Choosing the Rational Heat Treatment Conditions for High-Strength Cold-Resistant Weldable Steel with Yield Strength of more than 600 N/mm$^2$

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Abstract. Rational heat treatment conditions for the new weldable cold-resistant steel grade 20G2SMRA ensuring a guaranteed yield strength $\sigma_{0.2} \geq 600$ N/mm$^2$ combined with the lowtemperature impact strength $KCV-60 \geq 50$ J/cm$^2$ have been searched. The effect of various quenching and tempering conditions on the steel microstructure parameters, hardness, and impact strength at a temperature of $-60 \, ^\circ C$ has been studied. The dependencies of the microstructure parameters, hardness (HV1), and impact strength ($KCV-60$) on the quenching and subsequent tempering temperature are represented. Rational heat treatment conditions have been found for a new weldable cold-resistant steel with high yield strength.

1. Introduction
The need for high-strength cold-resistant weldable steels to retrofit the mining and construction equipment has increased with the development of hard-to-reach northern and Arctic regions. These industries experience high demands on reducing metal consumption and manufacturing costs, as well as increasing load-bearing capacity, reliability, and service life. Correspondingly, complex requirements are applied to the mechanical characteristics of materials used for the manufacture of welded supporting system elements, i.e. high strength ($\sigma_{0.2} \geq 600$ N/mm$^2$, $\sigma_e = 700–1100$ N/mm$^2$) and weldability ($Ceqv \leq 0.53$), while maintaining allowable ductility and toughness at low temperatures ($KCV-60 \geq 50$ J/cm$^2$) [1–4].

According to the lean alloying concept, the steel quality and the highest chemical composition properties are determined by the heat treatment conditions [5–10]. In this case, choosing the processing scheme and parameters is of great importance.

According to [11–14], in the world and domestic practice, thermally improved high-strength weldable thick steel plates with a high yield strength are mainly supplied, capable of ensuring a yield strength of over 600 N/mm$^2$ combined with low-temperature toughness.

The main advantage of using quenching technology with high tempering relative to the direct heat treatment, in particular, for the development of new steel products with a thickness within 8 ... 50 mm is the removal of the size assortment restrictions for thicknesses above 20 mm at a minimum steel alloying degree [11].
In this case, the best combination of strength and toughness may be ensured if the steel hardness after quenching exceeds the minimum permissible values, which, in turn, is possible if quenched steel contains at least 90% martensite [12, 15–17]. Herewith, the choice of tempering temperature should ensure softening required to achieve a satisfactory strain capacity and machinability of the steel supplied [18].

Thus, the work objective is studying the effect of heat treatment conditions (quenching and tempering) on the structure and properties of new high-strength steel with elevated cold resistance.

2. The Research Material and Technique

The research material was specimens of the newly developed steel grade 20G2SMRA with a below chemical composition (Table 1) [19].

Table 1. Chemical Composition of the New Steel Grade 20G2SMRA.

| Steel Grade | C    | Si   | Mn    | S    | P    | Cr+Cu | Ni+Mo | Al  | Ti  | B  | Ceqv  |
|-------------|------|------|-------|------|------|-------|-------|-----|-----|----|-------|
| 20G2SMRA    | 0.200| 0.550| 1.60  | 0.005| 0.012| 0.16  | 0.35  | 0.050| 0.005| 0.0050| 0.53  |

The manufacture of experimental flat steel specimens and their subsequent heat treatment was performed at the scientific and production complex of LLC EC Thermodeform-MSTU and the CUC RI NanoSteel under FSBEI HE Nosov Magnitogorsk State Technical University (Magnitogorsk). The quenching and tempering temperature varied within the below ranges:

- quenching temperature gradually increased from Ac$_3$+30 °C to Tmax = 1000 °C in increments of 50 °C (with a holding of 2.5 min/mm at a quenching temperature);
- tempering temperature increased from 200 to 600 °C in increments of 100 °C (with a tempering duration of 2.5 min/mm + 25 min).

After quenching and tempering, the specimens were cooled by water and air, respectively.

According to the results of tests for micro-hardness and impact bending, for each steel, a heat treatment option has been determined, which provides the best combination of impact strength and the required level of hardness.

