Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2022 vol. 24 no. 4 pp. 113–126
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2022-24.4-113-126

NSTU NETI

Obrabotka metallov -
Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

The effect of heat treatment on the formation of MnS compound in low-carbon structural steel 09Mn2Si

Roman Sokolov [a, *], *Vitaly Novikov* [b], *Ilja Kovenskij* [c], *Kamil Muratov* [d], *Anatolii Venediktov* [e], *Larisa Chaugarova* [f]

Tyumen Industrial University, 38 Volodarskogo, Tyumen, 625000, Russian Federation

[a] https://orcid.org/0000-0001-5867-8170, falcon.rs@mail.ru, [b] https://orcid.org/0000-0002-1987-351X, vitaly.nowikov2017@yandex.ru, [c] https://orcid.org/0000-0003-3241-8084, kovenskijim@tyuiu.ru, [d] https://orcid.org/0000-0002-8079-2022, muratows@mail.ru, [e] https://orcid.org/0000-0002-6899-4297, annattoliy@gmail.com, [f] https://orcid.org/0000-0002-6376-2868, chaugarovalz@tyuiu.ru

ARTICLE INFO

Article history:
Received: 20 June 2022
Revised: 11 July 2022
Accepted: 08 September 2022
Available online: 15 December 2022

Keywords:
SEM
Microstructure
MnS compound
Structural steel
Nonmetallic inclusions
Grain size

Acknowledgements
Research were partially conducted at core facility "Structure, mechanical and physical properties of materials".

ABSTRACT

Introduction. The properties of steels are determined by many factors, including the manufacturing process and subsequent treatment. Some features of these processes lead to the fact that in steel, apart from alloying elements added to obtain a certain level of physical and mechanical properties, there are also foreign impurities that enter it at various stages. Foreign elements can not only dissolve in the matrix, but also participate in the formation of particles of nonmetallic inclusions acting as defects. Its presence significantly affects the performance characteristics of the material. That is why it is necessary to understand the processes that lead to the appearance of nonmetallic inclusions and affect its shape. **Purpose:** to consider the effect of heat treatment, leading to the appearance of a ferrite-martensitic structure, on the shape and size of nonmetallic inclusions; to determine its influence on the physical and mechanical properties of the material. **In the work**, samples of rolled steel *09Mn2Si* after heat treatment are studied. **Research methods.** To study the properties and structure of steel *09Mn2Si*, the following methods were used: scanning electron microscopy – to study the structure of the material, chemical composition in the local area and the site under study and to determine the accumulation of impurities; *SIAMS 800* software and hardware complex – to compare the structure of the material with the atlas of microstructures, to determine the score of the grain structure, differences in the structural and phase composition occurring during heat treatment; portable X-ray fluorescence analyzer of metals and alloys *X-MET 7000* - to determine the chemical composition of the samples under study in percentage terms; Vickers hardness tester with a preload of 20 kg – to measure the hardness of the samples under study. **Results and discussions.** It is found that in the low-alloy low-carbon structural steel *09Mn2Si* in most cases there are nonmetallic inclusions of the type of manganese sulfide formed during its manufacture. When this steel is heated to the temperatures of the intercritical transition, this compound is formed in the area of grain boundaries in the form of spherical inclusions. The presence of these inclusions significantly affects the strength and corrosion properties. Manganese sulfide acts as the point of the corrosion process initiation.

For citation: Sokolov R.A., Novikov V.F., Kovenskij I.M., Muratov K.R., Venediktov A.N., Chaugarova L.Z. The effect of heat treatment on the formation of MnS compound in low-carbon structural steel 09Mn2Si. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2022, vol. 24, no. 4, pp. 113–126. DOI: 10.17212/1994-6309-2022-24.4-113-126. (In Russian).

Introduction

Heat treatment processes largely determine the final properties of steels. It is known that for certain steel grades, generally, the use of certain heat treatment processes is not typical due to its small effect on the properties of the steel. For example, the quenching process is not used in everyday practice for low-carbon steels. However, the studies [1-5] show that the application of the quenching process with a temperature range corresponding to the intercritical interval, leads to the formation of two-phase ferrite-

*** Corresponding author**
Sokolov Roman A., Post-graduate Student, Assistant
Tyumen Industrial University,
38 Volodarskogo str.,
625000, Tyumen, Russian Federation
Tel.: 8 (919) 925-88-47, **e-mail:** falcon.rs@mail.ru

martensitic structures. Such structures have a positive effect on the mechanical and corrosion properties of the material [5].

However, in addition to heat treatment, the properties of the material are affected by the defectiveness of its structure [6]. The study [6] indicates that there are also foreign impurities that get into steels at various stages of metallurgical processes. Such impurities, in addition to alloying elements, are introduced into the composition of steels to obtain a certain level of properties. At the same time, many impurities (most often these are: sulfur, oxygen, manganese, silicon, calcium, etc.) can not only dissolve in the matrix of the base material, but also participate in the formation of particles of non-metallic inclusions [7].

The presence of impurities in steel leads to the formation of areas where local internal stresses act. The authors in the study [8] believe that internal stresses arising near structural defects stimulate the migration of point defects to this area. It leads to the clusters of point defects around the impurities, its subsequent expansion and the disc-shaped clusters of vacancies. This process is typical for rapid material cooling. For example, during the quenching process, point and linear defects of the structure do not get around to migrate to the drains, which are the body surfaces and grain boundaries. As a result, the matrix is oversaturated with defects. In view of this, non-metallic impurities significantly reduce the mechanical properties of the material.

In addition, the studies [9–12] indicate that the presence of non-metallic impurities of various compositions in steel directly affects the rate of corrosion in local areas. However, the authors in the study [9] note that there is no correlation between the percentage of impurities and corrosion in the local area when assessing the content of non-metallic impurities by the standard method [13]. The studies [11, 12] show that the main cause of abnormally high corrosion rates of oilfield pipelines is the steel contamination with non-metallic corrosive impurities [14], which are inclusions based on manganese sulfide (*MnS*).

The most common grades of oilfield pipelines' steels are *09G2S* and *15ChSNC*. There are situations when local corrosion sources are observed on the surface of these steels, which often have a spherical shape associated with the inclusions [14].

The influence of heat treatment on the shape and size of non-metallic inclusions determining the physical and mechanical properties of low-alloy low-carbon steel *09G2S* is considered in this paper. This heat treatment leads to the formation of a ferrite-martensitic structure.

