doi: 10.18323/2782-4039-2024-2-68-5

The study of transformations of supercooled austenite during step quenching of 20Cr2Mn2SiNiMo steel

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Received 26.06.2023 *Accepted 26.01.2024*

Abstract: Currently, step quenching of steels in the temperature range of martensitic transformation, including quenching – partitioning, has found wide application in the automotive industry. Step quenching technology is successfully used to increase a set of properties, which most often include temporary tensile strength and relative elongation. The authors carried out a dilatometric study of the supercooled austenite transformations occurring in the 20Cr2Mn2SiNiMo steel, when implementing various options of step quenching with holding in the martensitic region. It was found that after single-stage quenching, single-stage quenching followed by tempering, and two-stage quenching, primary martensite, isothermal bainite, and secondary martensite are formed in various quantitative ratios. Using X-ray diffraction phase analysis, the amount of residual austenite was determined during step quenching. It has been shown that two-stage quenching makes it possible to stabilise up to 14 % of residual austenite, in the structure of the studied steel, at room temperature. Research has revealed that 20Cr2Mn2SiNiMo steel is characterised by a decrease in the crystal lattice parameter of the residual austenite, with an increase in its content in the steel structure. Uniaxial tensile and impact bending tests were carried out, and the values of the mechanical properties were determined. It has been found that during two-stage quenching, higher strength and elongation values, with lower values of relative contraction and impact strength are achieved compared to oil quenching and low-temperature tempering. The study showed that, with regard to the structural reliability of machine-building parts, step quenching is not the optimal heat treatment mode for the steel under study. The best combination of strength, ductility and impact hardness is achieved after quenching and low-temperature tempering.

Keywords: supercooled austenite transformations; step quenching; 20Cr2Mn2SiNiMo steel; 20Cr2Mn2SiNiMo; quenching – partitioning; isothermal quenching; quenching and tempering; residual austenite; primary martensite; isothermal bainite; secondary martensite.

Acknowledgments: The study was supported by the Russian Science Foundation grant No. 22-29-00106, https://grant.rscf.ru/prjcard_int?22-29-00106.

The paper was written on the reports of the participants of the XI International School of Physical Materials Science (SPM-2023), Togliatti, September 11–15, 2023.

For citation: Maisuradze M.V., Kuklina A.A., Nazarova V.V. The study of transformations of supercooled austenite during step quenching of 20Cr2Mn2SiNiMo steel. *Frontier Materials & Technologies*, 2024, no. 2, pp. 53–65. DOI: 10.18323/2782-4039-2024-2-68-5.

INTRODUCTION

Step quenching of steels, in the temperature range of martensitic transformation, has found wide application in the automotive industry. In particular, the quenching – partitioning concept was developed, which is based on the assumption of the quasi-equilibrium of martensite α-phase, and austenite γ-phase during isothermal holding in the range from the beginning to the end of the M_n...M_k martensitic transformation [1]. If this condition is met, carbon from the supersaturated martensite α-phase diffuses into the surrounding unconverted austenite, thereby changing its chemical composition. As a result, upon further cooling to room temperature, no transformations occur, and the carbon-enriched residual austenite remains in a stable state. However, to implement such a scenario, it is necessary that there are no competing processes leading to a decrease in the residual austenite amount, and the degree of its enrichment with carbon (the formation of bainite and precipitation of carbide phase particles).

The quenching – partitioning technology of step quenching, in various variants is successfully used to increase a set of properties, which most often include tensile strength and relative elongation [2; 3], as the most important for the production of high-strength sheet parts for the automotive industry using deep drawing. For this purpose, special grades of Quenching–Partitioning steels (QP steels) alloyed mainly with silicon, manganese and aluminium are being developed [4]. Step quenching is also used when producing mechanical engineering parts from structural steels [5]. In this case, as in the case of specially developed QP steels, significant deviations of the practically obtained results, from the theoretically predicted ones, are observed [6]. In particular, the volume fraction of residual austenite in the structure of steels after step quenching in the vast majority of cases turns out to be less than the calculated value [7]. This is related to the fact that it is almost impossible to exclude the formation of bainite and carbides in the steel structure during isothermal holding. The precipitation of carbides and the formation of bainite cannot but affect such properties of steel as impact strength and relative contraction. These characteristics are rarely analysed in published works, despite their practical significance in relation to constructional steels: the impact strength of steel has a certain correlation with wear resistance [8; 9], and the relative contraction – with the endurance limit [10; 11].

The purpose of this work is to study the transformations occurring in high-strength constructional 20Cr2Mn2SiNiMo steel during step quenching.

METHODS

The chemical composition of the steel under study is given in Table 1.

The transformation of supercooled austenite was studied using a LINSEIS L78 R.I.T.A dilatometer. Dilatometric samples had a diameter of 4 mm and a length of 10 mm. Heating and holding at the austenitisation temperature (900 °C, 20 min) were carried out in a vacuum; cooling of the samples to the isothermal holding temperature, was carried out at a given rate (20 °C/s) in a helium flow. Fig. 1 shows the diagram of heat treatment modes (QP1 – single-stage quenching; QP2 – two-stage quenching; QPT – single-stage quenching with tempering), of the steel under study during dilatometric studies.

To assess quantitatively the microstructure formed in 20Cr2Mn2SiNiMo steel during step quenching, the lever rule was used in relation to dilatometric curves [12; 13]. The temperature of the first quenching stage (280 °C), was determined according to the procedure used for QP steels [14; 15]. According to calculations, at a given cooling interruption temperature, the maximum amount of residual austenite (up to 25 %) should be stabilised in the structure of the steel under study. The temperature of the second stage of holding (350 °C) was chosen in the M_n temperature region of the steel under study (345±5 °C).

The indicated step quenching modes were implemented, during laboratory heat treatment of prismatic blanks with the dimensions of 12×12×65 mm, from which samples for mechanical uniaxial tension and impact bending tests were subsequently made. For heat treatment, SNOL laboratory chamber furnaces (austenitisation, tempering) and SShOL shaft crucible furnaces (isothermal holding) with molten salt (50 % KNO_3 + 50 % $NaNO_3$) were used. Cooling of the samples to room temperature was carried out in I20A quenching oil. After step quenching, all samples were subjected to low-temperature tempering at 180 °C for 2 h.

Mechanical properties under uniaxial tension, were determined in accordance with GOST 1497 on an Instron installation at room temperature. For the analysis, cylindrical samples (type III) with a working part diameter of 6 mm, and a working part length of 30 mm were used. Impact bending tests were carried out using a pendulum impact tester, in accordance with GOST 9454, at room temperature on standard samples, with a *V*-shaped stress concentrator (type 11).

