Study of the Impact of Heat Treatment Modes on Formation of Microstructure and a Given Set of Mechanical Properties of High-Strength Flat Products with Guaranteed Hardness (400 to 450 HB) from Low-Alloyed Steel

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Abstract. The results of the study of influence of heat treatment modes on microstructure, size and shape of grains, mechanical properties of high-strength flat products from low-alloyed C-Mn-Cr-Si-Mo steel microalloyed by boron are presented. Heat treatment modes, which provide a combination of high impact viscosity at negative temperatures and guaranteed hardness, are determined.

1. Introduction

Production of high-strength rolled products (with hardness of 400 HB and more) with high impact viscosity, especially at negative temperatures, in combination with required mechanical properties is a challenging issue for steels used for manufacturing of mining equipment parts operated under conditions of high wear and impact stress.

Currently applied high-strength wear resistant steels represent low-alloyed C-Mn-Si steels containing about 0.15 to 0.25% of C, 0.8 to 1.5% of Mn, up to 0.6% of Si, usually micro-alloyed by boron and with the microstructure of lath high-dislocation martensite [1–3]. Hardness in such steels is proportional to carbon content in martensite [4, 5]. Mo, Cr, Ni and other elements are often added into steel to increase hardenability and resistance to softening during tempering, however, the amount of such elements is limited by requirements to weldability [2, 5, 6]. Increase of carbon content in martensite results in decrease of impact viscosity and cold resistance [4]. It is possible to increase impact viscosity of high-strength wear resistant steels by tempering, however, tempering at high temperatures causes considerable softening of steel, and low temperature tempering does not lead to significant improvement of the impact viscosity value [7, 8]. Moreover, reduction of impact energy because of cementite precipitation on boundaries of martensite laths is observed at low-temperature tempering in the temperature range of 300 to 400ºC. It is necessary to find additional ways to increase impact viscosity. Decrease of structure elements – grains or martensite packets – is an effective way to enhance strength and brittle fracture resistance at the same time. It is known that the martensite packet size directly depends on the initial austenite grain size. Decrease of the martensite packet size by means of reduction of the austenite grain size before quenching results in significant increase of steel viscosity characteristics [15].
Heat treatment, specifically quenching and tempering, provides a given set of mechanical properties in finished rolled products thanks to changes in the size and morphology of structural components [16]. Correct selection of heat treatment modes contributes to generation of austenite fine-grained structure before quenching and generation of the target structure providing a required set of steel properties. Addition of microallying elements also contributes to that [17].

The goal of this paper is to study the influence of heat treatment temperature parameters on formation of the microstructure, which ensures a combination of high strength and viscosity characteristics and hardness in flat products.

2. Materials and Research Methods

Samples of rolled products of industrial production out of low-alloyed C-Mn-Cr-Si-Mo steel microalloyed by boron were used for conducting the study. Chemical composition of the steel being studied is presented in Table 1. The study of kinetics of phase transformations with construction of a continuous cooling transformation diagram of austenite transformation at continuous cooling, provided on Figure 1, was carried out for steel of given composition. It can be seen that the martensite microstructure is formed in case of cooling at speed more than 20°C/sec. Critical points of phase transformations at steel heating, determined experimentally, represent the following values: $A_{c1}=740°C$ and $A_{c3}=840°C$.

| Table 1. Chemical composition of study steel. | Elements mass fraction, % | CEV, % | CET, % |
|-------------------------------------------|---------------------------|--------|--------|
| S  | Si  | Mn | P  | S  | Cr,Ni, Mo, Cu, Al, V, Ti, B, Nb, etc. | ≤ 2.0 | 0.57 | 0.40 |
| 0.24 | 0.61 | 1.01 | 0.009 | 0.002 | |

Note: Calculation of values of CEV and CET carbon equivalents is performed according to formulas:

$\text{CEV}=C+\frac{Mn}{6}+(Cr+Mo+V)/5+(Cu+Ni)/15$, %;

$\text{CET}=C+(Mn+Mo)/10+(Cr+Cu)/20+Ni/40$, %,

where C, Mn, Cu, Cr, Ni, Mo, V are mass fractions of chemical composition elements.

Flat products were manufactured by hot rolling on Mill-5000 at PAO Severstal. The study of influence of heat treatment modes on structure and mechanical properties was conducted on samples, thermally treated in laboratory furnaces. Temperature of heating of flat samples during quenching ranged from 770°C to 950°C with an interval of 30°C. After quenching, samples were subject to low temperature tempering. The received specimens were used for making samples for tensile testing (GOST 1497-84) and impact bending testing (GOST 9454-78), and for measuring hardness and studying microstructure, including through the use of transmission electron microscopy means. In order to determine boundaries of the initial austenite grain, pickling was performed in boiling oversaturated water solution of picric acid with addition of surface active agents. Quantitative parameters of microstructure were evaluated by Image Expert Pro 3 program.
3. Study Results and Their Discussion

Figure 2 shows a typical view of microstructure at different heat temperatures for quenching after special pickling to determine boundaries of prior austenite grains.

