Using of thermal cycling to improve the strength properties of steel

V. B. Kuskov, Cand. Eng., Associate Prof., Dept. of Mineral Processing[1]*, e-mail: Kuskov_VB@pers.spmi.ru;*
E. S. Iliin, Ph. D. Student, Dept. of Mineral Processing[1]*, e-mail: s235069@stud.spmi.ru*

[1] *Empress Catherine II Saint Petersburg Mining University (Saint Petersburg, Russia)*

Ferrum is the metal which is mostly used by people. Our usual life is impossible in conventional way without ferrum. Ferrum is also the base for iron and steel, and steel is the most widely used construction material for the industries. The properties of this material are very important and steel application areas are determined depending on these properties. Different methods of steel processing are used for improvement of its quality. One of this methods is presented by heat treatment, in particular – thermal cycling, which allows to improve substantially mechanical properties of steel. There are many variants of heat treatment for steels, however, thermal cycling has still large field for further investigations.

Based on the modern technical level, heat treatment processes can be carried out with heating rate varying from parts of grades per second to hundreds of grades per second. It is also possible to vary number of heating and cooling cycles, what has significant effect on mechanical properties of processed steel. Additionally, the processes after heat treatment provide apparent influence on these properties. Mechanical steel processing after conducted heat treatment also has the effect on steel properties. Conduction of metal processing according to incorrect operating modes can have very negative consequences for steel properties. Wrong operation with material can seriously deteriorate obtained steel properties after heat treatment.

The paper presents the experiences of thermal cycling of ShKh-15 steel and the conditions allowing to obtain optimal steel strength properties are determined.

Key words: thermal cycling, cycle, quenching, tempering, annealing, critical point, internal steel grain, hardness, wear resistance.

DOI: 10.17580/cisisr.2024.01.09

Introduction

The role of mineral resources in the mankind life can be hardly overestimated. All material objects, which were created by people, are or made either from mineral resources, or using products of processing of mineral resources [1–5].

Ferrum, or really its alloys, is the metal which is mostly used by people. Steel is known as the most widely used Fe-based alloy, it is used in all industrial branches – from food to aerospace industry. Steel quality plays the most important role and mainly determines the quality of finished products. The required quality of steel and steel products can be provided, for example, by heat treatment, alloying, surface coating and other methods [6–11].

Thermal cycling (TC) is also one of the ways of steel processing, it is a kind of heat treatment with cyclic technological process [12–18].

Thermal cycling processes can be conducted with heating rate varying from parts of grades per second to hundreds of grades per second. It is possible to vary number of cycles during TC, what provide essential influence on mechanical properties of processed steel. The processes conducted after TC, such as tempering, annealing, ageing etc., have apparent effect on these properties. These “finishing” processes are aimed on saving the positive variations, which were acquired during TC, and probably to strengthen them if possible [13, 14, 19, 20].

Development of the concrete thermal cycling modes is carried out for the concrete materials, i.e. TC mode essentially depends on the properties of processed material. It is evident, that the most close are material properties, the most close will be processing modes. The main idea of development of TC different modes is selection of such mode from rather wide number of the processes, occurring during thermal cycling, and to promote the most complete conduction of those processes that provide improvement of steel mechanical properties. The a.m. number of processes includes dissolution, crystallization, extraction of phases, stresses, deformations etc. [13, 14, 19, 20].

Unlike non-cyclic heat treatment methods, thermal cycling is characterized by appearance of other “sources” having effect on steel properties; they are connected only with cyclic features of the process. Phase transformations, temperature gradients, thermal volumetric and inter-phase stresses etc. can be mentioned among these “sources” [13, 14].

Variation of the structure during thermal cycling is connected, in particular, with variable solubility of different material components. It creates conditions for redistribution of elements and variation of phases, owing to multiple dissolution – extraction. Such processes are available only for thermal cycling, from all heat treatment operations [13, 21].

The main thermal cycling methods differ rather essentially from each other. The main TC variants are presented in the **Fig. 1**.

