Influence of heat treatment on forming the complex of properties for high-strength cold-resistance steel

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Creation of materials for application in the extremal operating conditions, including Arctic and Far North regions, is connected with solving of several problems caused by the effect of static, cyclic and dynamic loads, intensive wear, extra low temperatures etc. A group of scientists from Nosov Magnitogorsk State Technical University has developed the unique combinations of requirements for production of new steels, which are characterized by simultaneous high strength and ductility as well as wear resistance, atmospheric resistance and cold resistance at the temperature down to minus 70 °C. Such properties determine possibility of multirole application of these steels in constructions and objects of Russian oil and gas industry as well as in the areas of bridge construction, building, transport and heavy machine-building and other industries. Production of such steels with different alloying systems, i.e. Si-Mn-Mo and Si-Mn-Ni-Mo with microalloying is mastering at Magnitogorsk Iron and Steel Works in cooperation with Nosov Magnitogorsk State Technical University, within the framework of solving the problem of foreign import replacement. In this case the range of requirements for different concrete grades of multi-functional materials is varied within rather wide range: $\sigma_в$ – from 580 to 1500 MPa, $\sigma_{0,2}$ – from 500 to 1100 MPa, δ_5 – from 10 to 20 %, KCV^{-70} – from 25 to 100 J/cm^2. Influence of heat treatment procedures (quenching with consequent tempering) on forming the complex of mechanical properties and low-temperature impact strength for high-strength low carbon steels with Si-Mn-Mo and Si-Mn-Ni-Mo alloying systems is examined in this research.
Key words: low carbon high-strength steels, Si-Mn-Mo and Si-Mn-Ni-Mo alloying systems, quenching, tempering, structure, mechanical properties, low-temperature impact strength.
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Introduction

At present time absorption and sustainable development of the Northern territories and Arctic area is among the priority tasks, it has decisive influence on development of national economics and power engineering. Creation of materials for application in the conditions of Arctic and Far North regions is connected with solving of several problems caused by the effect of static, cyclic and dynamic loads, intensive wear, extra low temperatures etc. [1, 2]. In this case majority of the existing innovations provide production of materials with extremely specialized purposes. In this connection, the unique combinations of requirements for production of new steels, which are characterized by simultaneous high strength and ductility as well as wear resistance, atmospheric resistance and cold resistance at the temperature down to minus 70 °C were developed by the group of scientists from Nosov Magnitogorsk State Technical University [3-5]. Such properties determine possibility of simultaneous multirole application of these steels in constructions and objects of Russian oil and gas industry as well as in the areas of bridge construction, building, transport and heavy machine-building and other industries.

Production of such steels with different alloying systems, i.e. Si-Mn-Mo and Si-Mn-Ni-Mo with microalloying is mastering at Magnitogorsk Iron and Steel Works in cooperation with Nosov Magnitogorsk State Technical University, within the framework of solving the problem of foreign import replacement. Use of microalloying by titanium, vanadium, niobium promotes forming of the fine-grained structure, while boron microadditives up to 0.006 % with low content of carbon and alloying elements are efficient for rise of hardenability [6]. In this case the range of requirements for different concrete kinds of multi-functional materials is varying within rather wide amplitude:

- kind 1: $\sigma_{0,2}\geq500$ MPa; σ_B 580-950 MPa, $A_5\geq20$ %, $KCV^{-70}\geq100$ J/cm^2;
- kind 2: $\sigma_{0,2}\geq800$ MPa, σ_B 950-1200 MPa, $A_5\geq14$ %, $KCV^{-70}\geq50$ J/cm^2;
- kind 3: $\sigma_{0,2}\geq950$ MPa, σ_B 1200-1500 MPa, $A_5\geq13$ %, $KCV^{-70}\geq37{,}5$ J/cm^2;
- kind 4: $\sigma_{0,2}\geq1100$ MPa, $\sigma_B\geq1500$ MPa, $A_5\geq10$ %, $KCV^{-70}\geq25$ J/cm^2 [6-10].