X-ray structural phase analysis, was carried out on a Bruker D8 Advance X-ray diffractometer in Co–Kα radiation, in the range of reflection angles of 2θ=45...130° at voltage U=35 kV, tube current I=40 mA. Quantitative X-ray phase analysis was carried out according to the reference-free full-profile Rietveld analysis method using the TOPAS® 4.2 software package.

The microstructure was studied using a Jeol JSM 6490 scanning electron microscope.

RESULTS

A dilatometric study of the transformations occurring in 20Cr2Mn2SiNiMo steel during QP1 single-stage quenching showed that upon cooling to the first stage temperature (280 °C), a significant amount of M1 primary martensite is formed. The temperature at which primary martensite begins to form in the steel under study is 345 °C (arrow 1 in Fig. 2 a). During cooling interruption and holding for 10 min (arrow 2 in Fig. 2 a), the size of the sample continues to increase, which indicates the development of an isothermal bainite transformation (Fig. 2 b). Upon final cooling from a temperature of 280 °C, the formation of M2 secondary martensite is observed (arrow 3 in Fig. 2 a). The temperature at which the secondary martensitic transformation begins in the case of single-stage quenching is 215 °C.

Table 1. *Chemical composition of 20Cr2Mn2SiNiMo steel*
Таблица 1. *Химический состав стали 20Cr2Mn2SiNiMo*

Chemical element	C	Cr	Mn	Si	Ni	Mo	S	P
wt. %	0.220	1.960	2.020	0.960	1.090	0.310	0.002	0.010

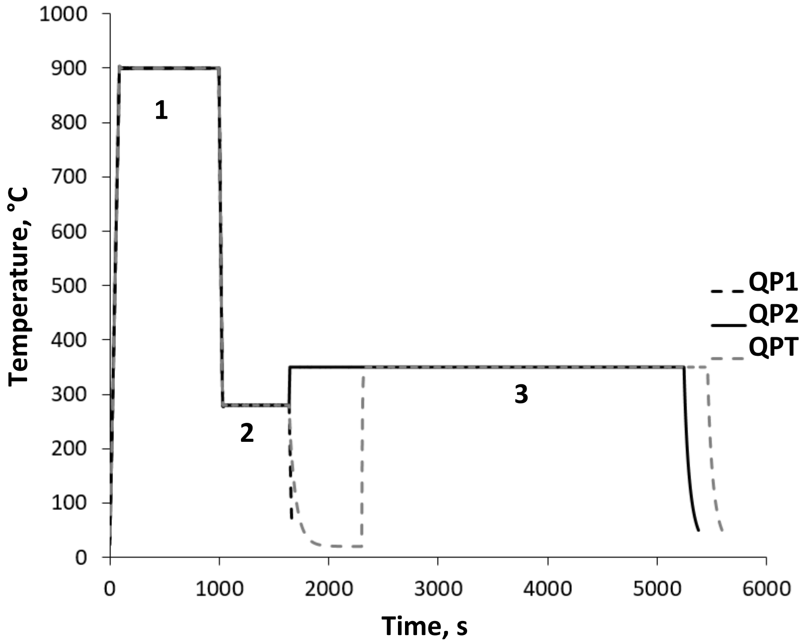


***Fig. 1.** Scheme of implemented modes of step quenching of 20Cr2Mn2SiNiMo steel:*
QP1 – single-stage quenching; QP2 – two-stage quenching;
QPT – single-stage quenching with tempering.
1 – austenitisation, 900 °C, 20 min; 2 – first stage, 280 °C, 10 min;
3 – second stage, 350 °C, 60 min
***Рис. 1.** Схема реализованных режимов ступенчатой закалки стали 20Х2Г2СНМА:*
QP1 – одноступенчатая закалка; QP2 – двухступенчатая закалка;
QPT – одноступенчатая закалка с отпуском.
1 – аустенитизация, 900 °C, 20 мин; 2 – первая ступень, 280 °C, 10 мин;
3 – вторая ступень, 350 °C, 60 мин

In the case of QP2 two-stage quenching, upon cooling from the austenitisation temperature to the first stage temperature (280 °C), just as in the case of QP1, the formation of M1 primary martensite occurs (the transformation onset temperature is 345 °C, arrow 1 in Fig. 3 a), after which some isothermal bainite is formed (arrow 2 in Fig. 3 a). After holding at a temperature of 280 °C for 10 min, the sample was heated to a temperature of 350 °C to increase the carbon diffusion rate. However, as dilatometric studies showed, when the second stage temperature was reached, the formation of bainite continued in the steel under study (Fig. 3 b).

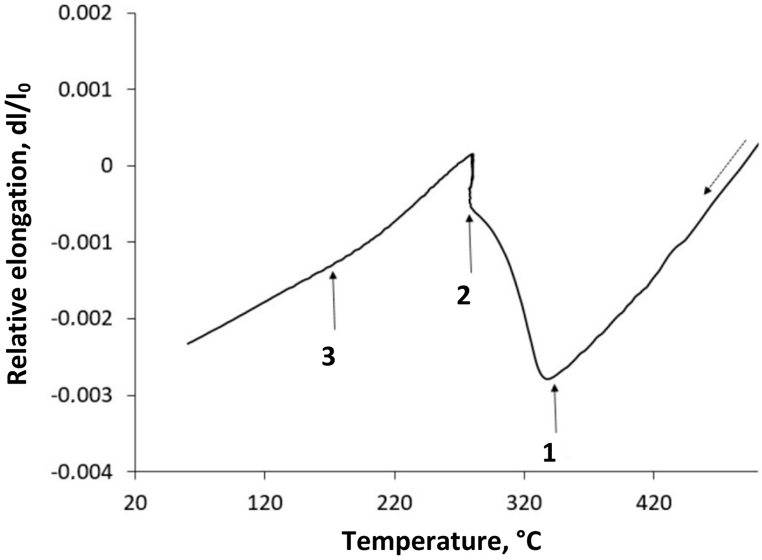
In the case of QPT single-stage quenching with medium-temperature tempering, a mixture of M1 primary martensite (arrow 1 in Fig. 4 a), isothermal bainite formed at the first stage of treatment at a temperature of 280 °C (arrow 2 in Fig. 4 a), and M2 secondary martensite, the temperature of the formation onset which is 215 °C (arrow 3 in Fig. 4 a), was heated to a temperature of 350 °C. During holding at a temperature of 350 °C, no changes in the sample dimensions occur (Fig. 4 b), and upon subsequent cooling, only a slight deviation from the linear dependence is observed, associated with the formation of no more than 3 % of a new portion of M2 secondary martensite (arrow 5 in Fig. 4 a).

