Shaping of structural and mechanical properties of heavy duty mandrels used for seamless pipe rolling

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Abstract The main spheres of high-strength seamless pipes application are oil and gas production sectors, as well as the defense industry. Therefore, increasing the piercing rolling efficiency, increasing the strength and durability of the tool are the main factors that ensure the smooth production of seamless pipes. The article justifies the choice of the steel grade and displays the developed manufacturing technological cycle of heavy duty mandrels used for piercing and helical rolling of seamless pipes.

Keywords: Seamless pipes, piercing rolling, alloy steels, processability, performance properties.

1. Introduction

Seamless pipes are mainly used in the oil and gas production sectors, as well as in the defense industry, which imposes special reliability and safety requirements. The metal products operating reliability significantly depends on the operating conditions [1-5], the nature of the material and the mode of its technological processing [6-7], and is largely due to the structure and properties of the materials used [8-10], and is provided by the technological processes optimization [11-13]. In this regard, the task of the steel grade selection and developing a manufacturing technological cycle for the heavy duty mandrel, resistant to physical and mechanical stress, used for piercing and helical rolling of seamless pipes, in order to ensure the required performance, is of current concern.

During the pipe manufacturing process, the central part of the round billet, heated to a predetermined temperature, is pierced in the piercing mill, getting a hollow pipe billet as a result, also called a "rough tube". The main tool for piercing holes in the pipe blank is a mandrel, which is mounted at the front end of the rod. The piercing temperature is about 1200°C.

Same diameter mandrels can be repeatedly used in the piercing mill, however during operation the mandrel is exposed to high temperatures and high contact pressures, which significantly reduces the service life of the tool. The mandrel resistance issue caused by aggressive operating conditions is typical for all piercing mills. To ensure the smooth operation of pipe manufacturing, it would be required to maintain a stock of a large number of mandrels, so that even in the case of frequent mandrel replacement, the shortage of these would not occur.

The main factors affecting the wear resistance of the piercing mandrels:

- properties of the rolling tool and the piercing material (steel grade, hardness, tool heat treatment modes, etc.);
- operating temperature conditions, temperature distribution throughout the tool volume;
• deforming mode (exhaust, compression before the toe of the mandrel, piercing time, etc.).

Due to the cyclic temperature impact, characterized by mandrel repeated heating and cooling, flame erosion cracks are formed. In the process of work, as the number of rolled pipes increases, the cracks continue to develop and these are oxidized due to the interaction with the aggressive lubricant medium and penetrate deep into the metal, which ultimately can lead to the formation of deep cracks, chipping of metal particles and, as a result, to the mandrel failure [14,15].

Piercing mandrels, as a rule, are made of die steels, which shall meet high technical requirements and have a certain set of properties: high heat capacity, high temperature strength, heat resistance (resistance to flame erosion), viscosity, wear and scale resistance, thermal conductivity, hardenability and low adhesion [16,17].

The aim of this work is to study the effect of heat treatment modes of steel grade 4H5MF1S on its microstructure and mechanical properties.

2. The study method

The steel grade selection for piercing and helical rolling depends on the mandrel purpose and its operating conditions. Therefore, it is important to select such steel grade that will provide all the necessary complex of performance properties.

The paper presents comparison of properties of steel grades 4H5MF1S, 4X5B2FS and 5XHM and selects the optimum steel grade 4H5MF1S of carbide class for mandrel manufacturing that provides the best combination of price and quality. This steel grade is widely used for the manufacture of molds for injection molding of zinc, aluminum and magnesium alloys, hammer and press inserts (with section of up to 200-250 mm) during hot deformation of structural steels, tools for planting blanks from alloyed structural and heat-resistant materials in horizontal forging machines.

As initial material, a circular cross-section forged steel rod with diameter of 60 mm was used, which was cut into individual blanks with length of 130 mm by plasma cutting. The forged rod is well suited for tool steel, since such a semi-finished product is obtained fine-grained and with a uniform distribution of alloying elements throughout the metal volume. The resulting final structure is an equilibrium fine-grained one.

To improve the secondary grip conditions and to reduce variation in wall thickness, a centering recess with diameter of 12 mm and depth of 7-8 mm was applied from one end of the blank by a cold state drilling. The misalignment of the blank and the centering recess did not exceed 0.15 mm.

The standard heat treatment mode for this steel grade includes quenching down from 1020°C in oil and tempering at 580°C in oil. It is known that after such heat treatment, the product along with high hardness (47-50 HRC) has a sufficiently high viscosity (39 J/cm²) and wear resistance. The presence of such a complex of mechanical characteristics allows to extend the steel range of applicability not only for the manufacture of tools, but also allows using it as a structural steel intended for the machine parts manufacturing.

To identify the microstructure, 5 cm³ of nitric acid and 50 cm³ of hydrochloric acid and 50 cm³ of distilled water were used in this study. Studies were conducted on samples of prismatic shape with dimensions of 10x10x55. These samples were subjected to quenching down from 1070°C in oil and various tempering modes: 230, 550, 600, 650, 700, 750 °C and tempering exposure was 3 hours.

Tensile tests of samples No. 7 type II according to GOST 1497, and impact resistance tests of samples with the U-shaped field shaper (type 8 with the working section height of 5 mm) at positive (+20 °C) temperatures as per GOST 9454, microstructural analysis of the samples, measurement of the Rockwell hardness were executed.