Research methodology

In this work, the samples made from sheet metal, steel grade *09G2S* (*S* – 0.11%, *Si* – 0.15%, *P* – 0.05%; *S* < 0.028; *Cr* – 0.07%; *Mn* – 1.91%; *Ni* – 0.11%; *Cu* – 0.22%) are studied. The fabricated samples had the following linear dimensions: 4.0 x 70.0 x 25.0 mm. The process of heat treatment of the samples under study is shown in Table 1

The hardness measurement of the samples is carried out on a *Vickers Indentec 6030LKV* hardness tester with a preload of 20 kg. Each sample was indented five times. The hardness measurement error does not exceed 1% according to the passport data.

The grain structure is analyzed with the software package "*SIAMS 700*" and "*SIAMS 800*". Some of the results are reflected in the studies [16, 17].

Microphotographs of the local area are obtained and its chemical composition is determined using a *JEOL 6008A* scanning electron microscope. The samples are treated with a 3% solution of nitric acid to reveal the microstructure.

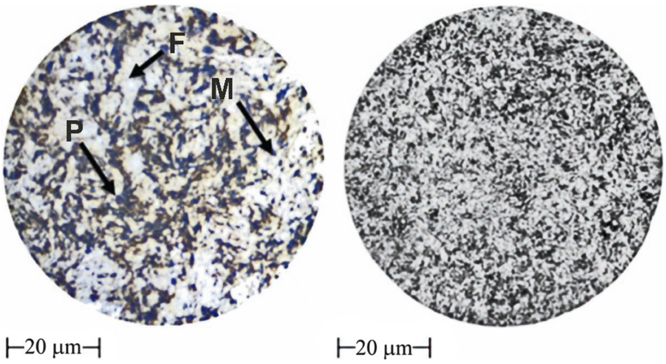
Table 1

Heat treatment of the *09Mn2Si* steel samples

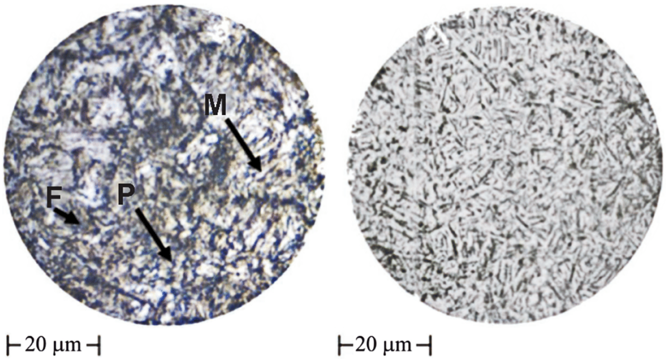
Heat treatment
Heating up to 930±20 ^{o}C; water quenching Tempering at 200, 350, 500, 650 ^{o}C for 1 hour; air cooling

Results and their discussion

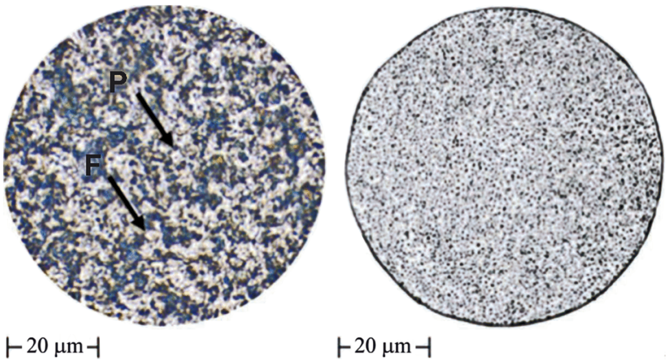
The studied samples' microstructure after various heat treatment modes is shown in Figure 1. The figure shows a comparison of the obtained microphotographs of samples (left side) with microphotographs characterizing the reference image for identification from the atlas of microstructures (right side). The letter **F** denotes the ferritic phase; **P** – perlite; **M** – martensite.



a



b



c

Fig. 1. The structure of the samples obtained by analysis in the *SIAMS 800* software and hardware complex in comparison with micrographs from the atlas of microstructures:

a – water quenching; *b* – tempering at 200 °C; *c* – tempering at 650 °C

One of the main indicators of the steel mechanical properties is its hardness. It has a correlation with the ultimate strength [15]. Although, according to the literature, the steel in question is not subjected to a quenching process, the properties obtained on such steel differ significantly from the original properties. The hardness value given in Table 2, obtained on the samples under study, is an average of five measurements.

Table 2

Hardness of the *09Mn2Si* steel samples

Heat treatment	HV20
Water quenching	1515.86
Tempering at 200 °C; air cooling	1761.02
Tempering at 350 °C; air cooling	1558.48
Tempering at 500 °C; air cooling	858.52
Tempering at 650 °C; air cooling	516.3

The data in Table 2 shows that there is a non-monotonic change in the hardness value. The increase in hardness is observed at the medium and low tempering. It is associated with a decrease in the number of grains and an increase in its average size [16, 17], causing changes in internal stresses. Then phase transitions occur, leading to the new phases' grains appearance due to the decomposition process of the martensite structure into ferrite and perlite. The number of grains increases but average size decreases.

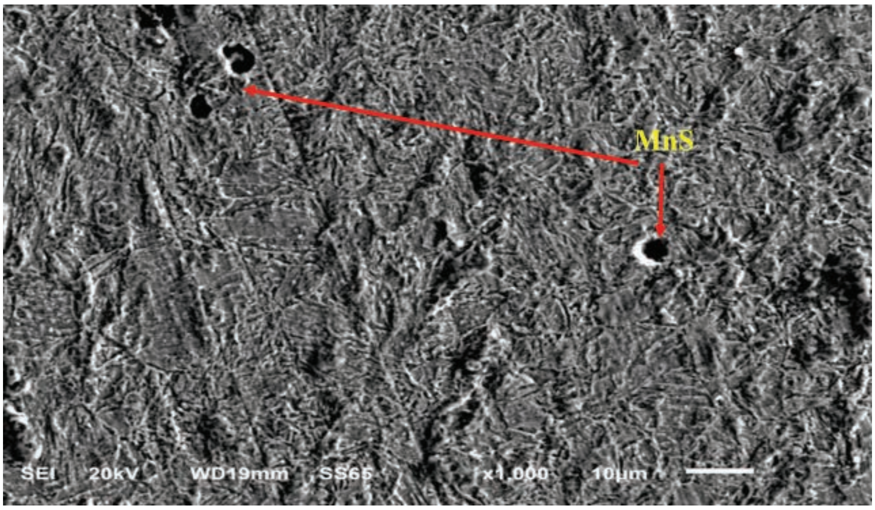
As a result of the polished section microanalysis, it is found that after quenching on the studied samples made of steel *09Mn2Si*, a martensitic structure is observed with a slight presence of the ferrite and pearlite phases. In the case of quenching, the main initial structure observed in microphotographs is martensite. It occurs as a result of the steel heating to the intercritical interval. The martensite nucleus formation occurs when the alloy is cooled from the austenitic state and nucleuses are located at the interphase boundaries of the initial ferrite-cementite phase and at the boundaries of ferrite grains [30]. While heating the unstable martensite, obtained as a result of quenching, it decomposes into a mixture of ferrite and cementite. At the same time, *Mn* is concentrated mainly in the carbide phase [29] which is cementite in the structure under consideration.