It is known that obtaining of the required combination of mechanical properties and functional parameters in high-strength steels is provided by conduction of quenching and tempering [11-14]. It is recognized that forming of martensite-bainite structure with high density of dislocations in the process of $\gamma \rightarrow \alpha$-transformation leads to homogenous distribution of strengthening fine-dispersed carbide phase during tempering, while complex alloying provides the preset level of steel strength at increased tempering temperature [6]. However, at present time insufficient volume of published information about influence of heat treatment on structure and properties of low-alloy economically alloyed high-strength steels with summarized content of alloying elements ≤ 3.5 % requires additional researches in this direction. Thereby, research of influence of heat treatment procedures (quenching and consequent tempering) on forming of mechanical properties and low-temperature impact strength of low-alloy economically alloyed high-strength steels with Si-Mn-Mo and Si-Mn-Ni-Mo alloying systems is the aim of this work. It is shown that management of heat treatment procedures can provide high strength class in combination with good impact strength at low temperatures, depending on the requirements to finished products.

Materials and methods of researches

The research was carried out on the labour samples from cold-resistance high-strength steel with Si-Mn-Mo alloying system, with the following chemical composition (mass %): 0.16 C; 0.54 Si; 1.8 Mn; 0.23 Mo and from steel with Si-Mn-Ni-Mo alloying system, with the following chemical composition (mass %): 0.15 C; 0.23 Si; 1.2 Mn; 1.75 Ni; 0.23 Mo; 0.023 Ti; 0.0035 B.

Melting, hot rolling and consequent heat treatment of sheet metal samples with 10 mm thickness were conducted on the base of the scientific and production complex “Engineering center” at Nosov Magnitogorsk State Technical University.

To achieve the optimal complex of properties and to determine heat treatment procedures, providing high-strength state in combination with high resistance to brittle destruction and cold resistance in steels with the required compositions, quenching from the temperature 860 и 900 °C was carried out with consequent tempering at the temperatures 450, 500 и 600 °C during 1 hour.

