Heat treatment of mandrel steel for pipes’ piercing

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Abstract. Seamless pipes are mainly used in the oil, gas and defense industry, what places special demands on its reliability and safety. It is very important to select the steel grade and heat treat the mandrels for flashing and cross rolling of seamless pipes in order to ensure the required operational characteristics. The work is devoted to the substantiation of the choice of 4Kh5MF1S steel and the development of the technological cycle of manufacturing mandrels of increased strength for sheet and transverse-spiral rolling of seamless pipes. The optimal combination of strength and ductility of this steel during heat treatment was established, which includes quenching at 1070 °C and tempering in the temperature range of 650–700 °C. Based on the analysis of the structure and mechanical characteristics, an optimal mode of heat treatment of steel 4Kh5MF1S was proposed: quenching from 1070 °C in oil and tempering for 2 hours at the temperature of 650–700 °C, which makes it possible to recommend it for use as a heat-resistant structural material for highly loaded metal products with the yield stress σ0.2 from 750 to 1000 MPa.

1. Introduction
The task of ensuring the necessary performance of metal products is a key priority area of modern science and one of the most important goals of various branches of industry [1,2]. The performance indicators of structural materials intended for the manufacturing of highly loaded heat-resistant metal products are formed at all stages of metal conversion: from the choice of charge materials for metal smelting to the production of finished parts [3].

The main consumers of seamless pipes are oil and gas industries, as well as defense industry. This imposes special requirements in respect of operating reliability of these products. The metal products’ reliability depends on the operating conditions [4], the origin of material and the mode of its process treatment [5,6] and, to a large extent, is determined by the structure and properties of used materials [7-10] and is ensured by the optimization of the process operating conditions [11-14]. In this regard, the task of choosing a steel grade and developing a process cycle for the manufacture of mandrels with increased resistance to physical and mechanical stress arising in the process of piercing and transverse-spiral rolling of seamless pipes in order to ensure the required operating features, is very urgent.

During manufacturing of pipes the center of a round billet heated to a piercing temperature of about 1200 °C is pierced in a piercing mill, as a result of which a hollow billet called ‘a hollow sleeve’ is produced. The operating tool for piercing a hole in a pipe billet is a mandrel, which is installed on the front end of the rod.
During operation the mandrel is exposed to high temperatures and high contact pressures, and this reduces the possibility of multiple uses of mandrels of the same diameter in the piercing mill, significantly reducing the service life of this tool. In addition, the aggressive operating conditions, which are typical for all piercing mills, bring about the problem of mandrels’ durability. Therefore, in order to ensure the trouble-free pipes’ production, the enterprise has to maintain a stock of a large number of mandrels.

The wear resistance of pierced mandrels is influenced by a number of factors such as the properties of rolling tool and pierced material (steel grade, hardness, heat treatment modes of the tools, etc.); temperature conditions of work, temperature distribution over the volume of the tool; deformation mode (drawing, compression before the mandrel nose, piercing time, etc.).

The heat cracks are formed under the impact of cyclic temperature effect, characterized by repeated heating and cooling of mandrels. In the process of operation, as the number of rolled pipes increases, the development of cracks continues, they are oxidized due to interaction with an aggressive lubricant medium and penetrate inside the metal, which ultimately can lead to the formation of deep cracks, pitting of metal particles and, as a consequence, the failure of mandrel. Piercing mandrels, as a rule, are made of die steels, which must meet high technical requirements and have a certain set of properties: high heat capacity, heat resistance, thermal stability (fire resistance), toughness, wear and scaling resistance, thermal conductivity, hardenability and low adhesion.

Therefore, the purpose of this work is to substantiate the choice of a steel grade that provides the best combination of price and quality for production of mandrels and to choose the optimal mode on the basis of studying the effect of its heat treatment modes on microstructure and mechanical properties.

2. Materials and methods

Based on comparison of properties of 4Kh5MF1S, 4Kh5V2FS and 5KhNM steels, the carbide grade steel 4Kh5MF1S, optimal from the point of view of the best combination of price and quality, was selected for the production of mandrels in this work. This steel is widely used for the manufacture of die casting molds of zinc, aluminum and magnesium alloys, hammer and press inserts (with a cross section of up to 200-250 mm) during hot deformation of structural steels, for the manufacture of tools for heading blanks from alloyed structural and heat-resistant materials at horizontal forging machines.

Initial material was a forged steel bar with a circular cross-section (diameter 60 mm), which was divided by plasma cutting into piece blanks of 130 mm long. A forged bar is well suited for tool steel, because such semi-finished product has a fine-grained and uniform distribution of alloying elements throughout the metal volume, ensuring equilibrium and fine-grain of the final structure. To improve the conditions of the secondary grip and to reduce the wall thickness difference a recess with diameter of 12 mm and depth of 7-8 mm was performed by drilling in a cold state for centering from one end of the blank. In this case, the misalignment of blank and the centering recess did not exceed 0.15 mm.

Heat treatment of this steel according to standard mode, including quenching from 1020 °C in oil and tempering at 580 °C in oil, provides the product [30] with a sufficiently high viscosity (39 J/cm²) and wear resistance while maintaining high hardness (47-50 HRC). This combination of a set of mechanical characteristics makes it possible to expand the range of applicability of this steel not only for manufacturing of tools, but also for its use as a structural steel, for manufacturing of highly loaded heat-resistant machine parts.