By calculations, dependences of the formed α-phase fraction on the temperature were obtained not taking into account residual austenite (Fig. 5). In particular, it was found that when implementing QP1 single-stage quenching, 73 % of primary martensite, 11 % of bainite and 16 % of secondary martensite are formed in the steel structure (Fig. 5 a); and with QP2 two-stage quenching – 75 % of primary martensite, 16 % of bainite (in total at the first and second stages of treatment), and 9 % of secondary martensite (Fig. 5 b).

After setting the structural-phase composition of the steel under study, taking into account the amount of residual austenite, the diagram shown in Fig. 6 was constructed.

Fig. 7 shows the lattice parameter values of residual austenite in the 20Cr2Mn2SiNiMo steel structure, after step quenching and isothermal quenching, at a temperature of 320 °C. The highest austenite lattice parameter is observed during single-stage quenching followed by tempering (Fig. 7 a). In 20Cr2Mn2SiNiMo steel at a holding temperature of 320 °C, the amount of residual austenite in the structure increases with increasing holding duration from 5 to 10 %, and the austenite crystal lattice parameter decreases from 3.6068 to 3.6037 Å.

The results of a metallographic study of the 20Cr2Mn2SiNiMo steel microstructure are shown in Fig. 8. In the case of QP1 single-stage quenching and QPT single-stage quenching with tempering, a pronounced edging of the primary martensite and bainite packets with



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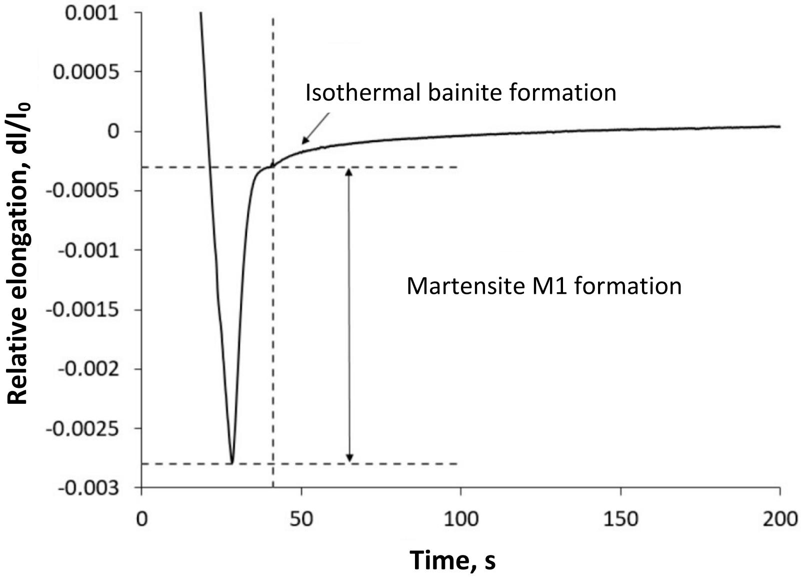


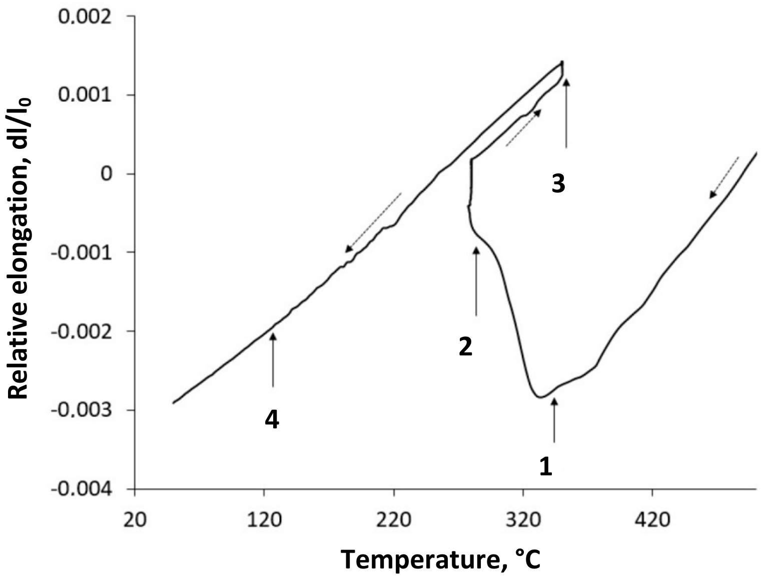
b

Fig. 2. *The dependence of relative elongation of the 20Cr2Mn2SiNiMo steel sample on the temperature (**a**) and time (**b**) when implementing QP1 single-stage quenching.*
1 – M1 primary martensite formation; 2 – isothermal holding at 280 °C, 10 min; 3 – M2 secondary martensite formation
Рис. 2. *Зависимость относительного удлинения образца стали 20Х2Г2СНМА от температуры (**a**) и времени (**b**) при реализации одноступенчатой закалки QP1.*
1 – образование первичного мартенсита М1; 2 – изотермическая выдержка при 280 °С, 10 мин; 3 – образование вторичного мартенсита М2

residual austenite, is observed (Fig. 8 a, 8 b). Moreover, in the case of QPT single-stage quenching with tempering (Fig. 8 b), the austenitic edging of the α-phase packets is more pronounced, which indicates an additional carbon outflow from martensite (primary and secondary) and bainite during the tempering process. In the case of two-stage quenching, no such pronounced boundaries were identified, and the secondary martensite/residual austenite areas have a diffuse structure (Fig. 8 c).

Table 2 shows the mechanical properties of the studied 20Cr2Mn2SiNiMo steel after step quenching, as well as after other heat treatment modes that provide a similar level of strength (isothermal quenching for 2 h at temperatures of 280 and 300 °C; oil quenching and tempering at temperatures of 200 and 300 °C).

Fig. 9 shows comparative diagrams of the mechanical properties of the steel under study after various heat treatment modes.



