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Selection and Application of the Optimal Surface Engineering Method to Restore the Properties of Rolling Equipment Elements that Have Been Reduced Due to Violations of Surface Grinding Technology

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Abstract. The methods of influence on the material using different energy sources are considered. The role of friction in several technological processes is emphasized. The technological process of heat treatment is proposed, which allowed to restore the properties of rolled rolls that were lost due to incorrect grinding conditions. Application of the proposed technological process has shown that: 40X steel can be hardened to martensite in oil, water, and in a 10 % aqueous solution of NaCI salt, but with different results (i); the most effective hardening mode for 40X steel rolls is quenching with cooling in a 10 % aqueous solution of NaCI salt and subsequent high-temperature tempering, which is necessary to remove dangerous residual stresses (ii); the structure of the surface working layer of 40X steel rolls, after the selected optimal heat treatment regime, consists of fine-needle martensite and a small amount of Cr carbides (iii); closer to the core of the rolls, in addition to martensite, there are areas of troostite-bainite structure (iv); the resulting structure of the rolled rolls is capable of ensuring their efficient and long-term operation, but under optimal conditions, when the rolls' heating temperatures do not exceed 200 °C, and the proposed temperature conditions are recommended for both operation and routine maintenance associated with periodic restorative grinding of the working surfaces of the rolled rolls (v).

1 Introduction

The surface condition of products largely determines their properties. And it should be emphasized that structural engineering of surface is closely related to the achievement of high functional properties of materials and, accordingly, provides an increase in the operational properties of tools, machine parts and structural elements.

The scientific and technological approach, which involves the use of friction as an energy source that can be used to rapidly change the structural state of various materials, is modern and relevant.

The relationship between friction and the structural states of materials, such as initial, intermediate, and final, plays an important role. Accordingly, it can be considered as one of the main factors in the implementation of a number of processes that involve the use of friction. For example, technologies such as thermofriction cutting (TFC), thermofriction machining (TFM) [1], thermofriction strengthening (TFS) [2], additional thermofriction strengthening (ATFS) [3], or thermofriction welding (TFW) are seemingly dissimilar, but have an important common component - friction. In this case, friction is the driving force that creates the conditions for obtaining the expected result for each specific technological process. Accordingly, this allows us to consider such processes as related. It should be noted that friction (frictional component) in the considered technological processes can be used in different conditions, according to different schemes, with different intensity, etc. For example, friction stir welding may involve the use of one or more materials [4]. In addition, it is possible to use different technological aspects, such as the schemes of use of tools, the use of tools of different materials and different shapes [5], etc. Also, it is sometimes advisable to include modeling methods in the research process when planning the application of any of the above or other technologies. This makes it possible not only to predict the desired result, but also to significantly accelerate its achievement. However, when it comes to solving a problem that has arisen once and could have caused a certain disruption of the overall technological process of operation or maintenance, conditions are created for technical creativity to solve it.

The issue of increasing the service life of equipment for rolling production is a timely one, as obtaining the properties necessary for efficient operation in the elements of such equipment is the key to its long-term use.

Rolling rolls, as a tool that is part of the equipment for rolling objects made of metals and alloys, operate under severe operating conditions, namely, under high loads, friction and elevated temperatures. This results in rapid wear of their working surfaces, which leads to a defect of range of products. Due to the generally high cost of rolls, it is more cost-effective to refurbish them, if possible, rather than replace them with new ones, as this is more economically viable. This approach can be realized by using various methods to influence the structural condition of the product surface. The use of, for example, the TFS technology [1, 3, 6] or other methods of surface hardening is quite possible to solve such problems. However, the feasibility of using a particular treatment method is determined by the ability to achieve the required properties while minimizing costs and meeting the requirements for each specific hardening object. For example, for small rolls, it is important to preserve the nominal dimensions as much as possible, and therefore a recovery treatment process should be developed that would ensure that the requirements are met.