Tests for impact bending were performed using an impact tester RKP 450 according to GOST 9454 on transverse specimens 10.0 x 5.0 mm in size with a V-shaped cut. Test specimens were cooled to -40 °C in a LAUDA master PL1 refrigerator-thermostat.

The Vickers hardness was measured according to GOST 9450-60 by indenting a diamond pyramid with a 136° angle between the opposite faces using a Buehler Micromet Hardness Tester at a load of 1 kg.

Critical points were determined by differential scanning calorimetry (DSC) using an STA Jupiter 449 F3 (NETSCH) simultaneous thermal analyzer at a heating rate of 10 °C/min to 1000 °C in argon of 99.998% purity, as well as complex dilatometric analysis using the Gleeble 3500 simulator [9, 10].

To study the microstructure, the specimens were ground polished and etched in a 4% nital by immersion of the polished surface in a bath with the reagent.

Qualitative and quantitative analysis was performed using an Axio Observer (Zeiss) optical microscope with a 50-1000-fold increase using the Thixomet PRO metallographic image processing software and a scanning electron microscope (SEM) - JSM 6490 LV.
The volume fraction of phases was determined by separating the fraction of the relevant structural components using the Thixomet PRO software with built-in techniques adapted according to GOST 8233-56 [20]. The data obtained were statistically processed in the Microsoft Office Excel environment.

The steel grain size was determined according to GOST 5639. The average austenite grain size was determined by linear measurements using software with built-in techniques [20], adapted according to GOST 8233 and GOST 5639. The former austenite grain boundaries were determined by etching specimens in a freshly prepared picric acid solution saturated at room temperature with the addition of (1–10) % surfactants while heating the reagent to (50–70) °C [21].

3. The Study Results

Based on the DSC results and dilatometric analysis, the critical points have been determined for the new steel grade 20G2SMRA (Table 2) [20].

| Steel Grade | Research Technique | Critical Temperature t, °C |
|-------------|--------------------|---------------------------|
|             |                    | $A_{c1}$ | $A_{c3}$ |
| 20G2SMRA    | DSC                | 725      | 814      |
|             | Dilatometer        | 730      | 820      |

The Results of the Quenching Temperature Effect on the Steel Structure and Properties

Using optical microscopy, it has been found that after quenching from 850 to 1000 °C in all cases, the steel grade 20G2SMPA studied has a similar morphological structure of packet (lath) martensite formed according to the diffusion-free shearing mechanism by transverse sliding (Figure 1, a, b).

Analysis performed using SEM (Figure 2, a, b) has shown that in the 20G2SMRA steel $\alpha$-phase structure, the predominant morphological component is lath martensite (Ml), the volume fraction of which exceeds 70%. The area of martensitic packets increases from 20 to 500 μm², depending on the quenching temperature. The width of the individual laths making up the packet varies within 150 to 800 nm. The total number of laths in the packet varies from 4–6 to 12–16 pieces.

Also, the structure includes individual plates, the transverse size of which is several times larger than the width of individual laths of martensite packets, and reaches 1–3 μm. The plate length is about 30 μm. This morphology can be identified as plate martensite (Mp), the presence of which causes a decrease in the stress amplitude and, as a result, a decrease in the risk of quenching cracks.
The results of studying the dependence of the steel microstructure parameters (actual size of austenite grain) on the quenching temperature and its relationship with mechanical properties are shown in Figure 3.

The data obtained (Figure 3) has shown that the smallest grain size is within 16-18 μm (grain No. 9). The increase in structural parameters observed indicates an increase in the actual austenite grain size (grain No. varies from 8 to 5) caused by an increase in the austenitization temperature, which leads to a decrease in the impact strength of steel within 850–1000 °C.

Within the entire temperature range under study, the hardness HV1 has similar values due to the constant chemical composition of the initial austenite in hypereutectoid steels, which changes when temperature increases above the AC3 point [22].

According to the experimental study results, the maximum impact strength KCV-60 combined with satisfactory hardness HV1 for steel grade 20G2SMPA is achieved at a quenching temperature of ~ 850 °C.