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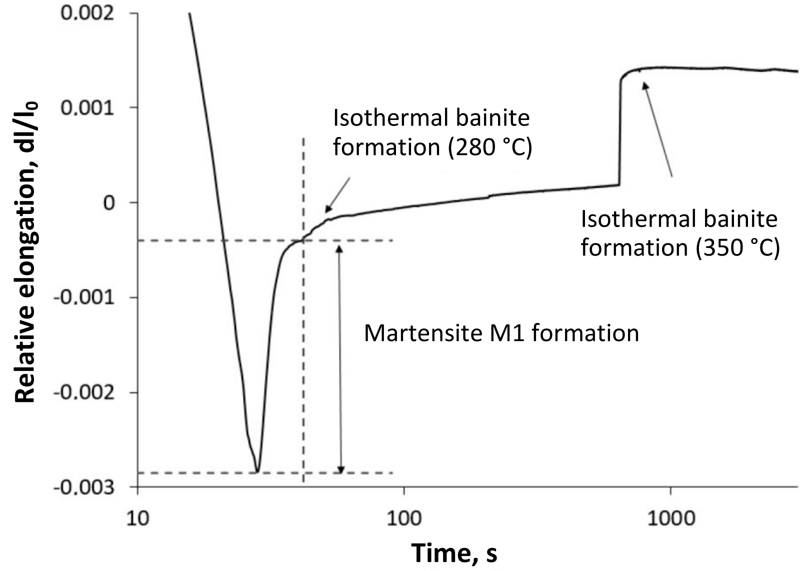


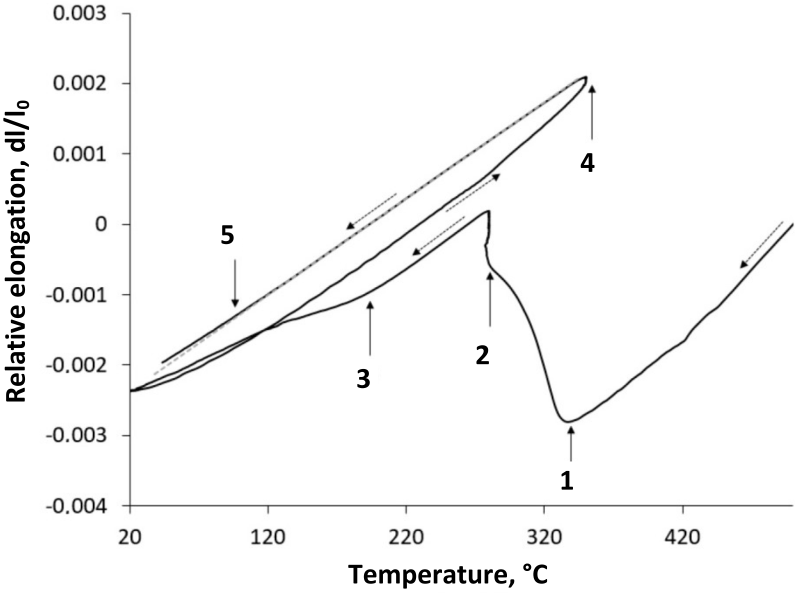
b

***Fig. 3.** The dependence of relative elongation of the 20Cr2Mn2SiNiMo steel sample on the temperature (**a**) and time (**b**) when implementing QP2 two-stage quenching.*
1 – M1 primary martensite formation; 2 – isothermal holding at 280 °C, 10 min;
3 – isothermal holding at 350 °C, 60 min; 4 – M2 secondary martensite formation
***Рис. 3.** Зависимость относительного удлинения образца стали 20Х2Г2СНМА от температуры (**a**) и времени (**b**) при реализации двухступенчатой закалки QP2.*
1 – образование первичного мартенсита M1; 2 – изотермическая выдержка при 280 °С, 10 мин;
3 – изотермическая выдержка при 350 °С, 60 мин; 4 – образование вторичного мартенсита M2

DISCUSSION

In 20Cr2Mn2SiNiMo steel, during QP1 single-stage hardening, the decrease in the martensitic transformation temperature after holding at a temperature of 280 °C (Fig. 2 a) is associated with the enrichment of unconverted austenite with carbon. Nevertheless, the presence of a secondary martensitic transformation indicates an insufficient carbon content in austenite to shift the M_n temperature below room temperature. This is a deviation from one of the main provisions of the quenching – partitioning theory (complete stabilisation of austenite during cooling suspension).

In the case of QP2 two-stage quenching during holding at 350 °C after the suspension of bainite formation, a decrease in sample size by 2 % is observed (Fig. 3 b), which is associated both with the processes of tempering the primary martensite and bainite α-phase, and with the diffusion carbon redistribution between the α-phase and austenite. With further cooling from the second stage temperature,



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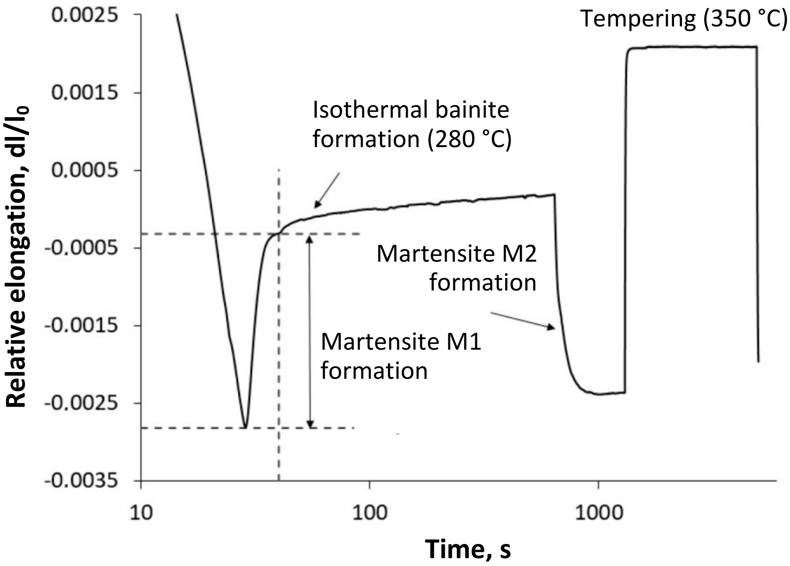
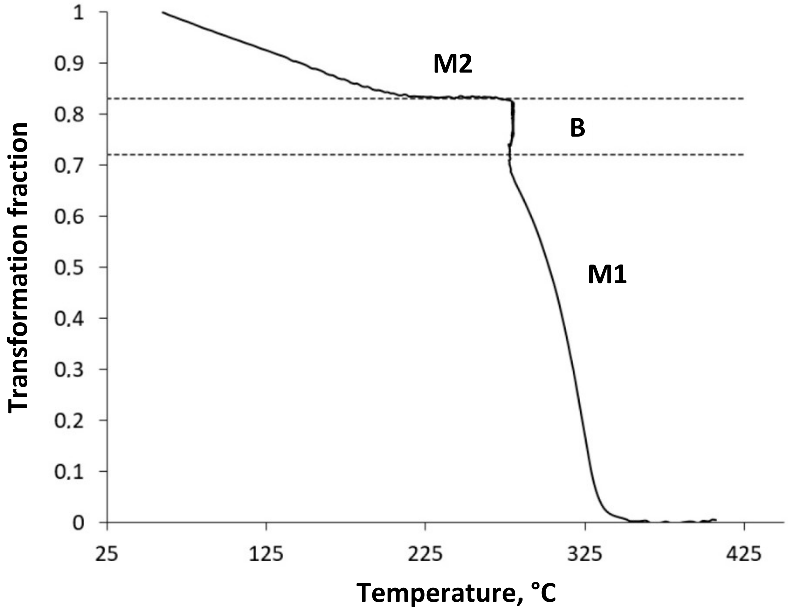