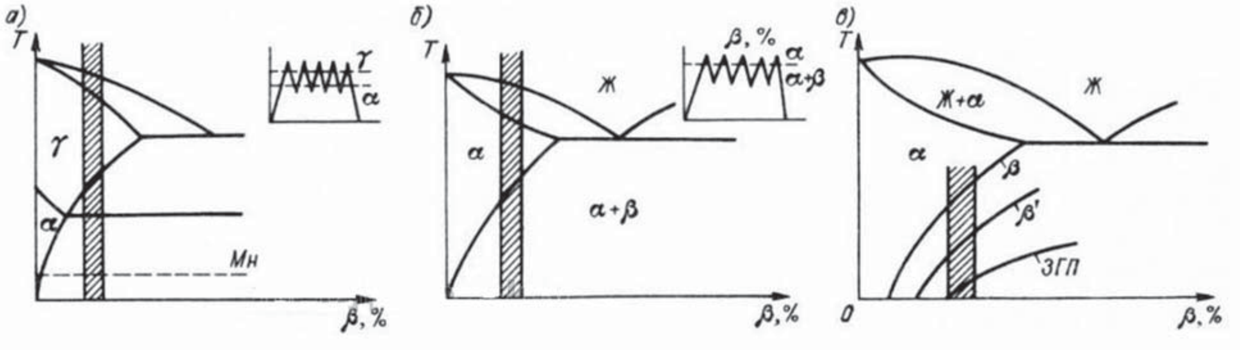

Fig. 1. The main thermal cycling methods: *a* – TC with complete or partial phase recrystallization; *b* – TC in the field of variable mutual solubility of elements; *c* – TC within the temperature range of dispersion hardening

The final structure of processed steel will depend on phase transitions, which are not connected with substantial variations of phase composition. Spheroidizing of phases and coalescence can be considered as such phase transitions. In this connection, the gradient of concentration of a chemical element between extractions of different size exists in solid solution [13, 14, 19, 20].

The tendency of reaching the most stable energy state by all phase transitions in the system is the main regularity. Depending on physical and chemical properties and material nature, the process of diffusion motion of atoms can occur via different mechanisms [22–24].

The aim of this research is examination of practical influence of thermal cycling on steel mechanical properties. Improvement of mechanical properties, in its turn, allows to improve the quality of finished steel products.

Solving the problem

Several experiments on thermal cycling of ShKh-15 steel were carried out; they cover 3 kinds of cycles for steel TC. As a result, the thermal cycling method for ShKh-15 steel is suggested, providing achievement of high hardness and wear resistance of metal. A bearing roller was used as raw material; it was then forged in a strip with thickness 7 mm and width 32 mm. Then steel was cut in 9 samples, each with size 7 × 7 × 32 mm (**Fig. 2**).

The muffle furnace with maximal heating temperature up to 1350 °C with electronic heat controller was used a heating furnace.

The following plan of the research was developed.

- annealing of the samples;
- determination of 3 rinds of cycles;
- preparation of 3 samples for each heating cycle;
- quenching of 3 samples with different number of cyclic heating iterations;
- low-temperature tempering of samples;
- hardness measurement for samples in two planes;
- destruction of samples in the middle of their length;
- qualitative assessment of internal grains size coarseness;
- determination of relationships of variations of hardness and coarseness of internal grains from number of iterations of cyclic temperature variation;
- determination of the cycle, when maximal hardness and minimal steel internal grain size were achieved.

Thermal cycling parameters accepted for the research

ShKh-15 steel has the critical point A_{c3} = 900 °C and quenching temperature 840 °C. 3 kinds of TC cycles were examined. One of them has no relation to the critical point A_{c3} and includes heating up to 840 °C with 1 min holding and consequent cooling to 800 °C with 1 min holding.

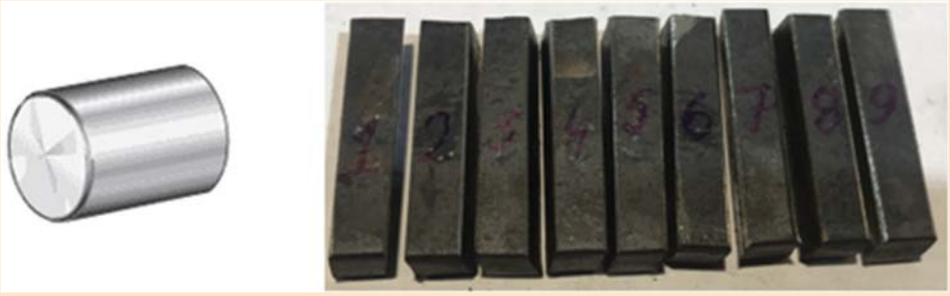

Fig. 2. Bearing roll and ShKh-15 steel samples

The second cycle takes into account the critical point A_{c3} and includes heating up to 900 °C with 1 min holding and consequent cooling to 750 °C with 1 min holding. The third cycle also takes into account the critical point A_{c3} and includes heating up to 960 °C with 1 min holding and consequent cooling to 840 °C with 1 min holding. All 9 samples were subjected to annealing at the temperature 800 °C with 2 hours holding and consequent cooling with the furnace to the temperature 20 °C. Engine oil heated to the temperature 60 °C was used as a cooling medium for all samples. All samples were subjected to quenching at the temperature 840 °C. After quenching, they are subjected to low-temperature annealing at the temperature 180 °C with 2 hours holding and consequent cooling with the furnace to the temperature 20 °C.