The Results of the Tempering Temperature Effect on the Steel Structure and Properties

During the study, it was found (Figure 4) that within the tempering temperature from 200 to 500 °C, there are no qualitative changes in the martensite morphology, and the lath α phase structure is preserved up to 500 °C. However, an ever-stronger distortion of the lath boundary shape and structure is observed with an increase in the tempering temperature caused by the formation of a fragmented substructure due to the...
relaxation of the defective structure formed as a result of the $\gamma \rightarrow \alpha$ transformation and rearrangement of the dislocation structure.

Also, the process is accompanied by the release of the second phase particles; the initial stage of the most intense decomposition of the supersaturated solid solution is fixed at 300 °C, which is accompanied by an increase in the ductile-brittle transition temperature. At a tempering temperature of 400 °C and more, coagulation and spheroidization of carbide particles are observed, contributing to a change in the $\alpha$ phase morphology in the sequence ‘tempered martensite $\rightarrow$ tempered troostite $\rightarrow$ tempered troostosorbite’. At a tempering temperature of 600 °C, tempered sorbite becomes the basic structural component.

![Steel Microstructure](image)

**Figure 4.** Steel Microstructure after Quenching from 850 °C and Subsequent Tempering at: 300 (a), 400 (b), 500 (c), 600 (d) °C. SEM.

The setup tempering temperature was determined based on its effect on structural changes and, as a result, the hardness HV$_1$ and impact strength KCV$^{-60}$ (Figure 5).

![Graph](image)

**Figure 5.** Effect of Tempering Temperature on the Distribution of Hardness HV$_1$ and Impact Strength KCV$^{-60}$ in Steel Grade 20G2SMRA.
Figure 5 shows that against the background of a monotonous decrease in hardness (HV$_1$) within 200 to 400 °C, the impact strength (KCV$_{60}$) decreases relative to the quenched state, which indicates the development of irreversible temper brittleness. When tempering within 500–600 °C, a drop in impact strength is not observed due to the Mo presence in the steel composition.

A change in the tempering temperature within 400–600 °C leads to a noticeable decrease in the microhardness magnitude by about 1.5 times due to a decrease in the internal shear stresses in lath martensite. Herewith, with a temperature increase, the cold brittleness threshold of steel grade 20G2SMRA is significantly reduced.

Thus, based on the dependencies obtained (Figure 3, 5), it has been found that the processing conditions of quenching from 850 °C followed by high tempering at 600 °C meet the requirements set for new steel grade 20G2SMPA.

4. Conclusion

As a result of studying the new weldable cold-resistant 20G2SMRA steel grade, dependencies of the microstructure parameters, hardness (HV$_1$), and impact strength (KCV$_{60}$) on the quenching and subsequent tempering temperature have been obtained.

It has been established that the best heat treatment conditions to strengthen flat products made of new high-strength steel grade 20G2SMRA are as follows:

- quenching from 850 ± 20 °C for 25 minutes, at which a mixed structure is formed consisting of 70 % lath martensite and about 30 % high-temperature plate martensite, which ensures
- maximum impact strength KCV$_{60} = 40$ J/cm$^2$ at satisfactory hardness HV$_1$ 452;
- subsequent high tempering at 600 °C for 40 min, at which a tempered sorbitol structure is formed, which ensures guaranteed achievement of the required hardness HV$_1$ 291 combined with impact strength KCV$_{60} = 61$ J/cm$^2$.

Ensuring such a favorable combination of strength and toughness at a test temperature of up to -60 °C allows using the new steel grade 20G2SMRA in structures operating in the Far North.