b

Fig. 4. *The dependence of relative elongation of the 20Cr2Mn2SiNiMo steel sample on the temperature (**a**) and time (**b**) when implementing QPT single-stage quenching with tempering.*
1 – M1 primary martensite formation; 2 – isothermal holding at 280 °C, 10 min; 3 – M2 secondary martensite formation; 4 – holding during tempering, 350 °C, 60 min; 5 – M2 secondary martensite formation
Рис. 4. *Зависимость относительного удлинения образца стали 20Х2Г2СНМА от температуры (**a**) и времени (**b**) при реализации одноступенчатой закалки с отпуском QPT.*
1 – образование первичного мартенсита М1; 2 – изотермическая выдержка при 280 °С, 10 мин; 3 – образование вторичного мартенсита М2; 4 – выдержка при отпуске, 350 °С, 60 мин; 5 – образование вторичного мартенсита М2

the secondary martensitic transformation begins at temperatures below 140 °C (Fig. 3 a). This is associated, firstly, with a smaller (compared to QP1) amount of unconverted austenite at the start of cooling, since the bainite transformation continues during holding at the second stage, and secondly, with a more effective stabilisation of residual austenite. As X-ray diffraction phase analysis showed, after QP1 single-stage quenching, the steel under study contains about 6 % of residual austenite, and when implementing QP2 two-stage quenching at room temperature, 14 % of residual austenite is stabilised.

In the case of QPT single-stage quenching, with medium-temperature tempering, the temperature at which the secondary martensite formation is observed is about 95 °C (Fig. 4 a). The amount of residual austenite stabilised in the structure of the steel under study, after QPT step quenching is practically no different from the result obtained with QP1, single-step quenching and is about 8 %. Thus, medium-



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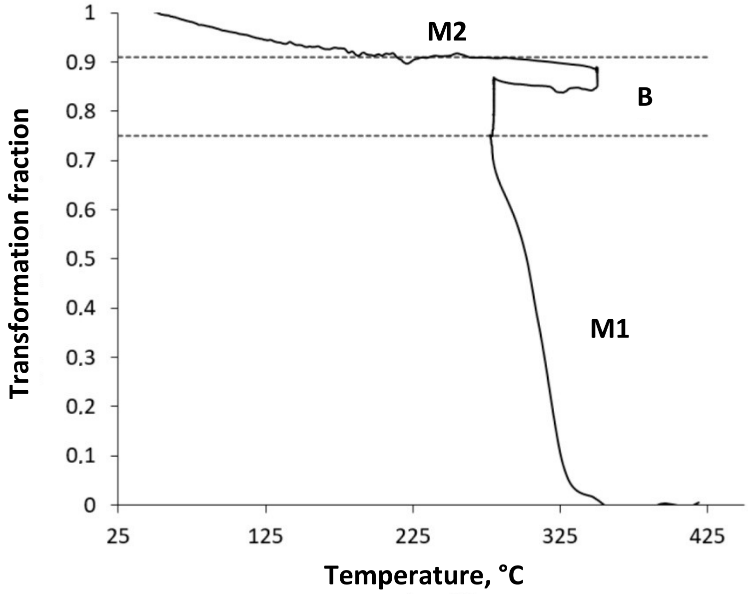


b

Fig. 5. *The dependence of the fraction of transformation of supercooled 20Cr2Mn2SiNiMo steel austenite, on the temperature, during step quenching (without taking into account residual austenite):* ***a*** *– QP1;* ***b*** *– QP2*

Рис. 5. *Зависимость доли превращения переохлажденного аустенита стали 20Х2Г2СНМА от температуры при реализации ступенчатой закалки (без учета остаточного аустенита):* ***a*** *– QP1;* ***b*** *– QP2*

temperature tempering after single-stage quenching does not lead to a noticeable change in the quantitative ratio of the structural components. During heating to a temperature of 350 °C, a nonlinear dependence of the relative elongation on the temperature is dilatometrically recorded, which indicates the occurrence of tempering and stress relaxation processes.

When implementing QPT single-stage quenching with tempering, the microstructure composition is practically no different from that obtained in the case of QP1 single-step quenching. Two-stage quenching leads to an increase in the residual austenite content in the structure, mainly due to a reduction in the secondary martensite amount (Fig. 6). In this case, the residual austenite lattice parameter after QP2 two-stage heat treatment, is less than after QP1 and QPT single-stage treatment (Fig. 7). Studies of 20Cr2Mn2SiNiMo steel have shown that it is characterised by a decrease in the residual austenite crystal lattice parameter, with an increase in its content in the steel structure. This phenomenon is associated with the fact that with an increase in the volume fraction of carbon-enriched unconverted austenite, present in the steel at the end of the isothermal holding, the carbon concentration in it is leveled out and averaged, which influences

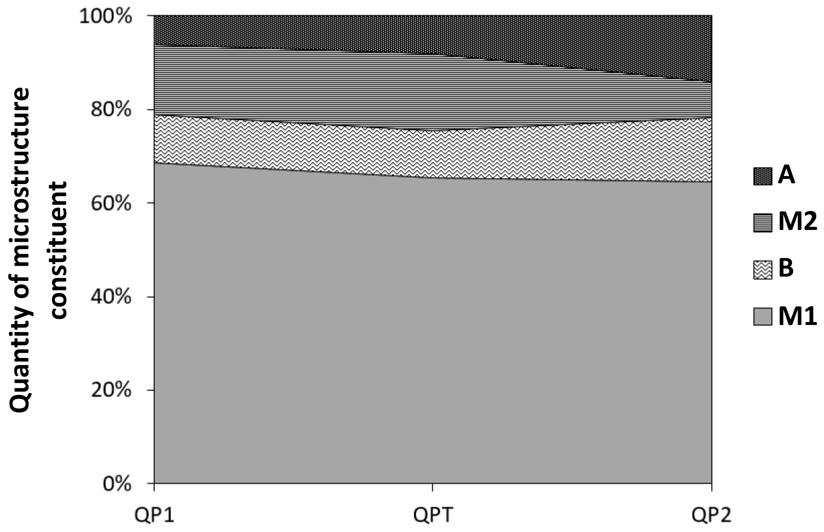


Fig. 6. *The ratio of the 20Cr2Mn2SiNiMo steel structural components after the implementation of various options of step quenching. M1 – primary martensite; B – bainite; M2 – secondary martensite; A – residual austenite*