**Figure 1.** Continuous cooling transformation diagram of high-strength steel after heating up to 950°C and cooling in the range of speed of 0.5 to 200°C/sec.

**Figure 2.** View of steel microstructure at different heat temperatures for quenching, x 400
(a) 770°C; (b) 800°C; (c) 860°C; (d) 890°C; (e) 920°C; (f) 950°C.
The microstructure analysis demonstrates that the shape of grains of steel being studied is changing from elongated to equiaxed with increase of heating temperature, which is related to the process of \( \alpha \rightarrow \gamma \)-transformation at heating. Grains have elongated shape (Figure 2 (a), (b)) at heating temperature for quenching in the range of 770 to 830°C, and new equiaxed grains (Figure 2 (c) start to appear at further increase of heating temperature at the boundaries of elongated grains, that is, the process of initial recrystallization takes place ending at the temperature of about 890°C (Figure 2 (d)). The process of accumulative recrystallization is observed upon further increase of temperature of heating for quenching: grains are growing due to integration with other adjacent grains (Figure 2 (e), (f)).

The average diameter of equiaxed grains depending on the temperature of heating for quenching was evaluated by Image Expert Pro 3 program. The average grain size grows from 8.5 µm to 14 µm with increase of temperature of heating for quenching from 890°C to 950°C, which corresponds to grain number 9 – 10 according to GOST 5639-82, and the grain maximal diameter at these temperatures ranges from 17.5 to 40.5 µm, which is shown on Figure 3.

![Figure 3. Diameter of the steel equiaxed grain depending on temperature.](image)

Quenching from temperature of 890°C results in formation of the completely recrystallized structure consisting of quite small packets of tempered martensite of equiaxed shape (Figure 4 (a)). At the same time, high level of strength and impact viscosity is provided after low temperature tempering. The results of transmission electron microscopy (TEM) of a sample with quenching temperature of 890°C demonstrated that the structure of matrix consists of packets of high-dislocation lath martensite (Figure 4 (b)). The size of packets is from several microns to more than 10 µm, the typical width of laths is ~ 0.1 to 0.5 µm (individual laths up to ~ 1.5 µm). Plate-shaped carbide precipitates (cementite) were systematically identified inside martensite laths (Figure 4 (c)). Length of carbide plates is from few nanometres to ~ 150,200 nm. Precipitation of cementite films deteriorating impact viscosity were not observed on the boundaries of packets.

Figure 5 presents the influence of temperature of heating for quenching on mechanical properties of high-strength rolled products from low-alloyed C-Mn-Cr-Si-Mo steel microalloyed by boron.
Figure 4. Microstructure of rolled strips from study steel after quenching with heating to 890°C and tempering: (a) optical microstructure (pickling in 4% solution of nitric acid (HNO₃) in ethyl alcohol), ×400; (b) lath martensite, TEM, ×15,000, dark field in martensite reflex; (c) cementite precipitation inside martensite laths, TEM, x 30,000, dark field in cementite reflex.

Figure 5. Influence of quenching temperature on mechanical properties of high-strength rolled products from study steel: (a) yield stress, ultimate tensile strength, relative elongation; (b) impact viscosity at temperature of -40°C; (c) hardness.

As one can see on Figure 5 (a), the highest values of strength performance – offset yield stress (1,365 MPa) and ultimate tensile strength (UTS) (1,575 MPa) – are achieved after heating up to 890°C, quenching and further tempering. Impact viscosity achieves the maximal value at temperature of -40°C after quenching from 800°C, and impact viscosity decreases first at quenching from higher temperatures, and then it gradually increases up to the value of 60 J/cm², which complies with requirements to steel used at negative temperatures under conditions of impact loading (Figure 5 (b)). Hardness value is over 400 HB when temperature of heating for quenching increases from 860°C (Figure 5 (c)). Quenching of rolled strips with higher heating temperature (950°C) results in modest reduction of strength properties and impact viscosity.

4. Conclusions
Variations of optimal modes of heat treatment providing a combination of high level of impact viscosity, strength properties and hardness of flat products are determined.

The obtained study results enable optimisation of processes of heat treatment of high-strength flat products from low-alloyed C-Mn-Cr-Si-Mo steel microalloyed by boron for certain application conditions.
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