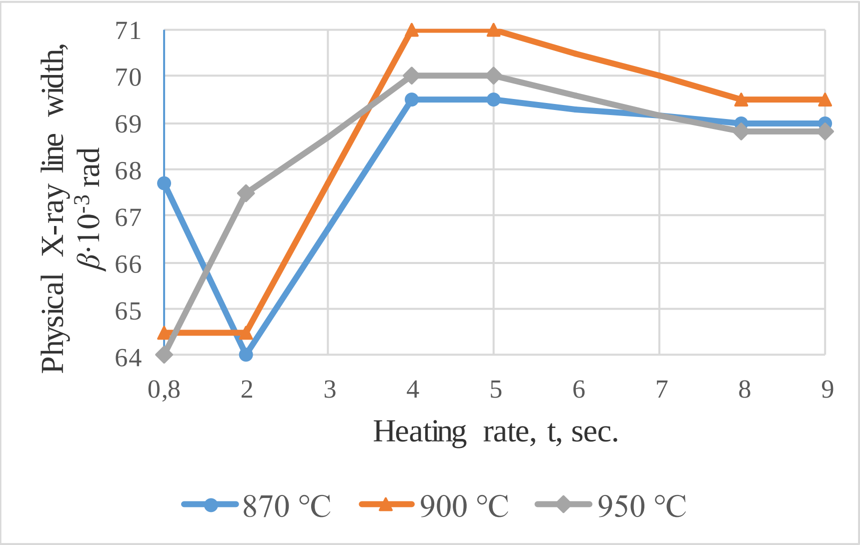


Figure 3: Dependence of the value of the defectiveness level of the crystalline structure of steels on the duration of cyclic heat treatment

The results of measurements on the wear resistance of steel 65G after induction heat treatment showed that they were different (uneven) depending on the location: in the middle part of the sample area, the hardness was 60 HRC, at the edges of the sample, the hardness was from 54 HRC to 60 HRC.

Therefore, it was decided to additionally release some of the samples to the same uniform hardness of 53-54 HRC and 55-56 HRC. Such processing makes it possible to evaluate wear resistance in the formation of the same hardness, and also meet the requirements given in the drawing of fine-grained gear parts [6].

To conduct a comparative analysis of the results, a mode of heat treatment of the teeth of a fine-modulus gear made of steel 65G was developed in the following order:

1. Cyclic heating at a temperature of 400-500 °C, cooling with air supply to a temperature of 80-100 °C. At an anode voltage of 6.5 kV, an anode current of 5.5 A, and a current value of 0.55 A, heating to a temperature of 450 °C was observed, the heating rate was 3-4 sec. The cooling time with the help of air supply to a temperature of 80-100 °C was 2 min 20 sec, the number of cycles was 3.
2. The order of thermal hardening after cyclic heat treatment: at an anode voltage of 9 kV, an anode current of 8.5 A, a current value of 0.8-1.8 A, heating to a temperature of 900 °C was observed, the heating rate was 7 sec, the cooling medium was oil .
3. Heating in a saltpeter bath within the temperature range of 180-200 °C for 60 minutes, tempering in air.

As a result of this order of heat treatment, the average diameter of the austenite grain in the middle of the structure of the gear tooth made of steel 65G averaged d_{av} = 0.055, which corresponds to 5-6 points, and the top of the tooth was d_{av} = 0.0927 - 0.0729 mm, this corresponds to 4-5 points according to GOST, in a thin layer on the surface of the gear teeth a coating with a hardened martensitic structure was formed.

As the analysis and comparison of the research results shows, the wear resistance of gear teeth made of steel 65G, pre-cyclically heat-treated and then heat-treated by induction heating, turned out to be 1.3-1.4 times higher in comparison with the wear resistance of gear teeth heat-treated by traditional induction heating and 1.2-1.3 times higher wear resistance of gear teeth made of nitrocarburized steel grade 18XGT.

4. Conclusions

1. It has been established that during preliminary reheating, this thermally stable dislocation serves as a source that forms a new dislocation at the α – γ – α transition.
2. It has been established that as a result of cyclic heating, a lamellar structure is formed in the steel structure and this structure is thermally stable.
3. It has been determined that if 65G steel is preliminarily subjected to triple cyclic heating in the temperature range of 450-500°C, then as a result of air cooling, the dislocation density in α-phase crystals will be high. This improves the performance properties of steel 65G.
4. It has been established that steel 65G, previously subjected to triple cyclic heating in the temperature range of 450–500 °C, forms a complete lamellar structure. The lamellar structure serves to improve the mechanical properties of steels.

It has been determined that for cyclic heating by a high-frequency current up to a temperature of 450 °C, a current strength of U = 6.5 kV., I = 0.55 A, U = 9 kV., I = 0.8–1.8 A is provided. The values are used to accurately determine the temperature of the induction heating annealing.

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