It is emphasized that at metallurgical enterprises, rolls, even those of the same type, may experience unequal wear during operation [7]. Therefore, under conditions of constant friction, heating, and uneven load, defects may appear on the surfaces of the rolls, which, during the rolling process, leave traces on the surfaces of the workpieces. This can even lead to rejection of finished parts. However, it has been concluded that it is not advisable to use roll restoration methods, such as surfacing, when the wear is up to 1 mm. It is possible to restore their surfaces by grinding (regrinding) [7]. It is also noted that a group of researchers analyzed the issue of price-quality relationship for the manufacture and use of rolls in different countries [8], since the high cost of energy resources requires taking into account economic aspects in the manufacture and use of rolling equipment. The goal is to ensure that the rolled rolls have high resistance to wear and tear, shock loads and temperatures, bending and torque [9]. Ukraine has developed a technological process for the production of hot strip mill rolls with a working layer of special cast iron [10, 11]. Also, for individual parts requiring high surface wear resistance, the micro-arc oxidation (MAO) method can be used [12]. The use of MAO allows for the production of wear-resistant corundum coatings. However, this method is used mainly for non-ferrous metals and alloys based on them. Therefore, for each specific material, the most optimal processing method should be chosen, which is able to provide the required operational properties of the product and its use is economically feasible.

2 Experimental Part

In this research, we studied the effect of heat treatment modes on the hardness recovery of rolled rolls (Fig. 1). Three full-scale samples with a diameter of 30 mm and a length of 45 mm were manufactured and examined to simulate real rolls, but in miniature. This was necessary to compare their surface hardness and hardenability when selecting the optimal heat treatment regime. Based on the results obtained, it is plans to use this mode for real rolls based on the requirements for restoring their properties.

Fig. 1. A pair of rolls (40X steel) that need to be restored to their original performance.

The material used in this study was 40X steel, as the rolls that needed to be restored were made of this steel grade. The samples under consideration were heat treated by oil quenching at 860°C and low-temperature tempering at 180 °C. This was necessary to simulate the original properties of the rolls that required recovery treatment. Thus, after the production heat treatment (before the start of operation), these rolls had a hardness of 55 HRC. After a certain period of operation, it was necessary to grind their surfaces to restore surface cleanliness, as they had undergone deformation changes. However, after grinding, due to overheating of the surface layer of the rolls to 350-400 ºC, the hardness of their working surfaces decreased to 43–47 HRC. This level of hardness is insufficient for their operation to ensure the required quality of the rolled surface. According to the analytical studies of the rolls' hardening depth, the hardness reduction occurred to a depth of about 1 mm.

Fig. 2. Rockwell hardness tester measuring the surface hardness of one of the rolls.

To remedy this situation and restore the required hardness of the rolls, three heat treatment modes were applied:

– quenching with heating to 860 ºC and cooling in water;
– quenching with heating to 860 ºC and cooling in a 10 % aqueous solution of NaCl salt;
– quenched with heating to 860 °C and cooling in mineral oil.

Mcrosections of these samples were made and etched according to standard methods.

To determine the effect of the cooling rate on the structure formation and hardness of the steels under study after quenching, cooling was performed in different environments where the cooling rates were equal:

– $V_{cool} \approx 30$ °C/s for oil;
– $V_{cool} \approx 600$ °C/s for water;
– $V_{cool} \approx 680$ °C/s for a 10% aqueous solution of NaCI salt.

The results of measuring the hardness after quenching the samples under different cooling conditions are shown in Table 1.

Table 1. Effect of cooling rate on the hardness of 40X steel

Material	Output hardness of rolled rolls, [HRC]	Rolls hardness after grinding, [HRC]	Hardness after water hardening, [HRC]	Hardness after hardening in mineral oil, [HRC]	Hardness after hardening in 10 % aqueous salt solution NaCI, [HRC]	Hardness after low-temperature tempering, [HRC]
40X steel	55	43–45	50–53	45–47	55–58	55–57

Note: The austenitization temperature is t_h=860 °C.