The martensite formed during quenching has a lath or packet (dislocational) structure. Crystals of such martensite are thin laths 0.2-2 µm thick, elongated in one direction. A set of elongated martensite crystallites parallel to each other forms packets. Martensite is separated by thin layers of residual austenite with a thickness of 10-20 nm. Both phases have a high density of defects in the crystal lattice structure [25, 27, 31–32]. The defects in the form of non-metallic inclusions of manganese sulfide [14] in most cases have a spherical shape (Figure 2) in such structure.

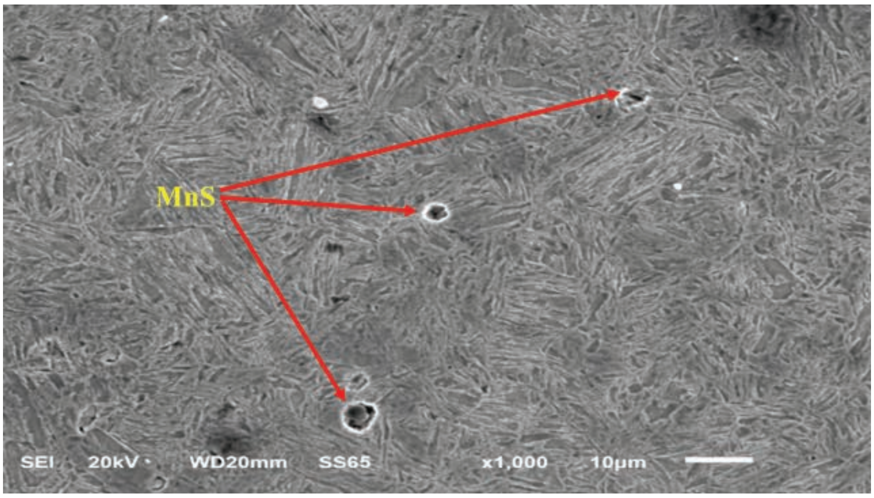
The *MnS* compound formation occurs in the presence of manganese and sulfur in the steel composition. This process occurs due to the fact that sulfur, participating in the chemical process, forms a *FeS* compound with iron at a melting temperature of 988 ºC. [18, 19]. The manganese presented in the steel (*09Mn2Si*) is slightly soluble in iron alloys and replaces it in the compound, forming manganese sulfide. The cavities filled with manganese sulfide are formed in the metal due to diffusion processes and the dissolution of large inclusions during the smelting and manufacture of rolled products. The study [25] indicates that with an increase in the manganese content in a solid solution, the solubility of sulfur decreases due to the chemical reaction between sulfur and manganese. The sulfide is formed consequently. The inclusions size and number of manganese sulfide increases [26] with a sulfur content of about 0.023 %. Such inclusions are corrosive areas that contribute to an increase in the rate of metal corrosion in the local area. The connection between such inclusions and the metal matrix of the material is weak. It leads to the removal of this compound and the cavity formation on the surface under external influence. The aggressive effect of the corrosive medium in this area increases [20] due to the weak diffusion backoff. Figure 3 shows a pipe fragment made of *09Mn2Si* steel with observed corrosion damage, which has a characteristic pitting shape.

The process of martensite decomposition occurs during tempering. It leads to the formation of a ferrite-carbide mixture with a granular carbide morphology [20]. At the same time, the ongoing processes lead to a change in the shape of inclusions from rounded to lamellar. The approach of the structure to the equilibrium state is accompanied by the elements' redistribution. It occurs as a result of diffuse processes when the initial quenched structure is heated i.e. under conditions of high density of interfacial boundaries and small diffusion paths through an acicular mixture of phases [30].

The martensite grain-size number increases from 2 to 5 during low tempering (200 °C). The areas with the ferrite and perlite phases practically do not change. The carbon atoms in tempering and other impurities presented in the steel diffuse from the supersaturated solid solution of martensite into structural imperfections of the crystal structure (dislocations and intergranular boundaries). The formation of carbide phase components occurs by the interaction of carbon and the boundary layer, which is a depleted martensite or ferritic phase. The occurrence of regions with a reduced carbon content leads to a decrease in the overall hardness of the steel. Due to the high density of defects in the crystalline structure of the primary phase (martensite), the resulting pearlite-ferrite structure will also has a high density of defects and is highly distorted. The shape of manganese sulfide inclusions is distorted in such structure. It has an elliptical shape (Figure 4). The carbon begins to diffuse into the area where the sulfide is located and forms clouds around it.



a



b

Fig. 2. The structure of the samples after water quenching, obtained using a scanning electron microscope:

a – shooting mode 1; *b* – shooting mode 2

Fig. 3. Fragment of a pipe after being in sea water

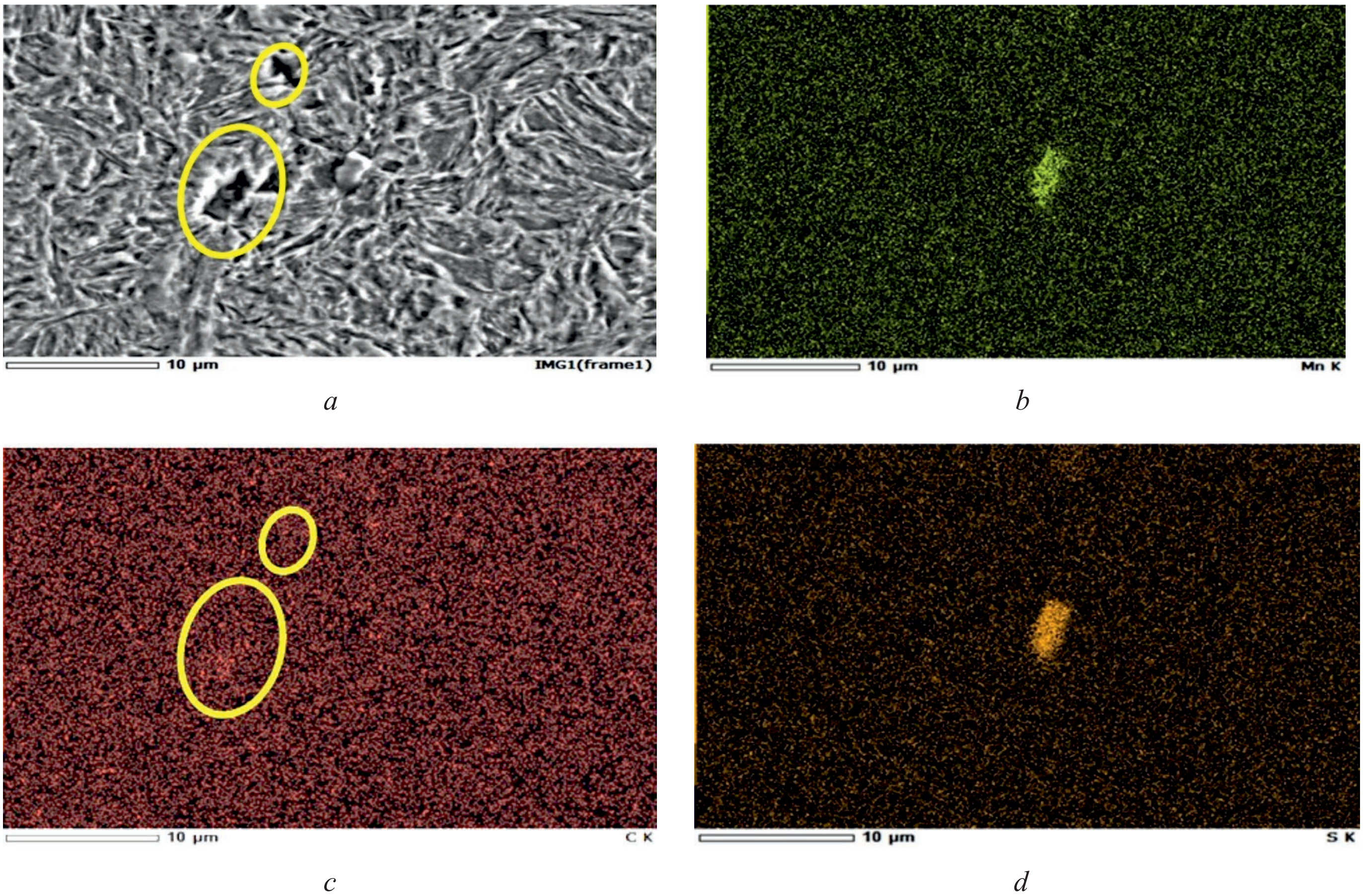


Fig. 4. Inclusions of manganese sulfide in a *09Mn2Si* steel sample after low-temperature tempering:
a – spherical inclusions in a micrograph obtained using a scanning electron microscope; *b* – the distribution of manganese in the micrograph shown in *a*; *c* – the distribution of carbon in the micrograph shown in *a*; *d* – the distribution of sulfur in the micrograph shown in *a*

The martensite grain-size number increases to 7 with a further raise in the tempering temperature to 350 °C. At the same time, a certain martensite quantity begins to decompose into ferrite and perlite. There is a diffusive carbon outflow from the martensitic matrix [22, 25]. These processes occurring in the structure lead to softening, which is associated with a decrease in internal stresses and, as a result, a decrease in the defectiveness of the crystal lattice due to a decrease in the dislocation density and various structural defects, as well as a lower hardness of the resulting ferrite phase [27–30, 31–34]. This process clearly reflects the dependence of the value of internal stresses on the tempering temperature. These results are presented in [21] and are based on the analysis of X-ray diffraction patterns taken on a *DRON-7* X-ray diffractometer [35]. The results show that the value of internal stresses decreases with an increase in the tempering temperature in this temperature range.

The removal of distortions of the cementite crystal lattice, which is part of perlite, leads to its transition to an equilibrium state. The cementite becomes “highly coercivity material” overall. However, a decrease in the amount of martensite and an increase in depleted phases (both martensite and ferrite) leads to a decrease in the overall level of both hardness and coercitive force. In accordance with Kersten’s theory of “inclusions” it is associated with a small contribution to the total value. The manganese sulfide is expanded by internal forces in the direction of internal stresses into the form of elongated inclusions or chains [21] when the temperature rises. The coefficient of thermal expansion of manganese sulfide is higher than that of iron [22, 23]. Therefore, this compound experiences greater compression than the matrix [24] when the material is cooled. As a result, the appearance of elongated manganese sulfide particles is observed

(Figure 5). The processes caused by the containment of dislocations on impurity elements of the structure during its interaction through Cottrell atmospheres should be taking into account.