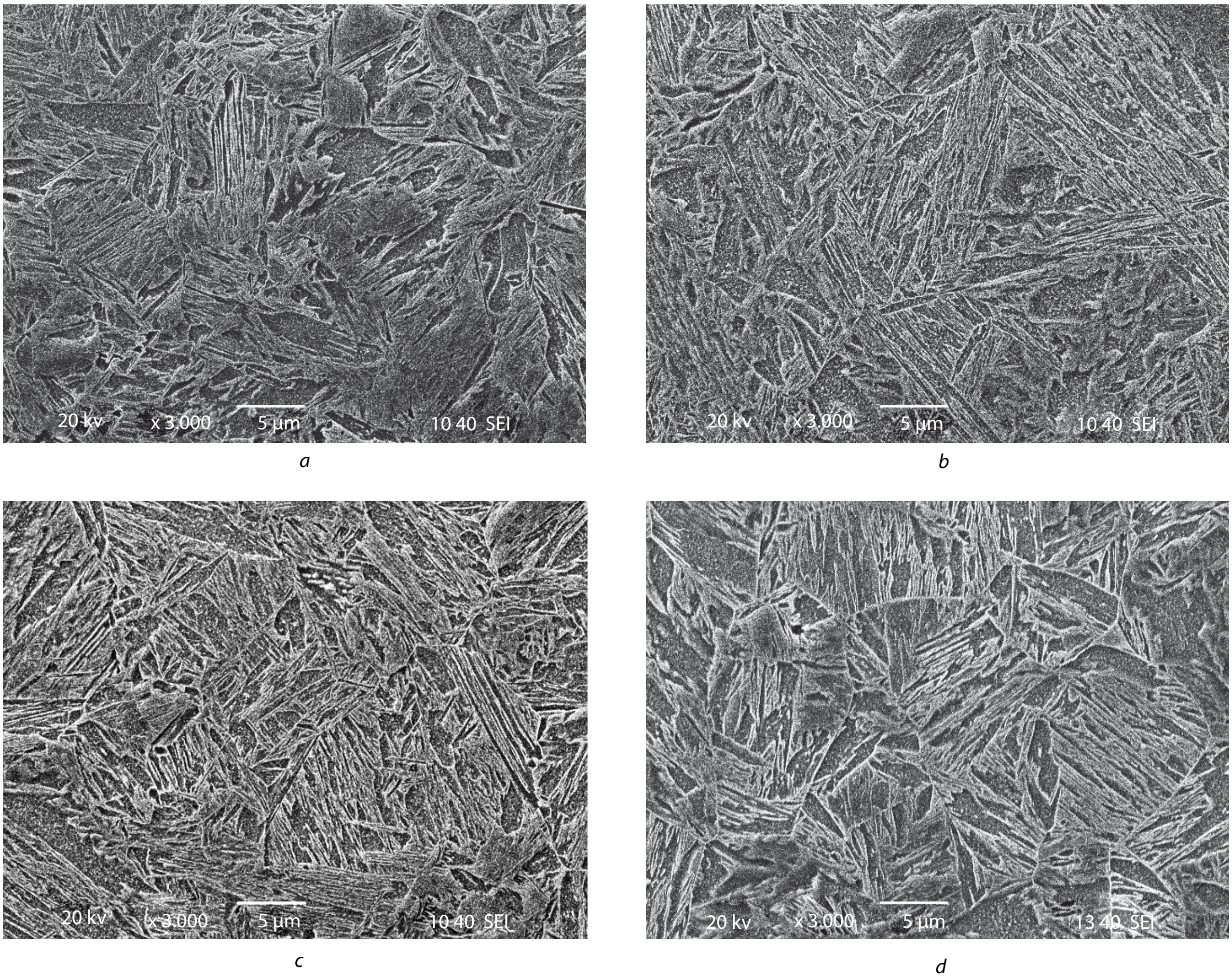


Fig. 1. Microstructure of steels with the Si-Mn-Mo (*a*, *b*) and Si-Mn-Ni-Mo (*c*, *d*) alloying systems, quenched from the temperatures 860 °C (*a*, *c*) and 900 °C (*b*, *d*)

Metallographic examinations using scanning electron microscope (SEM) JSM 6490 LV in secondary electrons were conducted in the Centre of common use at "Nanosteels" Scientific and research institute of Nosov Magnitogorsk State Technical University. Micro polished sections were manufactured for micro-analysis via the standard technique at the sample preparation line of Buehler. To reveal microstructure, the surface of polished sections was subjected to pickling in 4 % HNO_3 solution in ethyl alcohol via dipping of polished surface in a bath with a reagent. Quantitative relationship of volumetric part of the structural