Table 1 shows that cooling in a 10 % aqueous solution of NaCI made it possible to obtain the highest level of steel hardness of the three cases considered

40X steel has lower hardness values when cooled in oil (oil quenching) and in water. This can be explained by the fact that the rolling shaft can be decarburized. Some samples of this alloy steel quenched in water showed areas with a reduced hardness of 43–45 HRC. It can be assumed that these are decarburized areas formed as a result of carbon burnout during long holding times of the previous full annealing.

40X steel has a high supercooled austenite stability and can show quite high hardness values - up to 53 HRC - when cooled in oil.

As for the tendency of 40X steel to temper brittleness, accelerated cooling during tempering increases the impact strength of this steel.

Based on the data on the mechanical properties of 40X steel, the following conclusions can be drawn:

1. Hardening of 40X alloy steel rolls is possible when cooled in water, in a 10 % aqueous solution of NaCI salt and in oil (the latter is for small parts), but hardening in a 10 % aqueous solution of NaCI salt allows for higher hardness values.
2. To relieve residual stresses in such products, it is necessary to perform low-temperature tempering at 180 °C after quenching.

Metallographic analysis with photography was performed to study the microstructure of the samples after heat treatment, as it is important for understanding the changes in properties in the samples under study. The hardness distribution and visual assessment of the microstructure using a metallographic microscope indicate the contribution of heat treatment to the change in material structure. Metallographic studies were performed on the samples after hardness measurements. Microstructures were analyzed and photographed using metallographic microscope ZEISS AXIO Vert. A1 and digital camera adapted to the microscope. The results of microscopic analysis are presented in Figs. 3–5.

Analysis of the microstructures showed that all three hardening modes, namely cooling in water, mineral oil, and a 10 % aqueous solution of NaCI, resulted in a predominantly martensitic structure. However, the hardness level obtained in these samples is slightly different. After all, quenching with cooling in mineral oil provides a hardness of 45–47 HRC, in water 50–53 HRC, and in a 10 % aqueous solution of NaCI salt 55–58 HRC (see Table 1).

The morphology of the microstructures of the three test samples is almost identical. Therefore, the difference in hardness after cooling in different media can be explained by the different completeness of the martensitic transformation, which depends on the cooling ability of different media when used. It is likely that during cooling in oil (Fig. 3), already at the initial stage, the cooling rate became lower than the critical one, which involved the initial processes of diffusion transformations and the appearance of a small amount of troostite-bainite structure. This could have caused a partial decrease in the overall level of hardness in the surface.

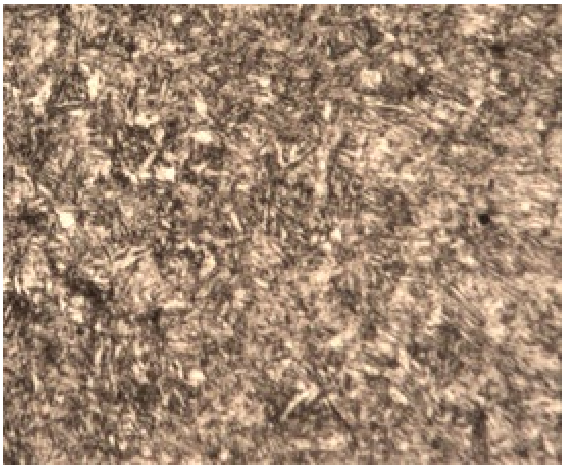

Fig. 3. Microstructure of 40X steel after quenching with cooling in mineral oil, ×500.

Cooling in water (Fig. 4) resulted in a hardening level close to that of cooling in a 10 % aqueous solution of NaCI, but the cooling properties of the salt solution are higher than those of water. And this allowed the martensitic transformation to occur fuller. Cooling in a 10 % aqueous solution of NaCI salt provided the formation of a fine-needle martensitic structure of steel and a small amount of Cr carbides, as shown in Fig. 5.