Рис. 6. *Соотношение структурных составляющих стали 20Х2Г2СНМА после реализации различных вариантов ступенчатой закалки. M1 – первичный мартенсит; B – бейнит; M2 – вторичный мартенсит; A – остаточный аустенит*

the crystal lattice parameter value. In the case of QP1 single-stage quenching, the temperature and duration of isothermal holding (280 °C, 10 min) are insufficient for the bainite transformation completion and diffusion equalisation of the carbon concentration in unconverted austenite. As a result of this, austenite is significantly enriched in carbon only in volumes immediately adjacent to the martensite and bainite packets (which amounted to 6...8 % of the total metal volume), and in the remaining volume of unconverted austenite, the carbon concentration is insufficient to lower the M_n temperature below room temperature. Due to this, cooling from the isothermal holding temperature led to the formation of M2 secondary martensite at a temperature of 215 °C and below.

In the case of two-stage quenching, heating to a temperature of 350 °C ensured a more complete occurrence of the bainite transformation, due to which the volume of unconverted austenite was largely crushed by α-phase packets. Along with the increased temperature, this contributed to a more intense diffusion of carbon atoms from the boundaries with α-phase deep into the unconverted austenite volumes. As a result, the secondary martensitic transformation during cooling proceeded less intensely and at a lower temperature (140 °C) compared to the QP1 mode (single-stage quenching), and the volume of austenite enriched in carbon sufficiently to reduce the M_n temperature below 20 °C turned out to be significantly larger (14 %). This is confirmed by the results of metallographic research (Fig. 8).

QP2 two-stage quenching provides the maximum difference between the offset yield strength and tensile strength, as well as a rather high relative elongation, which is associated with the TRIP (Transformation-Induced Plasticity) effect. With regard to the PSE criterion, widely used in foreign practice, (the product of tensile strength and relative elongation, MPa×% [16, 17]) applied mainly for automotive sheet steels, the best result for the studied 20Cr2Mn2SiNiMo steel is provided by QP2 two-stage quenching (PSE=22,490 MPa×%). However, in terms of structural reliability required for mechanical engineering parts operating under conditions of alternating loads and wear, relative contraction and impact strength are also important characteristics. In this regard, the level of properties obtained during step, and isothermal quenching, is significantly inferior to the properties obtained after quenching and low-temperature tempering.

Thus, depending on the purpose of the part, the studied 20Cr2Mn2SiNiMo steel can provide a different combination of mechanical properties (strength, ductility, impact strength), and high stability of supercooled austenite of this steel [18; 19] allows implementing the heat treatment modes using only convective cooling media.

As one can see, to achieve both high strength and ductility, 20Cr2Mn2SiNiMo steel should be subjected to step quenching according to the QP2 mode. To achieve high impact strength and relative contraction, it is recommended to carry out quenching and low-temperature tempering at a temperature of no more than 200 °C. It is worth noting that the QPT single-stage quenching, and tempering mode provides the lowest impact strength, and the QP2 two-stage quenching mode provides the least contraction. The first is associated with the manifestation of the α-phase temper brittleness; the second is associated with the residual austenite transformation during deformation accompanied by an increase in the volume, and the formation of brittle high-carbon martensite.

CONCLUSIONS

1. A dilatometric study of the supercooled austenite transformations in the 20Cr2Mn2SiNiMo steel was carried out during step quenching in different modes: QP1 single-

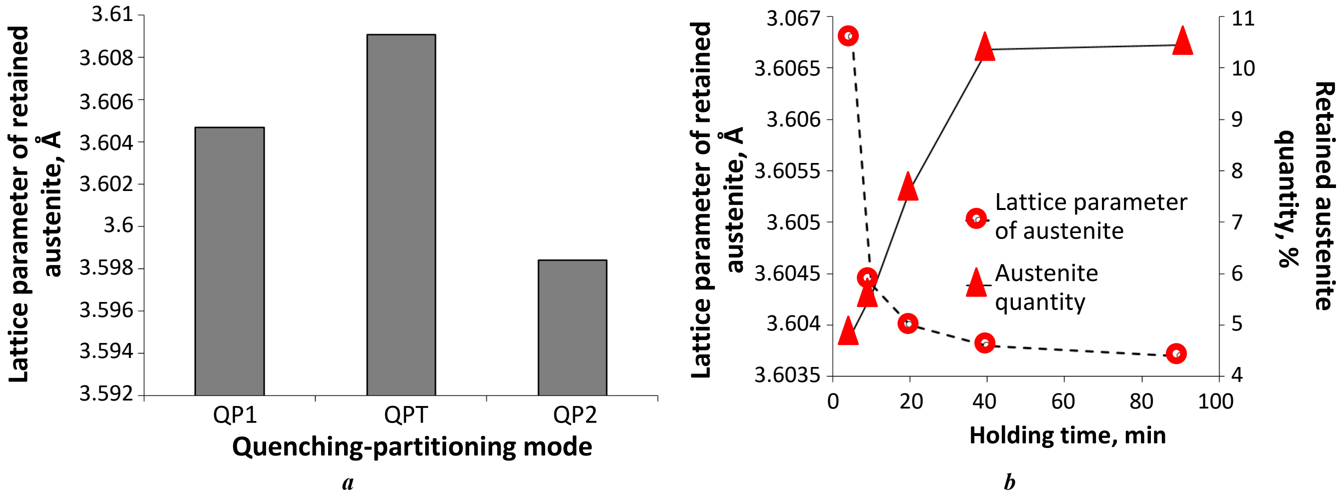


Fig. 7. Values of the lattice parameter of residual austenite in the structure of 20Cr2Mn2SiNiMo steel after various heat treatment modes:
***a** – step quenching; **b** – isothermal quenching at 320 °С*
***Рис. 7.** Значения параметра решетки остаточного аустенита в структуре стали 20Х2Г2СНМА после различных режимов термической обработки:*
***a** – ступенчатая закалка; **b** – изотермическая закалка при 320 °С*