3. Results and discussion

In the tempering temperature range of 230-550°C, the hardness is almost constant (54.2–52.9 HRC). Starting with a tempering temperature of 600°C, there is a sharp decrease in hardness. At tempering starting from 600°C the hardness is 47 HRC, at tempering under 750°C it reaches 24.3 HRC (Fig. 1).

The persistence of steel grade 4H5MF1S high hardness up to 550°C is due to its high heat resistance. The hardness of the steel is formed by hardening, namely during the dissolution of alloying elements in austenite. Due to this, the doped martensite formed after hardening has a high resistance against
tempering. Therefore, in the tempering temperature range of 230-550°C, steel grade 4H5MF1S has a constant and a high hardness.

When increasing the tempering temperature above 550°C the steel hardness value is reduced. This is due to the carbide phase separation process development (carbides type $\text{Me}_2\text{3C}$ and $\text{Me}_6\text{C}$), the transition from one type of carbides to the other, coagulation of these and the reduction of internal (hardening) stresses.

Figure 1. Steel grade 4H5MF1S hardness dependence on the tempering temperature.

The character of hardness measurements is in good agreement with the results of metallographic studies. After hardening, the steel structure consists of martensite and residual austenite. When tempering at 230°C no significant changes in the structure occur. The main structural component is martensite, however as a result of heating up to 230 °C, the etchability of microslices slightly increases, which is probably due to some decrease in hardening stresses.

A significant increase in the etchability of the samples is observed after tempering at 550 ° C. The matrix has a roughly needlelike structure. Probably, at this tempering temperature, the character of the martensite structure is revealed more clearly. It should also be noted that after this tempering, the dispersed carbide particles begin to be visually observed in the structure. With an increase in the tempering temperature of up to 600 °C, an increase in the amount of the carbide phase occurs, the degree of matrix acicularity decreases.

Tempering at 650°C activates the matrix recrystallization processes whereas the acicularity is not detected. The structure consists of the dispersed ferrite-carbide mixture (tempering troostosorbite). Further increase in the tempering temperature of up to 750°C leads to the carbide phase separation and coagulation processes intensification, the microstructure is classified as a tempering sorbite.

This suggests that tempering at temperatures of not above 600°C for steel grade 4H5MF1S is low. In this temperature range, the first and the second tempering transformations take place. The microstructure consists of martensite with hardness of 52-55 HRC. In this structural state, steel grade X5MF1S has maximum strength and minimum ductile characteristics, which does not allow it to be used as a structural material.

With the aim of identifying the heat treatment mode that gives the optimum combination of strength and ductility, the investigation of mechanical characteristics of steel grade 4H5MF1S was carried out on the blanks, tempered after hardening at 600°C and higher.

An increase in the tempering temperature from 600 to 700°C leads to a continuous decrease in strength limit ($\sigma_v$), tensile yield ($\sigma_{0.2}$) and to an increase in ductility and viscosity of steel. Mechanical properties of the samples at tempering temperatures of 650°C and 700°C in this case significantly differ from the samples tempered at 600°C (Fig. 2).
Figure 2. Dependence of various tempering modes on tensile yield and ultimate stress.

The strength characteristics have decreased:
- $\sigma_{0.2}$ by 30% (from 1448.6 to 1015 MPa),
- $\sigma_v$ by 29% (from 1705.4 to 1210 MPa, after tempering at 650°C);
- $\sigma_{0.2}$ by 47.7% (from 1448.6 to 756.5 MPa),
- $\sigma_v$ by 43.8% (from 1705.4 to 957.7 MPa, after tempering at 700°C).

The ductility and impact properties of the samples after tempering at 650°C have changed slightly compared to the samples tempered at 600°C. The relative elongation has increased from 5.6 to 7.9 %, the impact strength has increased from 11 to 14.8 J/cm$^2$ (Fig. 3). The value of the contraction ratio $\psi$ has remained almost unchanged (14.7–14.9 %).

Figure 3. Dependence of various tempering modes on impact toughness.

A significant increase in plasticity and viscosity is observed after tempering at 700°C:
- impact toughness has increased by 67% (from 11 to 34.2 J/cm$^2$),
- relative elongation $\delta$ - by 41.57,
- contraction ratio $\psi$ – by 42.94%.

Metallographic examination performed and analysis of the resulting mechanical properties have revealed an optimum combination of strength and ductility of steel grade 4H5MF1S during heat treatment, including quenching, down from 1070°C and tempering in the temperature range of 650-700°C. The tempering temperature selection in this case depends on the required metal product strength category.

The tempering temperature of 600°C in the case of steel grade 4H5MF1S, used as a structural material, is not recommended, due to the low impact strength and the presence of acicularity in the structure, inherited from the hardening martensite.
4. Summary
Based on the property comparison for steel grades 4H5MF1S, 4X5B2FS and 5XHM we have chosen an optimal steel grade 4H5MF1S for mandrel manufacturing that provides the best combination of price and quality. Analysis of the structure and mechanical properties allowed choosing the heat treatment mode for steel grade 4H5MF1S: hardening down from 1070°C in oil and tempering for 2 hours at a temperature of 650-700 ° C. After such treatment, this steel can be used as a heat-resistant structural material for metal products with a tensile yield σ0.2 from 750 to 1000 MPa.

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