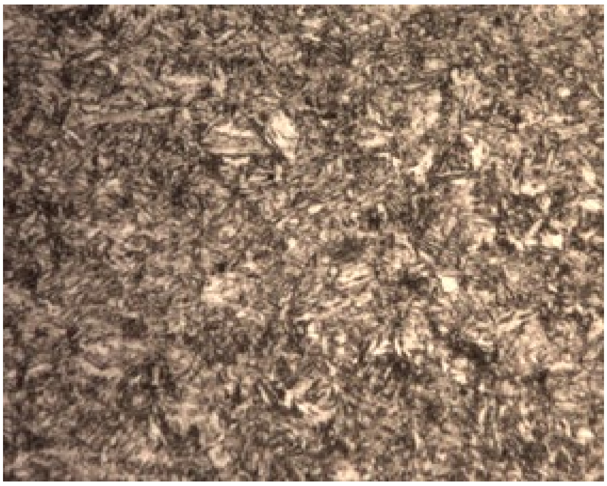

Fig. 4. Microstructure of 40X steel after quenching and cooling in water, ×500.

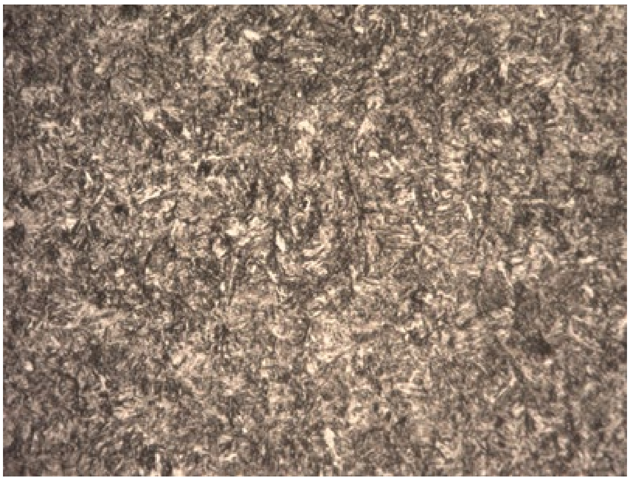

Fig. 5. Microstructure of 40X steel after quenching with cooling in a 10 % aqueous solution of NaCI, ×500.

The higher level of hardness obtained in this case is explained by the more intense ability to cool the steel with an aqueous solution of NaCI salt.

3 Conclusion

In the course of this research, a technological process of heat treatment was proposed, which made it possible to restore the surface hardness of rolls lost due to an incorrect grinding mode. The results obtained showed that:

1. 40X steel can be hardened to martensite in oil, water, and a 10 % aqueous solution of NaCI salt, but with different results.
2. The most effective hardening regime for 40X steel rolls is quenching with cooling in a 10 % aqueous solution of NaCI and subsequent high-temperature tempering, which is necessary to remove dangerous residual stresses. It is therefore noteworthy that the initial hardness of the products before operation was 55 HRC, after incorrect grinding it dropped to 43 HRC, and after restorative heat treatment it reached 57 HRC, which is even slightly higher than the pre-operational hardness level.
3. However, operational recommendations were made that should be followed. After all, the resulting structure of the rolled rolls is capable of ensuring their efficient and long-term operation, but under optimal conditions, when the rolls' heating temperatures do not exceed 200 °C. Moreover, the proposed temperature conditions are recommended both for operation and for routine maintenance associated with periodic regrinding of the working surfaces of the rolls.
4. The structure of the surface working layer of 40X steel rolls, after the selected optimal heat treatment regime, consists of fine-needle martensite and a small amount of Cr carbides.
5. Taking into account the low hardenability of 40X steel, it can be argued that, in addition to martensite, areas of troostite-bainite structure are observed closer to the core of the rolls.

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