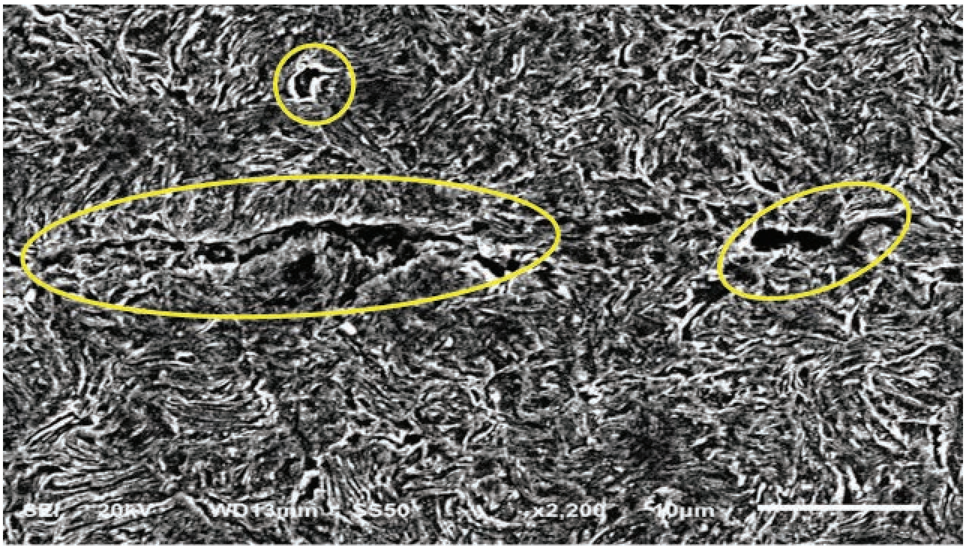


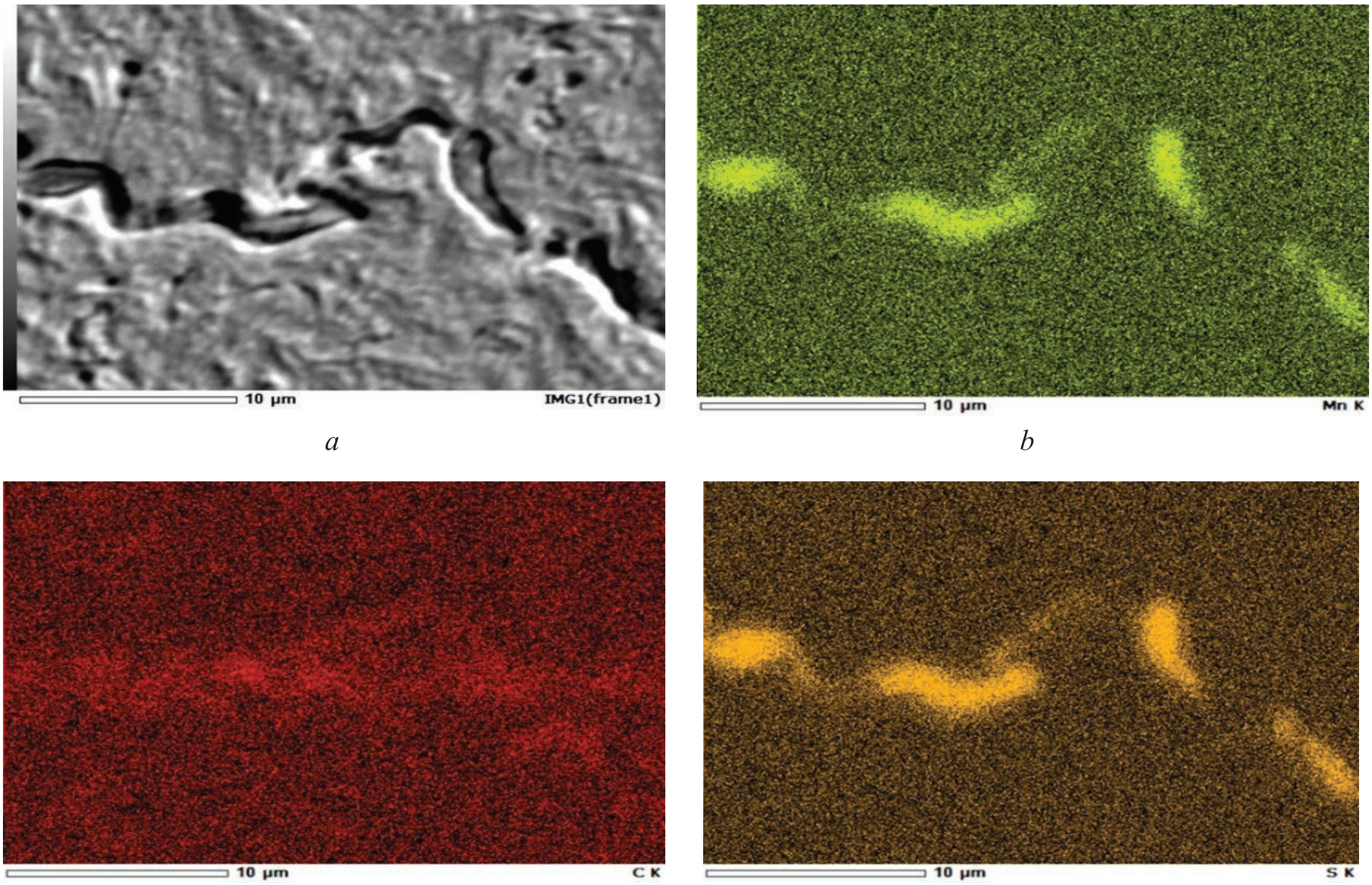
Fig. 5. Inclusions of manganese sulfide in a *09Mn2Si* steel sample after medium-temperature tempering (350 °C)

The mobility of crystal lattice's defects in the form of dislocations is very important in steels with a low content of alloying elements. It strongly affects the hardness value, which decreases quite quickly with an increase in the tempering temperature. It is also worth mentioning that the presence of alloying elements, such as *Mn*, in the steel composition during the tempering process can alloy cementite [27].

The structure transforms into ferrite-pearlite with an insignificant percentage of the observed phase of residual martensite at a tempering temperature of 500 °C. This tempering reduces the density of dislocations and plane defects of the crystal structure. As a result, the distorted cementite passes into a more equilibrium state. The proportion of ferrite in this mixture is 60.9 % and the proportion of perlite is 39.1 %. The total grain-size number of the structure is 7. At this temperature, further stretching of manganese sulfides occurs along the boundaries of the grain structure, which is associated with an increase in the plasticity of this compound. There are atmospheres formed by diffusing carbon atoms, which form additional areas with high corrosion activity around the inclusions (Figure 6).

The structure acquires an equilibrium state with the further temperature increasing to 650 °C. The appearance of granular pearlite is observed. The proportion of ferrite is 64.6 %, the proportion of perlite is 35.4 % and the structure grain-size number is 7. The perlite grain-size number increases due to the process of coagulation of the cementite particles that are part of the mechanical mixture. The structure approaches the equilibrium state [22–25]. It causes a decrease in the magnitude of internal stresses. The increase in the number of grains is due to the ferrite phase fragmentation. Although the pearlite grain size increases, there is a decrease in the average grain size observed on the microsection due to the appearance of smaller ferrite grains. An increase in the number of grains and the system dispersion leads to an increase in intergranular boundaries. Fragmentation continues until the grain reaches a "critical size". The reduction of internal stresses in this situation is associated with a decrease in the crystal lattice distortion because of the increase in the length of boundaries between the grains. The hardness of the material is reduced due to these processes. Carbon diffused in the area of *MnS* inclusions is redistributed in the matrix between the formed phases (Figure 7).

The corrosion rate of such material decreases (Figure 8) as a result of these processes. More details on the results of corrosion studies of the steel under consideration can be found in [16].



a *b* *c* *d*

Fig. 6. Inclusions of manganese sulfide in a *09Mn2Si* steel sample at an after medium-temperature tempering (500 °C):

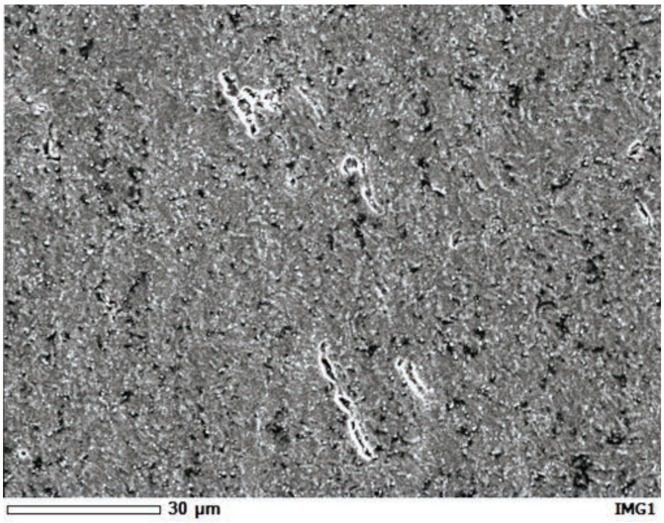
a – inclusions in a micrograph obtained using a scanning electron microscope; *b* – the distribution of manganese in the micrograph shown in *a*; *b* – the distribution of manganese in the micrograph shown in *a*; *c* – the distribution of carbon in the micrograph shown in *a*; *d* – the distribution of sulfur in the micrograph shown in *a*