components was determined via manual measurements, by extraction of their square. The complex of testing of mechanical properties ($\sigma_{0,2}$, $\sigma_в$, δ_5 и KCV^{-70}) was carried out in the Central quality labour at Magnitogorsk Iron and Steel Works. Extension testing and impact bending testing (at the temperature -70 °C) were conducted according to GOST 1497-84 and GOST 9454-78 respectively.

Results and discussion

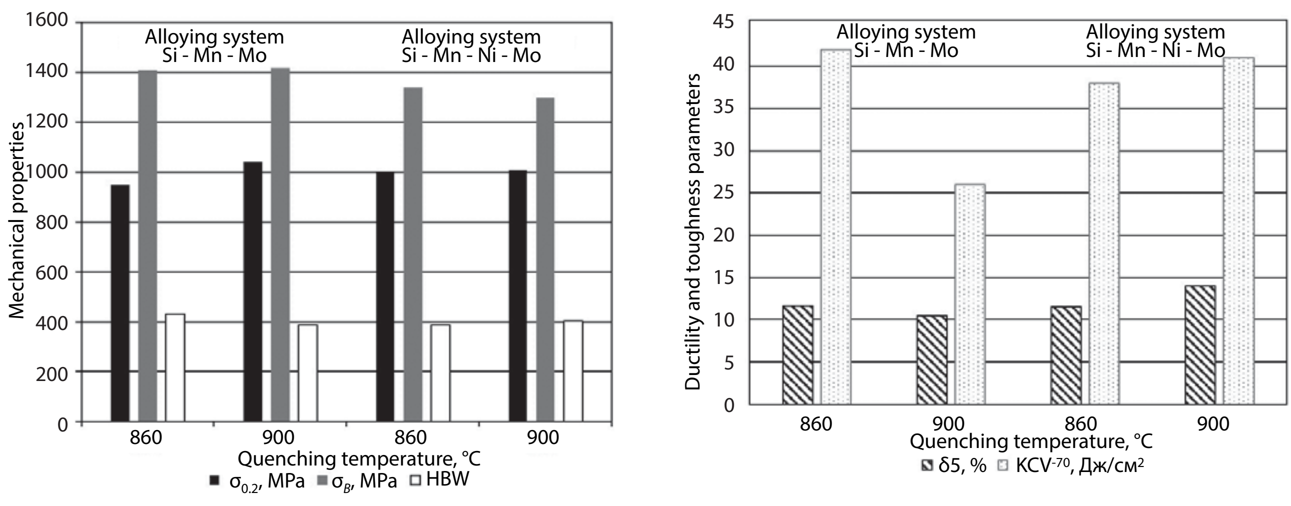
Metallographic analysis displayed that microstructure of steel with Si-Mn-Mo alloying system, with the following chemical composition (mass %): 0.16 C; 0.54 Si; 1.8 Mn; 0.23 Mo contains martensite and bainite after quenching from 860 °C, and amount of bainite constitutes 30-40 % (**Fig. 1**, *a*). Length of needles makes 12 μm (ball 7 according to the GOST 8233).