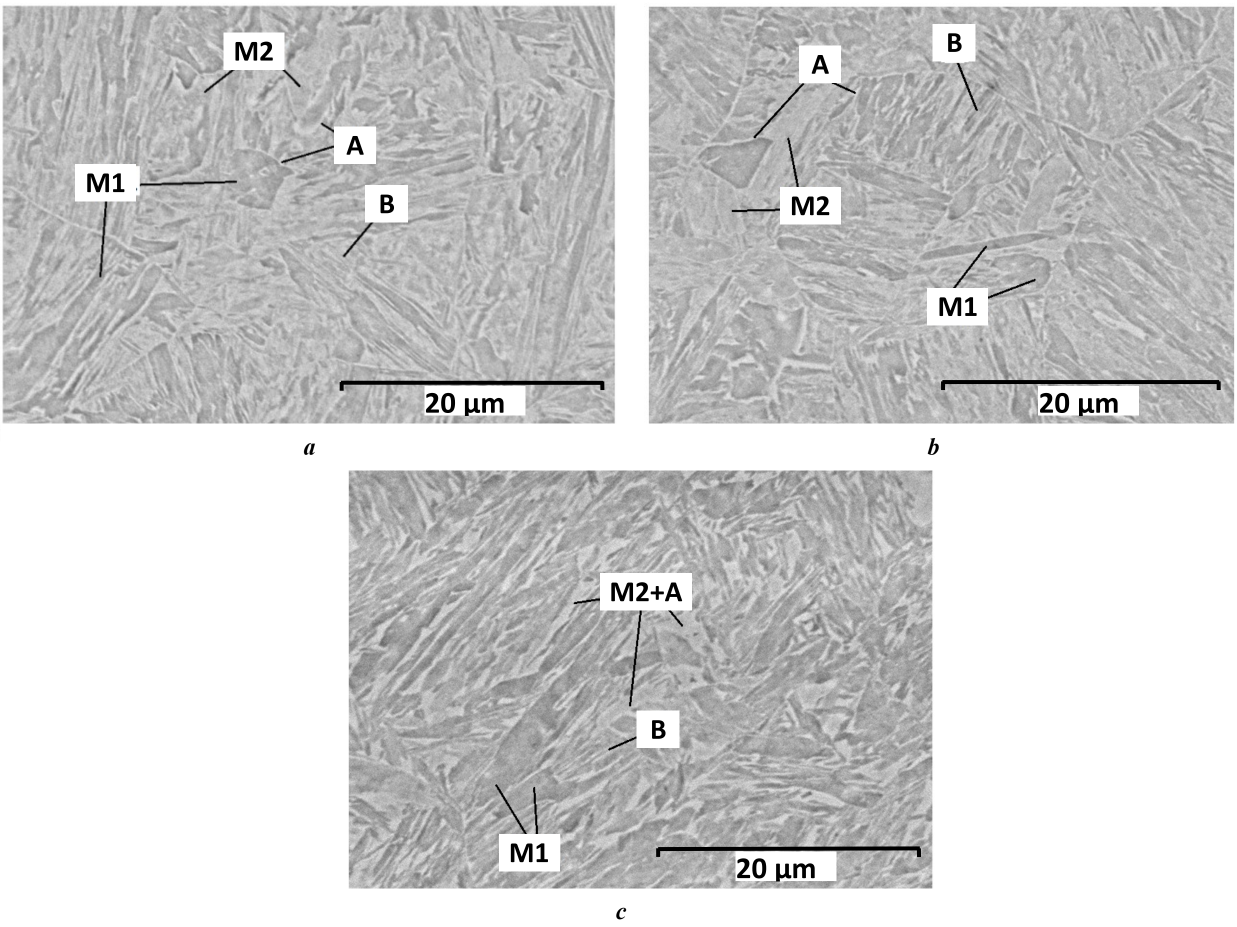
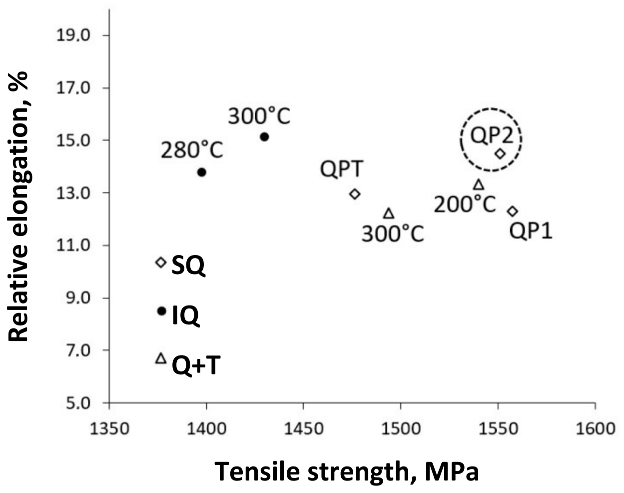


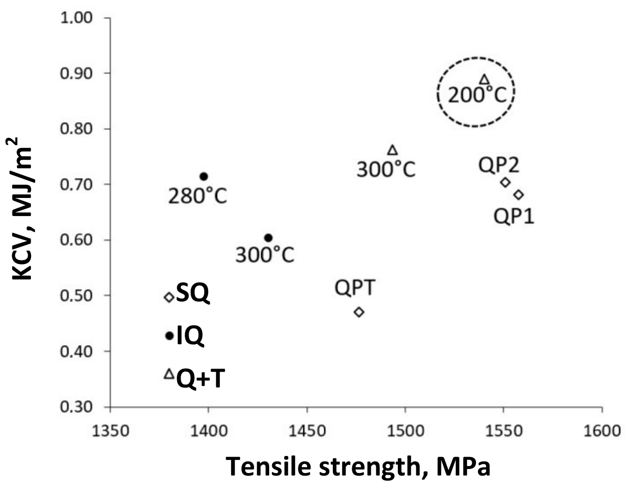
***Fig. 8.** The microstructure of 20Cr2Mn2SiNiMo steel after various options of step quenching (scanning electron microscopy): **a** – QP1; **b** – QPT; **c** – QP2.*
M1 – primary martensite; B – bainite; M2 – secondary martensite; A – residual austenite
***Рис. 8.** Микроструктура стали 20Х2Г2СНМА после различных вариантов ступенчатой закалки (растровая электронная микроскопия): **a** – QP1; **b** – QPT; **c** – QP2.*
M1 – первичный мартенсит; B – бейнит; M2 – вторичный мартенсит; A – остаточный аустенит

Table 2. *Mechanical properties of 20Cr2Mn2SiNiMo steel after various heat treatment modes*
Таблица 2. *Механические свойства стали 20Х2Г2СНМА после различных режимов термической обработки*