Reference

[1] Khlusova E I and Sych O V 2018 Creating Cold-Resistant Structural Materials for the Arctic. History, Experience, Current State Innovations 11(241) 85–92
[2] Stolyarov V I, Nikitin V N, Efron L I and Lazko V G 1993 State and Prospects of Development of Technology and Composition of High-Strength Weldable Steels with a Yield Strength of 700 N/mm$^2$ Steel 6 61–67
[3] Chukin M V, Poletskov P P and Nabatchikov D G 2017 Analysis of Technical Requirements for Ultra-Cold-Resistant Flat Products Bulletin of the South Ural State University. Series: Metallurgy 17(2) 52–60
[4] Chukin M V, Poletskov P P and Gushchina M S 2019 Development of Import-Substituting Technology to Manufacture Flat Products from High-Strength Structural Steel of the Northern Version Manufacture of Flat Products 4 5–11
[5] Solntsev Y P and Titova T I 2002 Steel for the North and Siberia (St. Petersburg: Khimizdat) p 352
[6] Solntsev Yu P 2005 Cold Resistant Steels, and Alloys (St. Petersburg: Khimizdat) p 480
[7] Poletskov P P, Gushchina M S and Berezhnaya G A 2015 Studying the Effect of Heat Treatment on the Mechanical Properties of High-Strength Flat Products Bulletin of the Nosov Magnitogorsk State Technical University 4(52) 88–92
[8] Salganik V M, Poletskov P P and Gushchina M S 2015 Specifics of Obtaining Nanostructured High-Strength Flat Products Bulletin of the Sukhoy Gomel State Technical University 1(60) 27–30
[9] Poletskov P P, Denisov S V and Nikitenko O A 2019 Studying the Decomposition of Supercooled Austenite in Low-Carbon Pipe Steel Using the Gleeble 3500 Complex News of Higher Educational Institutions. Ferrous Metallurgy 62(3) 235–240
[10] Poletskov P P, Nikitenko O A, Kuznetsova A S and Efimova Y Y 2019 Investigation of the Effect of Nickel Content on the Structural and Phase Transformation and Properties of High-Strength Cold-Resistant Complex-Alloyed Steel Journal of Chemical Technology and Metallurgy 54(6) 1291–1297

[11] Nikitin V N, Nastich S Yu and Smirnov L A 2016 High-Strength Steels with Lean Alloying for Quarrying and Mining Equipment Steel 10 57–66

[12] Pontremoli M, Weber L, Dilg K, Schwinn F, Knauf G, Lippe M, Erhardt B, Finger M 2006 High-Strength Steels for Thick Sheets, Pipes, and Profiles Ferrous Metals 4 58–66

[13] Schröter F 2003 Höherfeste Stähle für den Stahlbau – Auswahl und Anwendung Bauingenieur 78(9) 426–432

[14] Kern A and Schriever U 2005 Niobium in Quenched and Tempered HSLA-Steels Recent advances of niobium containing materials in Europe Proceedings of the symposium of the 30th anniversary of Niobium Products Company 109–119

[15] Yeh Y 1979 Heat Treatment of Steel (Moscow: Metallurgy) p 264

[16] Juna H J, Kanga J S, Seob D H, Kangb K B and Park C G 2006 Effects of Deformation and Boron on Microstructure and Continuous Cooling Transformation in Low Carbon HSLA Steels Materials Science and Engineering A 422 157–162

[17] Luxenburger G, Bockelmann M and Wolf P 2004 High Strength Quenched and Tempered (Q T) Steels for Pressure Vessels International Journal of Pressure Vessels and Piping 81(2) 159–171

[18] Meskin V S 1964 Steel Alloying Fundamentals (Moscow: Metallurgy) p 684

[19] Poletskov P P, Nikitenko O A, Kuznetsova A S and Salganik V M 2020 Studying the Kinetics of Phase Transformations during the Decomposition of Supercooled Austenite of New High-Strength Steel of High Cold Resistance CIS Iron and Steel Review 19 56–59

[20] Koptseva N V, Chukin M V and Nikitenko O A 2012 Use of the Thixomet PRO software for Quantitative Analysis of the Ultrafine-Grain Structure of Low-and Medium-Carbon Steels Subjected to Equal Channel Angular Pressing Metal Science and Heat Treatment 54(7–8) 387–392

[21] Poletskov P P, Gushchina M S and Alekseev D Yu 2018 Studying the Effect of Controlled Pipe Steel Rolling on the Structural State of Hot-Deformed Austenite Bulletin of the Nosov Magnitogorsk State Technical University 16(3) 67–77

[22] Sadovsky V D and Fokina E A 1986 Residual Austenite in Quenched Steel (Moscow: Nauka) p 113

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