If we shall rise the temperature to 900 °C, martensite and bainite are also presented in microstructure, but amount of bainite decreases approximately to 25 % (Fig. 1, *b*). Maximal size of racks increases to 20 μm (ball 9 according to the GOST 8233). Increase of the part of martensite component leads to definite rise of the yield strength ($\sigma_{0,2}$=1,040 MPa) and lowering of low-temperature impact strength (KCV^{-70}=26 J/cm^2) in comparison with the properties which were formed after quenching from the temperature 860 °C ($\sigma_{0,2}$=950 MPa, KCV^{-70}=42 J/cm^2) (**Fig. 2**).

After quenching from the temperatures 860 and 900 °C of steel with Si-Mn-Ni-Mo alloying system, with the following chemical composition (mass %): 0.15 C; 0.23 Si; 1.2 Mn; 1.75 Ni; 0.23 Mo; 0.023 Ti; 0.0035 B, its structure (as the structure of steel with Si-Mn-Mo alloying system) contains martensite component and small amount of bainite component (see the Fig. 1, *c*, *d*). After quenching from the temperature 860 °C, amount of bainite constitutes 30-40 % (Fig. 1, *c*), while after quenching from the temperature 900 °C it makes 20-25 % (Fig. 1, *d*). Maximal size of martensite racks remains constant for different quenching temperatures and is equal to 16 μm (ball 8 according to the GOST 8233). It is connected with titanium presence in steel chemical composition; titanium forms carbonitrides, which restrict growth of austenite grain during heating [6, 15, 16].

Mechanical properties after quenching from different temperatures of steels with both alloying systems remain approximately at the same level (Fig. 2, *a*), while tensile strength value of the steel with Si-Mn-Ni-Mo alloying system is a little smaller in comparison with properties of the steel with the Si-Mn-Mo alloying system. Low-temperature impact strength of the steel with Si-Mn-Ni-Mo alloying system after quenching from the temperature 860 °C is approximately at the same level as the steel with the Si-Mn-Mo alloying system, while after quenching from the temperature 900 °C it essentially exceeds the values of impact strength of the steel with the Si-Mn-Mo alloying system. It can be connected with alloying of this steel by nickel, which dissolves in α-phase and promotes impact strength rise of this steel [17, 18].

It is concluded that the temperature 900 °C should be recognized as the rational quenching temperature (with consequent tempering) for the steels with Si-Mn-Mo and Si-Mn-Ni-Mo alloying systems from the point of view of



a *b*

Fig. 2. Variation of mechanical properties after quenching via different procedures in steels with Si-Mn-Mo and Si-Mn-Ni-Mo alloying systems