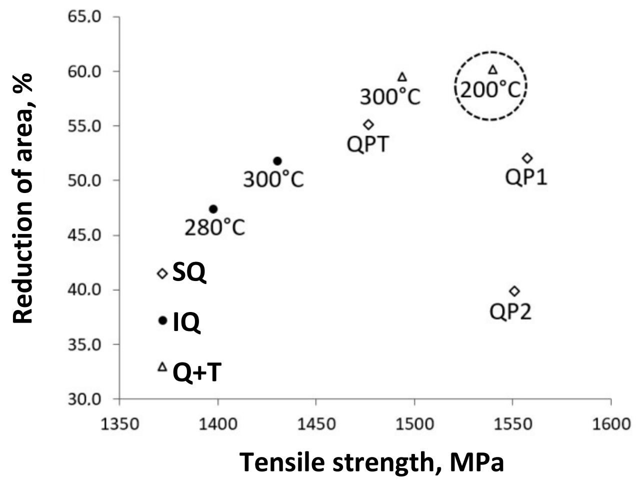
Technology	Mode	$\sigma_{0.2}$, MPa	σ_{UTS}, MPa	δ, %	ψ, %	KCV, MJ/m^2	PSE, MPa×%
Step quenching	QP1	1 292	1 558	12.3	52.1	0.68	19 157
	QPT	1 297	1 477	13.0	55.2	0.47	19 121
	QP2	945	1 551	14.5	39.9	0.70	22 490
Isothermal quenching	280 °C, 2 h	1 038	1 398	13.8	47.5	0.72	19 286
	300 °C, 2 h	1 045	1 430	15.2	51.9	0.61	21 665
Oil quenching and tempering	200 °C, 3 h	1 294	1 540	13.3	60.2	0.89	20 533
	300 °C, 3 h	1 269	1 494	12.2	59.5	0.76	18 273



a



b



c

Fig. 9. *Diagrams of the mechanical properties of 20Cr2Mn2SiNiMo steel after various heat treatment options.*
SQ – step quenching; IQ – isothermal quenching; Q+T – quenching and tempering;
parameters of heat treatment modes are indicated next to the corresponding markers
Рис. 9. *Диаграммы механических свойств стали 20Х2Г2СНМА после различных вариантов термической обработки.*
SQ – ступенчатая закалка; IQ – изотермическая закалка; Q+T – закалка и отпуск;
параметры режимов термообработки указаны возле соответствующих маркеров

stage quenching, QPT single-stage quenching with tempering, and QP2 two-stage quenching. It was found that during the step quenching process, the following structural components are formed in steel: primary martensite at temperatures below 345 °C, isothermal bainite at temperatures of 280 and 350 °C, and secondary martensite at temperatures below 215 °C (for QP1, QPT) and 140 °C (QP2).

2. It is shown that QP2 two-stage quenching promotes stabilisation of 14 % of residual austenite in the steel structure at room temperature, and provides a smaller amount of secondary martensite. At the same time, the carbon content in residual austenite characterised by the crystal lattice parameter, after two-stage quenching is less than after one-stage quenching.

3. Based on the data of dilatometric and X-ray diffraction analysis, the structural-phase composition of the steel under study, was identified after the implementation of step quenching in different modes: 65...70 % of primary martensite; 10…14 % of bainite; 8…16 % of secondary martensite; 6…14 % of residual austenite.

4. The mechanical properties of the studied steel were determined after various types of step quenching. QP2 two-stage quenching provides a combination of high strength (1550 MPa) and relative elongation (14.5 %), but the contraction is minimal (40 %). Single-stage quenching and tempering leads to a significant decrease in impact strength (KCV 0.47 MJ/m^2), which is caused by the manifestation of tempering brittleness.

5. It is shown that, in terms of the structural reliability of machine-building parts, step quenching is not the optimal heat treatment mode for the steel under study. The best combination of strength (1540 MPa), ductility (relative elongation is 13 %, relative contraction is 60 %) and impact strength (KCV 0.89 MJ/m^2) is achieved after quenching and low-temperature tempering.

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Исследование превращений переохлажденного аустенита при ступенчатой закалке стали 20Cr2Mn2SiNiMo

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Поступила в редакцию 26.06.2023 *Принята к публикации 26.01.2024*

Аннотация: В настоящее время ступенчатая закалка сталей в температурном интервале мартенситного превращения, в т. ч. quenching – partitioning, нашла широкое применение в автомобильной промышленности. Технология ступенчатой закалки успешно применяется для повышения комплекса свойств, к которым чаще всего относят временное сопротивление разрыву и относительное удлинение. Проведено дилатометрическое исследование превращений переохлажденного аустенита, протекающих в стали 20Х2Г2СНМА, при реализации различных вариантов ступенчатой закалки с выдержкой в мартенситной области. Установлено, что после одноступенчатой закалки, одноступенчатой закалки с последующим отпуском, двухступенчатой закалки образуются первичный мартенсит, изотермический бейнит, вторичный мартенсит в различных количественных соотношениях. С помощью рентгеноструктурного фазового анализа определено количество остаточного аустенита при реализации ступенчатой закалки. Показано, что двухступенчатая закалка позволяет стабилизировать в структуре исследуемой стали при комнатной температуре до 14 % остаточного аустенита. Исследования выявили, что для стали 20Х2Г2СНМА характерно уменьшение параметра кристаллической решетки остаточного аустенита при увеличении его содержания в структуре стали. Проведены испытания при одноосном растяжении и на ударный изгиб, определены значения механических свойств. Установлено, что при двухступенчатой закалке достигаются более высокие по сравнению с закалкой в масле и низкотемпературным отпуском показатели прочности и относительного удлинения при меньших значениях относительного сужения и ударной вязкости. Показано, что с точки зрения конструктивной надежности машиностроительных деталей ступенчатая закалка не является оптимальным режимом термической обработки исследуемой стали. Наилучшее сочетание прочности, пластичности и ударной вязкости достигается после закалки и низкотемпературного отпуска.

Ключевые слова: превращения переохлажденного аустенита; ступенчатая закалка; сталь 20Х2Г2СНМА; 20Cr2Mn2SiNiMo; quenching – partitioning; изотермическая закалка; закалка и отпуск; остаточный аустенит; первичный мартенсит; изотермический бейнит; вторичный мартенсит.

Благодарности: Исследование выполнено за счет гранта Российского научного фонда № 22-29-00106, https://grant.rscf.ru/prjcard_int?22-29-00106.

Статья подготовлена по материалам докладов участников XI Международной школы «Физическое материаловедение» (ШФМ-2023), Тольятти, 11–15 сентября 2023 года.

Для цитирования: Майсурадзе М.В., Куклина А.А., Назарова В.В. Исследование превращений переохлажденного аустенита при ступенчатой закалке стали 20Cr2Mn2SiNiMo // Frontier Materials & Technologies. 2024. № 2. С. 53–65. DOI: 10.18323/2782-4039-2024-2-68-5.