Nitric acid 5 cm³, hydrochloric acid 50 cm³, and distilled water 50 cm³ were used during etching of the samples’ surface to reveal the microstructure. The samples of a prismatic shape with dimensions of 10x10x55, which were quenched at the temperature from 1070 °C in oil and various tempering modes: 230, 550, 600, 650, 700, 750 °C, holding during tempering for 3 hours were studied. Tensile tests were carried out on samples No. 7, type II, in accordance with GOST 1497; impact tests were performed on samples with a U-shaped concentrator (type 8 with a work section height of 5 mm) at positive (+20 °C) temperatures in accordance with GOST 9454; with microstructure analysis, Rockwell hardness measurement.
3. Results and discussion

It has been established (Table 1) that within the tempering temperature range of 230-550 °C the hardness practically does not change (54.2–52.9 HRC).

Table 1. The influence of the tempering temperature after the 4Kh5MF1S steel hardening.

| Tempering temperature, °C | 230 | 550 | 600 | 650 | 700 | 750 |
|---------------------------|-----|-----|-----|-----|-----|-----|
| Hardness, HRC             | 55.00 | 54.20 | 52.90 | 47.20 | 37.20 | 31.00 | 24.30 |

Starting from the tempering temperature of 600 °C, a sharp decrease in hardness occurs. When tempered at 600 °C, the hardness is equal to 47 HRC, when tempered at 750 °C, it is 24.3 HRC. The invariability of the high hardness of steel 4Kh5MF1S up to 550 °C is associated with its high heat resistance. The steel hardness is formed by dissolving alloying elements in austenite during the quenching operation, which leads to the fact that the alloyed martensite formed after quenching has a high resistance to tempering. This justifies the fact that within the tempering temperature range of 230-550 °C steel 4Kh5MF1S has a constant and high hardness.

An increase of the tempering temperature above 550 °C leads to the fact that the value of steel hardness level decreases due to separation of carbide phase (carbides of Me23C and Me6C types), transition from one type of carbide to another, their coagulation, as well as decrease of internal (quenching) stresses. After hardening, the steel structure consists of martensite and retained austenite. Tempering at 230 °C did not reveal any significant changes in the structure. Martensite remains the main structural component, however, as a result of heating to 230 °C, the etchability of microsections slightly increases, which may be due to a partial decrease of quenching stresses.

After tempering at 550 °C, a significant increase in etchability of the samples is observed. The matrix has a roughly needle-like structure. Probably, at a given tempering temperature, the type of the martensite structure is revealed more clearly. In addition, it should be noted that visually observed dispersed carbide particles have emerged in the structure after this tempering.

An increase of tempering temperature up to 600 °C leads to a decrease of the degree of acicularity of the matrix and to an increase of the amount of carbide phase. Tempering at 650 °C activates the processes of matrix recrystallization, the acicularity is not detected. The structure consists of a dispersed ferritic-carbide mixture (tempering troostosorbit).

A further increase of tempering temperature up to 750 °C leads to intensification of the processes of separation and coagulation of the carbide phase, forming secondary sorbite. This is due to the fact that at a temperature not exceeding 600 °C, tempering is low for 4Kh5MF1S steel. The first and the second transformations occur within this temperature range during tempering. The microstructure consists of martensite with a hardness of 52–55 HRC. 4Kh5MF1S steel in this structural state has maximum strength values and minimum values of plastic characteristics, which limits the possibility of its use as a structural material.

The next increase of tempering temperature from 600 to 700 °C causes a monotonic increase in the steel plasticity (Figure 1) and toughness (Figure 2), but a decrease in its strength (Figure 3).

Figure 1. Influence of the tempering temperature on the hardness of 4Kh5MF1S steel. Figure 2. Influence of the tempering temperature on the microhardness of 4Kh5MF1S steel.
temperature on the elongation and contraction of samples from steel 4X5MF1S.

\( \Psi \); \( \delta \) elongation.

The mechanical properties of samples at tempering temperatures of 650 and 700 °C at the same time significantly differ from the samples tempered at 600 °C. Compared with tempering at 600 °C, after tempering at 650 °C, the relative contraction \( \psi \) did not practically change (14.7–14.9%), while the relative elongation and impact strength increased from 5.6 to 7.9% and from 11 to 14.8 J/cm\(^2\), respectively.

![Figure 3. Influence of the tempering temperature on the yield stress and yield strength of 4X5MF1S steel](image)

Analysis of metallographic studies and obtained mechanical properties revealed the optimal combination of strength and plasticity of 4Kh5MF1S steel during heat treatment, which included quenching from 1070 °C and tempering in the temperature range of 650–700 °C. In this case, the choice of the tempering temperature is conditioned by the required strength category of the metal product.

The use of 4Kh5MF1S steel tempered at the temperature of 600 °C as a structural material is not advisable in view of the presence of hardening, acicularity and low impact strength in the structure inherited from martensite.

4. Summary

Comparison the properties of the steels grades 4Kh5MF1S, 4Kh5V2FS and 5KhNM for the production of mandrels from the point of view of providing the best combination of price and quality showed the advantage of steel 4Kh5MF1S.

Based on the analysis of the structure and mechanical characteristics, an optimal mode of heat treatment of steel 4Kh5MF1S was proposed: quenching from 1070 °C in oil and tempering for 2 hours at the temperature of 650–700 °C, which makes it possible to recommend it for use as a heat-resistant structural material for highly loaded metal products with the yield stress \( \sigma_{0.2} \) from 750 to 1000 MPa.

5. References

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