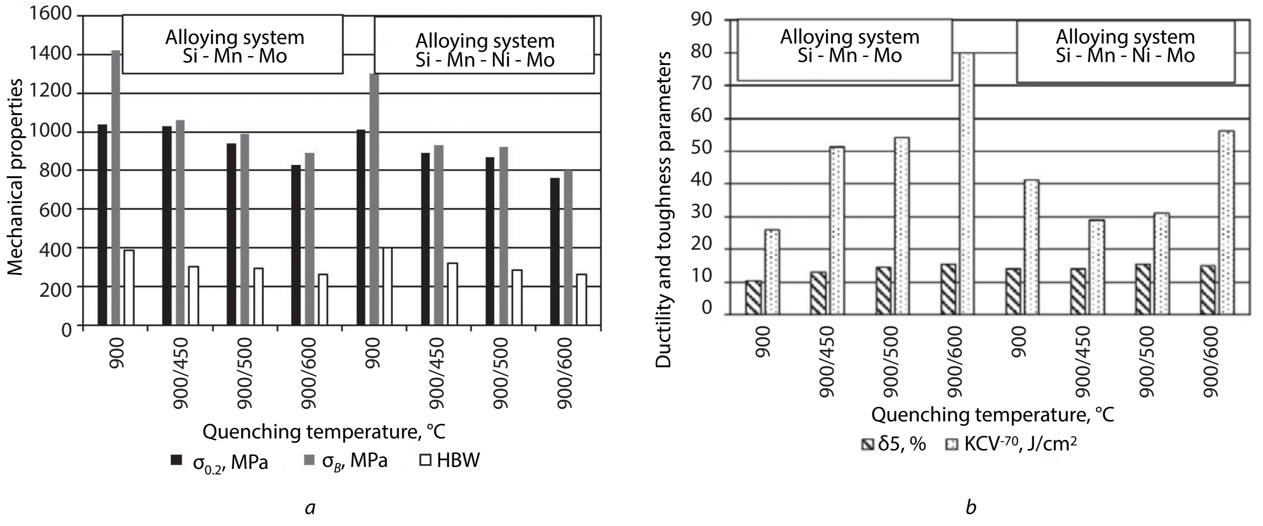


Fig. 3. Variation of mechanical properties after quenching from 900 °C and tempering via different procedures in steels with Si-Mn-Mo and Si-Mn-Ni-Mo alloying systems

more high mechanical properties. If we shall rise the tempering temperature from 450 to 600 °C for the steel with the Si-Mn-Mo alloying system, ductility parameter will increase by 2-3 times (**Fig. 3**). In this case, tensile strength decreases approximately by 35 % and yield strength by 20 % in comparison with quenched state (see Fig. 3). After tempering at the temperature 450 °C, a tempering troostite is observed in microstructure (**Fig. 4**, *a*), while at the temperature 500 °C spheroidizing process is starting, with forming of small amount of carbides of spheroid form and forming of tempering troostite-sorbite structure (Fig. 4, *c*); it leads to essential increase of impact strength in comparison with quenched state (see Fig. 3, *b*). Further tempering temperature rise up to 600 °C is accompanied by forming of tempering sorbite structure (Fig. 4, *d*), what explains achievement of maximal impact strength at this heat treatment procedure (see Fig. 3).

In the steel with the Si-Mn-Ni-Mo alloying system, the tempering temperature rise from 450 to 600 °C leads to lowering of mechanical properties (see Fig. 3, *a*) approximately for the same value, as in steels with the Si-Mn-Mo alloying system, what is connected with martensite decomposition and forming of tempered microstructure.

In this case, in the same way as in the steel with Si-Mn-Mo alloying system, after quenching at the temperature 450 °C, the tempering troostite microstructure is forming (Fig 4, *b*), while after tempering at 500 and 600 °C – the tempering troostite-sorbite (Fig 4, *d*) and sorbite (Fig 4, *f*) structures respectively. However, after tempering within the temperature range 450-500 °C, the values of low-temperature impact strength are lower, than after quenching (Fig. 3, *b*), it can be explained by development of tempering embrittlement processes. It is known, that tempering brittleness is expressed especially strongly in the case of joint presence of nickel and manganese in steel [12, 19, 20]. In this case steel susceptibility to tempering brittleness can be essentially decreased via addition 0.3-0.4 % of molybdenum in it. It is evident that introduction of 0.23 % Mo in steel with the Si-Mn-Ni-Mo alloying system is quite insufficient to prevent tempering embrittlement. Maximal ductile properties and impact strength are achieved only at the tempering temperature 600 °C (Fig. 3, *b*).

In general, mechanical properties of steels with Si-Mn-Mo and Si-Mn-Ni-Mo alloying systems are approximately at the same level. However, as soon as the tempering temperature increases, the values of impact strength of steel with the Si-Mn-Mo alloying system essentially exceeds the values of impact strength of steel with the Si-Mn-Ni-Mo alloying system, in which the processes of reversing tempering embrittlement are developing within the temperature range 450-500 °C.