Conclusions

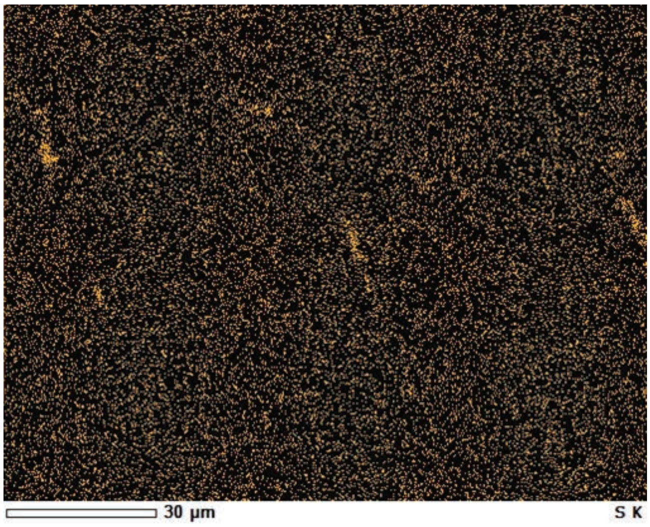
1. When analyzing the results obtained, it is found that in the low-alloy low-carbon structural steel *09Mn2S*, in most cases, there are non-metallic inclusions such as manganese sulfide. These inclusions are formed during steel production in the area of grain boundaries and have spherical form. When this steel is heated to the temperatures of the intercritical transition, in which a ferritic-martensitic structure is formed, this compound does not undergo significant changes. These inclusions significantly affect the strength and corrosive behavior. Manganese sulfide acts as the initiation point of the corrosion process.

2. It is found that carbon diffused from the main matrix forms a halo around the inclusions with a strong distortion of the crystal lattice. This leads to a change in the composition of the material in the local area, and, consequently, to a difference in mechanical and corrosion properties.

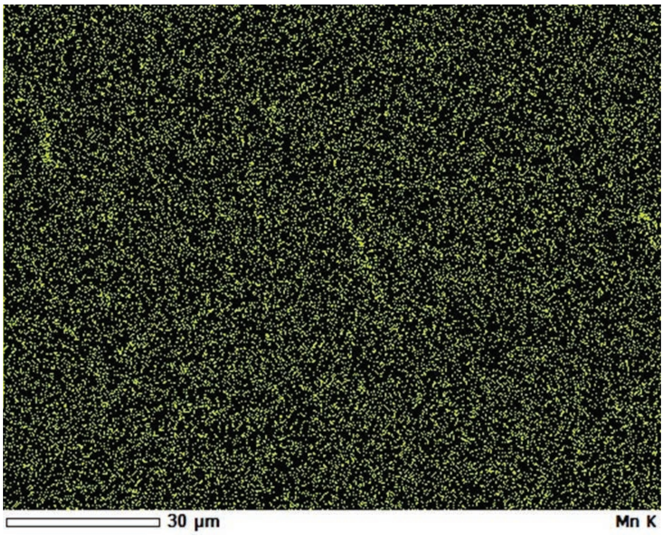
3. With an increase in the tempering temperature, the defect structure of the crystal lattice decreases due to a decrease in the number of dislocations and the decomposition of the unstable phase of martensite. As a result, internal stresses are reduced. However, there is a deformation of less strong inclusions of manganese sulfide. It begins to take on an elongated shape. This leads to an increase in the corrosive area. At high tempering, as a result of a decrease in the defect structure and the completion of the process of martensite decomposition, back diffusion of carbon into the depleted regions occurs. As a result, an increase in the concentration of this element is observed around the inclusions. These processes lead to some increase in the resistance of the material to corrosion processes.



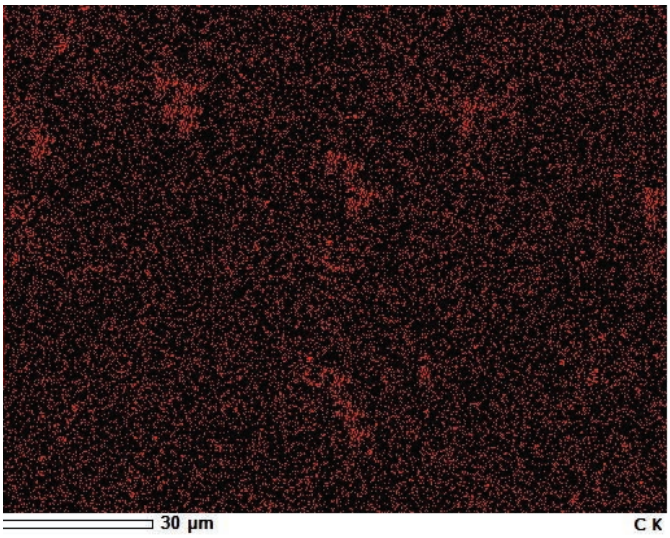
a



b



c



d

Fig. 7. Inclusions of manganese sulfide in a sample of steel *09Mn2Si* after medium-temperature tempering (650 °C):

a – an image obtained by *SEM*; *b* – distribution of sulfur over the surface; *c* – distribution of manganese over the surface; *c* – distribution of carbon over the surface

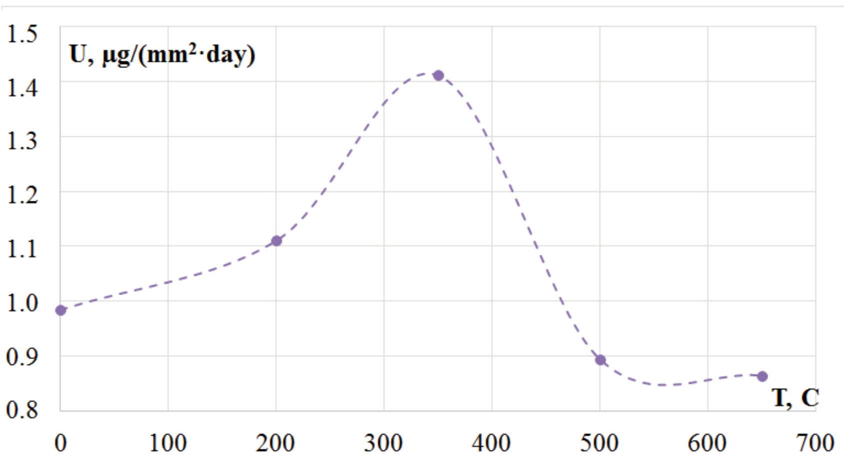


Fig. 8. Corrosion rate of steel *09Mn2Si* samples at different tempering temperatures in seawater

References

1. Sazonov B.G. Vliyanie vtorichnoi zakalki iz mezhkriticheskogo intervala na sklonnost' stali k obratimoi otpusknoi khrupkosti [The influence of secondary hardening from the intercritical interval on the tendency of steel to reversible tempering brittleness]. *Metallovedenie i termicheskaya obrabotka metallov = Metal Science and Heat Treatment*, 1957, no. 4, pp. 30–34. (In Russian).

2. Polyakova A.M., Sadovskii V.D. Mezhkriticheskaya zakalka konstruktsionnykh stalei ["Intercritical quenching" of structural steels]. *Metallovedenie i termicheskaya obrabotka metallov = Metal Science and Heat Treatment*, 1970, no. 1, pp. 5–8. (In Russian).

3. Vasil'eva A.G., Gulyaeva T.V., Sazonov V.G. Vliyanie iskhodnoi struktury i skorosti nagreva na svoistva stali posle mezhkriticheskoi zakalki [Influence of original structure and heating rate on the properties of steel after hardening from the intercritical range]. *Metallovedenie i termicheskaya obrabotka metallov = Metal Science and Heat Treatment*, 1981, no. 5, pp. 52–56. (In Russian).

4. Kogan L.I., Matrokhina E.F., Entin R.I. Vliyanie austenitizatsii v mezhkriticheskom intervale temperatur na strukturu i svoistva nizkouglerodistykh stalei [Influence of austenitization in the intercritical temperature range on the structure and properties of low-carbon steels]. *Fizika metallov i metallovedenie = The Physics of Metals and Metallography*, 1981, vol. 52, no. 6, pp. 1232–1241. (In Russian).

5. Golovanenko S.A., Fonshtein N.M. *Dvukhfaznye nizkolegirovannye stali* [Two-phase low-alloy steels]. Moscow, Metallurgiya Publ., 1986. 207 p.

6. Vinograd M.I., Gromova G.P. *Vklyucheniya v legirovannykh stalyakh i splavakh* [Inclusions in alloyed steels and alloys]. Moscow, Metallurgiya Publ., 1972. 215 p.

7. Kolotyrkin Ya.M., Freiman L.I. Rol' nemetallicheskikh vklyuchenii v korrozionnykh protsessakh [The role of nonmetallic inclusions in corrosion processes]. *Itogi nauki i tekhniki. Seriya: Korroziya i zashchita ot korrozii* [Results of science and technology. Series: Corrosion and corrosion protection]. Moscow, 1978, vol. 6, pp. 5–52.

8. Ryabov R.A., Geld P.V. K voprosu o mekhanizme obrazovaniya flokenov [On the question of the mechanism of formation of flocks]. *Metally = Russian Metallurgy (Metally)*, 1975, no. 6, pp. 114–116. (In Russian).

9. Reformatskaya I.I., Rodionova I.G., Beilin Yu.A., Nisel'son L.A., Podobaev A.N. Rol' nemetallicheskikh vklyuchenii i mikrostruktury v protsesse lokal'noi korrozii uglerodistykh i nizkolegirovannykh stalei [The effect of nonmetal inclusions and microstructure on local corrosion of carbon and low-alloyed steels]. *Zashchita metallov = Protection of Metals*, 2004, vol. 40, no. 5, pp. 498–504. (In Russian).

10. Rodionova I.G., Baklanova O.N., Zaitsev A.I. O roli nemetallicheskikh vklyuchenii v uskorenii protsessov lokal'noi korrozii neftepromyslovykh truboprovodov iz uglerodistykh i nizkolegirovannykh stalei [On the role of nonmetallic inclusions in the acceleration of local corrosion of oil-field pipelines made of carbon and low-alloy steels]. *Metally = Russian Metallurgy (Metally)*, 2004, no. 5, pp. 13–19. (In Russian).

11. Rodionova I.G., Baklanova O.N., Filippov G.A., Reformatskaya I.I., Podobaev A.N., Zinchenko S.D., Filatov M.V., Efimov S.V., Tishkov V.Ya., Golovanov A.V., Stolyarov V.I., Emelyanov A.V., Kuznetsova E.Ya. [The role of non-metallic inclusions in accelerating the processes of local corrosion of oilfield pipelines and other types of metal products and equipment made of carbon and low-alloy steels]. *Korrozionno-aktivnye nemetallicheskie vklyucheniya v uglerodistykh i nizkolegirovannykh stalyakh* [Corrosion-active nonmetallic inclusions in carbon and low-alloy steels: Proceedings of the scientific and practical seminar]. Moscow, 2005, pp. 7–15. (In Russian).

12. Rodionova I.G. Baklanova O.N., Filippov G.A., Reformatskaya I.I., Podobaev A.N., Zinchenko S.D., Filatov M.V., Efimov S.V., Tishkov V.Ya., Golovanov A.V., Stolyarov V.I., Emelyanov A.V., Kuznetsova E.Ya. The role of nonmetallic inclusions in accelerating the local corrosion of metal products made of plain-carbon and low-alloy steels. *Metallurgist*, 2005, vol. 49, no. 3–4, pp. 125–130. DOI: 10.1007/s11015-005-0065-3.

13. GOST 1778–70. *Stal'. Metallograficheskie metody opredeleniya nemetallicheskikh vklyuchenii* [State Standard 1778–70. Steel. Metallographic methods for the determination of nonmetallic inclusions]. Moscow, Standards Publ., 1970. 50 p.

14. Zaitsev A.I., Rodionova I.G., Mal'tsev V.V., Baklanova O.N., Zinchenko S.D., Lamukhin A.M., Filatov M.V., Efimov S.V., Lyatin A.B., Klachkov A.A., Krasil'nikov V.O. Istochniki vozniknoveniya v stali korrozionno-aktivnykh nemetallicheskikh vklyuchenii i puti predotvrashcheniya ikh obrazovaniya [Sources of corrosion-active nonmetallic

inclusions in steels and methods to prevent their formation]. *Metally = Russian Metallurgy (Metally)*, 2005, no. 2, pp. 3–11. (In Russian).