Conclusion

Analysis of the obtained results allows to conclude that steel the Si-Mn-Mo alloying system, with the following chemical composition (mass %): 0.16 C; 0.54 Si; 1.8 Mn; 0.23 Mo, after quenching from the temperature 860 °C provides the following complex of properties: $\sigma_{0,2}$ = 950 MPa, $\sigma_в$ = 1410 MPa, KCV^{-70} = 42 J/cm^2. Quenching temperature rise up to 900 °C leads to small increase of yield strength ($\sigma_{0,2}$ = 1040 MPa) and decrease of low-temperature impact strength (KCV^{-70} = 26 J/cm ^{2}), what is explained by increase of the part of martensite component in microstructure. Such combination of mechanical properties meets the requirements to material of the kind 3.

After quenching from the temperature 900 °C with consequent tempering at 450 and 500 °C, increase of the values of low-temperature impact strength (KCV^{-70} – 51 and 54 J/cm^2) and decrease of steel mechanical properties ($\sigma_{0,2}$ – 1030 and 940 MPa, $\sigma_в$ – 1060 and 990 MPa) is observed; it is stipulated by forming of tempering troostite and troostite-sorbite structure respectively. This combination of

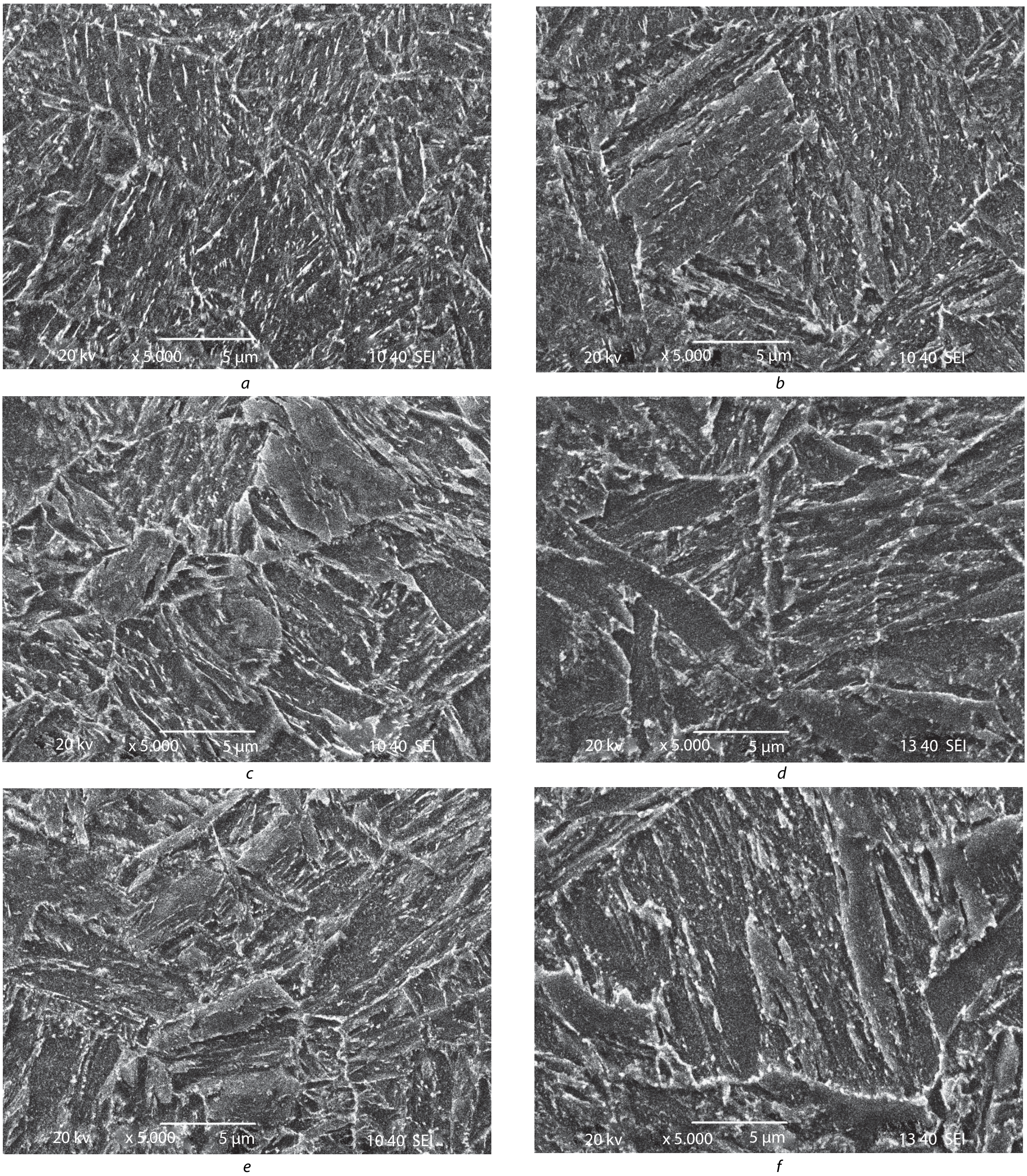


Fig. 4. Microstructure of steels with the Si-Mn-Mo (*a*, *c*, *e*) and Si-Mn-Ni-Mo (*b*, *d*, *f*) alloying systems after quenching from the temperature 900 °C and tempering at the temperatures 450 °C (*a*, *b*), 500 °C (*c*, *d*) and 600 °C (*e*, *f*)

mechanical properties meets the requirements to material of the kind 2.

The maximal values of low-temperature impact strength (KCV^{-70}=80 J/cM^2) are achieved after tempering at the temperature 600 °C, but also the most low values of mechanical properties ($\sigma_{0,2}$ = 830 MPa, $\sigma_{\text{в}}$ = 890 MPa), which do not satisfy the requirements to no one kind of materials.

Steel with the Si-Mn-Ni-Mo alloying system, with the following chemical composition (mass %): 0.15 C; 0.23 Si; 1.2 Mn; 1.75 Ni; 0.23 Mo; 0.023 Ti; 0.0035 B, has after quenching from the temperature 860 and 900 °C the combination of mechanical properties and low-temperature impact strength, meeting the requirements to material of the kind 3: $\sigma_{0,2}$ – 1000 and 1010 MPa, $\sigma_{\text{в}}$ – 1340 and 1300 MPa,

KCV^{-70} – 38 and 41 J/cm^2, respectively. It is explained by forming of more fine-dispersed and mainly martensite structure, unlike steel of the Si-Mn-Mo alloying system.

Heat treatment including quenching from the temperature 900 °C with consequent tempering at the temperatures 450, 500 and 600 °C does not provide achievement of the required combinations of properties for examined kinds of materials. It is explained by development of the processes of reversing tempering embrittlement within the temperature range 450-500 °C or softening during tempering at the temperature 600 °C.

Thus, we can provide high class of tensile strength in combination with good impact strength at decreased temperatures via control and management of heat treatment procedures for low-alloy economically alloyed high-strength steels with the Si-Mn-Mo and Si-Mn-Ni-Mo alloying systems, depending on the requirements for finished products. In this case steel with the Si-Mn-Mo alloying system is more preferential for multi-purpose application.