15. Sandomirskii S.G. Analiz svyazi koertsitivnoi sily s vremennym soprotivleniem uglerodistykh stalei [Coercive force and strength of carbon steel]. *Stal' = Steel in Translation*, 2016, no. 9, pp. 62–65. (In Russian).

16. *Sokolov R.A., Novikov V.F., Muratov K.R., Venediktov A.N.* Opredelenie vzaimosvyazi faktora raznozernistosti i skorosti korrozii konstruktsionnoi stali [Determination of the relationship between the factor of grain size factor and the corrosion rate of structural steel]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2020, vol. 22, no. 3, pp. 106–125. DOI: 10.17212/1994-6309-2020-22.3-106-125.

17. *Sokolov R.A., Novikov V.F., Muratov K.R., Venediktov A.N.* Otsenka vliyaniya dispersnosti struktury stali na magnitnye i mekhanicheskie svoistva [*Assessment of the effect of the steels structure dispersion on its magnetic and mechanical properties*]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2021, vol. 23, no. 4. pp. 93–110. DOI: 10.17212/1994-6309-2021-23.4-93-110.

18. Bashnin Yu.A., Ushakov B.K., Sekei A.G. *Tekhnologiya termicheskoi obrabotki stali* [Technology of heat treatment of steel]. Moscow, Metallurgiya Publ., 1986. 424 p.

19. Novikov I.I. *Defekty kristallicheskogo stroeniya metallov* [Defects in the crystal structure of metals]. Moscow, Metallurgiya Publ., 1975. 208 p.

20. Kiselev V.D., Ukhlovtsev S.M., Podobaev A.N.,. Reformatskaya I.I. Analiz korrozionnogo povedeniya stali 3 v khloridnykh rastvorakh s pomoshch'yu neironnykh setei [Analysis of corrosion behavior of steel 3 in chloride solutions by using neural networks]. *Zashchita metallov = Protection of Metals*, 2006, vol. 42, no. 5, pp. 493–499. (In Russian).

21. Onishchenko A.K., Beklemishev N.N. *Teoriya promyshlennoi kovki stali i splavov* [Theory of industrial forging of steel and alloys]. Moscow, Sputnik+ Publ, 2011. 245 p.

22. Gel'd P.V., Ryabov R.A., Kodes E.S. *Vodorod i nesovershenstva struktury metalla* [Hydrogen and imperfections of the metal structure]. Moscow, Metallurgiya Publ., 1979. 219 p.

23. Voronenko B.I. Vodorod i flokeny v stali [Hydrogen and flakes in steel]. *Metallovedenie i termicheskaya obrabotka metallov = Metal Science and Heat Treatment*, 1997, no. 11, pp. 12–18. (In Russian).

24. Fominykh E.A. *Sovershenstvovanie tekhnologii proizvodstva konstruktsionnoi legirovannoi stali dlya krupnykh pokovok*. Diss. kand. tekhn. nauk [Improvement of the production technology of structural alloy steel for large forgings. PhD eng. sci. diss]. South Ural State University. Chelyabinsk, 2007. 179 p.

25. Turkdogan E.T., Ignatowicz S., Pearson J. The solubility of sulphur in iron and iron-manganese alloys. *Journal of the Iron and Steel Institute*, 1955, vol. 180, pp. 349–354.

26. Yavoiskii V.I., Rubenchik Yu.I., Okenko A.P. *Nemetallicheskie vklyucheniya i svoistva stali* [Nonmetallic inclusions and properties of steel]. Moscow, Metallurgiya Publ., 1980. 174 p.

27. Huffman G.P., Errington P.R., Fisher R.M. Mossbauer study of the Fe–Mn carbides $(Fe_{1-X}Mn_X)_3C$ and $(Fe_{1.1}Mn_{3.9})C_2$. *Physica Status Solidi*, 1967, vol. 22 (2), pp. 473–481.

28. Schaaf P., Wiesen S., Gonser U. Mössbauer study of iron carbides: cementite $(Fe, M)_3C$ (M = Cr, Mn) with various manganese and chromium contents. *Acta Metallurgica et Materialia*, 1992, vol. 40, no. 2, pp. 373–379.

29. Shapovalov V.I. Trofimenko V.V. *Flokeny i kontrol' vodoroda v stali* [Flockens and hydrogen control in steel]. Moscow, Metallurgiya Publ., 1987. 160 p.

30. Rodionova I.G., Baklanova O.N., Filippov G.A., Zinchenko S.D., Filatov M.V., Efimov S.V., Stolyarov V.I., Kuznetsova E.Ya. O vliyanii roli nemetallicheskikh vklyuchenii osobogo tipa na uskorenie protsessov lokal'noi korrozii trub neftepromyslovogo naznacheniya [Influence of special nonmetallic inclusions on the acceleration of local corrosion in oil-field pipe]. *Stal' = Steel in Translation*, 2005, no. 1, pp. 86–88. (In Russian).

31. Smirnov M.A., Schastlivtsev V.M., Zhuravlev L.G. *Osnovy termicheskoi obrabotki stali* [Fundamentals of heat treatment of steel]. Ekaterinburg, Ural Branch of the Russian Academy of Sciences, 1999. 495 p.

32. Ueji R., Tsuchida N., Terada D., Tsuji N., Tanaka Yu., Takemura A., Kunishige K. Tensile properties and twinning of high-manganese austenitic steel with fine-grained structure. *Scripta Materialia*, 2008, vol. 59, iss. 9, pp. 963–966. DOI: 10.1016/j.scriptamat.2008.06.050.

33. Babicheva R.I., Semenov A.S., Dmitriev S.V., Zhou K. Vliyanie zernogranichnykh segregatsii na temperatury martensitnogo prevrashcheniya v bikristallakh NiTi [Effect of grain boundary segregation on martensitic

transformation temperatures in NiTi bicrystals]. *Pis'ma o materialakh = Letters on Materials*, 2019, vol. 9 (2), pp. 162–167. DOI: 10.22226/2410-3535-2019-2-162-167.

34. Li M., Kirk M.A., Baldo P.M., Xu D., Wirth B.D. Investigation of the evolution of defects by the TEM method with ion irradiation in situ and coordinated modeling. *Philosophical Journal*, 2012, vol. 92 (16), pp. 2048–2078. DOI: 10.1080/14786435.2012.662601.

35. Sokolov R.A., Novikov V.F., Venediktov A.N., Muratov K.R. Influence of surface treatment of construction steels on determination of internal stresses and grain sizes using X-ray diffractometry method. *Materials Today: Proceedings*, 2019, vol. 19 (5), pp. 2584–2585. DOI: 10.1016/j.matpr.2019.09.015.

Conflicts of Interest

The authors declare no conflict of interest.