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REFERENCES

1. Khlusova E. I., Sych O. V. Creation of cold-resistant construction materials for Arctic. History, experience current state. *Innovatsii*. 2018. No. 11 (241). pp. 85-92.
2. Buznik V. M., Vasilevich N. I. Materials for mastering the Arctic territories – challenges and solutions. *Laboratoriya i proizvodstvo*. 2020. No. 1 (11). pp. 98-107.
3. Poletskov P. P., Gulin A. E., Emaleeva D. G., Kuznetsova A. S., Alekseev D. Yu., Kukhta Yu. B. Analysis of actual directions of researches in the field of production of multi-functional materials for extremal operating conditions. *Vestnik Magnitogorskogo gosudarstvennogo tekhnicheskogo universiteta im. G. I. Nosova*. 2021. Vol. 19. No. 3. pp. 109–114.
4. Chukin M. V., Poletskov P. P., Gushchina M. S., Kuznetsova A. S., Nikitenko O. A., Alekseev D. Yu. Development of the import-substituting technology for rolled sheet production from high-strength structural steel for Arctic application. *Proizvodstvo prokata*. 2019. No. 4. pp. 5-11.
5. Poletskov P. P., Nikitenko O. A., Kuznetsova A. S., Alekseev D. Y. Development of Heat Treatment Modes for Novel Structural Sparingly Alloyed High-Strength Steel for Arctic and Far North Applications. *Metal Science and Heat Treatment*. 2021. Vol. 63. No. 3-4. pp. 171-177.
6. Sych O. V. Scientific-technological grounds for creation of cold-resistant steels with guaranteed yield strength 315-370 MPa for Arctic. Part 1. Alloying principles and requirements to the structure of rolled sheets. *Vorposy materialovedeniya*. 2018. No. 3 (95). pp. 22-47.
7. Sych O. V., Golubeva M. V., Khlusova E. I. Development of cold-resistant weldable steel of strength class 690 MPa for heavy-loaded machinery operating in Arctic conditions. *Tyazheloe mashinostroenie*. 2018. No. 4. pp. 17-25.
8. Influence of Heat treatment parameters on structure and mechanical properties of an HSLA-100 steel. *Steel Research*. 2002. No. 8 (73). pp. 347-355.
9. Khlusova E. I., Orlov V. V., Motovilina G. D., Korchagin A. A., Matrosov M. Yu. Influence of tempering on variation of structure and properties of high-strength tube strip steel of strength class X90 and X100 after thermomechanical treatment. *Metallurg*. 2010. No. 11. pp. 68-73.
10. Barényi A., Híreš O., Lipták P. Changes in Mechanical Properties of Armoured UHSLA Steel ARMOX 500 After Over Tempering. *Problems of Mechatronics, Armament, Aviation, Safety Engineering*. 2013. No. 4 (14). pp. 7-14.
11. Polteskov P. P., Kuznetsova A. S., Koptseva N. V., Nikitenko O. A., Yakovleva I. L. Study of Structure of High-Strength Cold-Resistant Steel After Quenching and Tempering. *CIS Iron and Steel Review*. 2021. Vol. 22. pp. 61-65.
12. Golosienko S. A., Motovilina G. D., Khlusova E. I. Influence of structure formed during quenching on the properties of high-strength cold-resistance steel after tempering. *Vorposy materialovedeniya*. 2008. No. 1 (53). pp. 32-44.
13. Aguiari M., Palombo M., Rizzo C. M. Performance characterization of high-strength steel and quenched and tempered steels and their joints for structural applications. *Welding in the World*. 2021. Vol. 65. pp. 289–300.
14. Sahoo G., Singh K. K., Kumar V. Quenched and Tempered High Strength Steel: A Review. *Materials and Minerals*. 2020. Vol. 30. No. 4. pp. 19-29.
15. Matrosov Yu. I., Zikeev V. N. Microalloying of low-carbon low-carbon steels by titanium. *Metallovedenie i termicheskaya obrabotka metallov*. 2021. No. 11. pp. 25-31.
16. Medina S. F., Chapa M., Vega M. I. Influence of Ti and N contents on precipitation and austenite grain size at high temperatures in structural steels. Thermomechanical Processing of steels: Church House Conference Centre. London, UK. 2000. pp. 214–220.
17. Poletskov P. P., Gushchina M. S., Koptseva N. V., Nikitenko O. A., Efimova Yu. Yu. Study of nickel influence on structure and phase transformations and properties of high-strength medium-carbon complex-alloyed steel. *Metallovedenie i termicheskaya obrabotka metallov*. 2019. No. 11. pp. 8-13.
18. Keehan E., Karlsson L., Andrén H.-O. Influence of carbon, manganese and nickel on microstructure and properties of strong steel weld metals: Part 1. Effect of nickel content. *Science and Technology of Welding and Joining*. 2006. Vol. 11. No. 1. pp. 1-8.
19. Utevskiy L. M., Glikman E. E., Kark G. S. Reversing tempering brittleness of steel and ferrous alloys. Moscow: Metallurgiya. 1987. 222 p.
20. Nosov S. I. Provision of stability of temperature transition to brittle state and mechanical properties of metal of welding seams for low-alloy Cr-Ni-Mo steel at the holding stage within the temperature range of tempering and thermal embrittlement. *Tyazheloe mashinostroenie*. 2011. No. 5. pp. 11-16.