To examine influence of the temperature boundaries of the cycle (including and not including the critical point A_{c3}) and number of cyclic iterations of heating and cooling on the final steel properties, the research accepts 3 kinds of of the temperature boundaries of the cycle and 3 variants of numbers of cyclic iterations of heating and cooling of samples. The required number of samples for conduction of experiments was stipulated by the number of mutually connected variable parameters. 9 steel samples are required for investigation for 3 variants of the temperature boundaries, on the condition of 3 variants of numbers of cyclic iterations of heating and cooling.

The first TC cycle was carried out with the samples No. 1–3. The samples No. 1, No. 2 and No. 3 were subjected to 2, 4 and 6 iterations of heating and cooling, respectively. The heating cycle is presented in the **Fig. 3**.

The second TC cycle was carried out with the samples No. 4–6. The samples No. 4, No. 5 and No. 6 were subjected to 2, 4 and 6 iterations of heating and cooling, respectively. The heating cycle is presented in the **Fig. 4**.

The third TC cycle was carried out with the samples No. 7–9. The samples No. 7, No. 8 and No. 9 were subjected to 2, 4 and 6 iterations of heating and cooling, respectively. The heating cycle is presented in the **Fig. 5**.

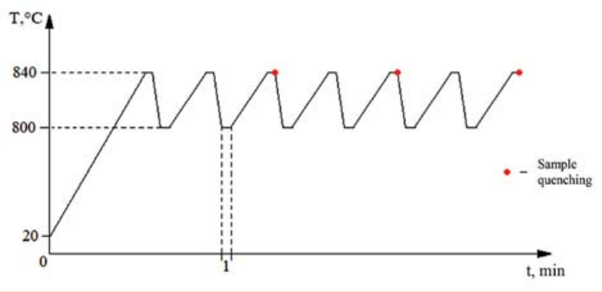

Fig. 3. The first heating cycle

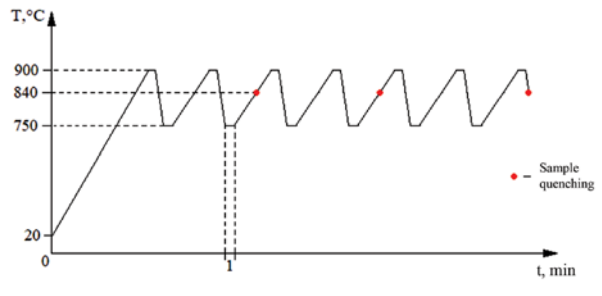

Fig. 4. The second heating cycle

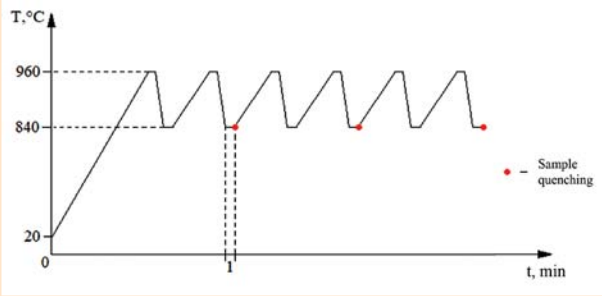

Fig. 5. The third heating cycle

The muffle furnace with operating modes for conduction of the first heating cycle with the steel samples No. 1–3 is shown in the **Fig. 6**. The temperature corresponds to the heating points of the first cycle 840 °C and 800 °C, which are maximally distant from each other. The temperature in the furnace is reflected on the monitor of thermal controller with red figures, while preset heating temperature is displayed with green figures.

Fig. 6. Muffle furnace and its operating modes for the first kind of TC cycle

The methods for samples examination

Visual assessment of coarseness of internal grains in ShKh-15 steel samples and quantitative assessment of samples hardness was conducted based on the results of different variants of thermal cycling. All samples were subjected to destruction in the central cross section by applying of external load, which exceeds the material tensile strength. Hardness measuring in the samples was carried out in two mutual perpendicular planes using stationary hardness meter HR-150A.

Visual assessment of coarseness of internal grains in the steel samples

To provide visual assessment of coarseness of internal structure of the samples, splitting of each steel sample was carried out. Fracture of the samples was conducted across the middle cross section of the sample, with the same external force effect (shearing) using electromechanical guillotine. Fracture was observed in the middle cross section of the sample. Unfortunately, the technical possibility to determine the size of steel internal structure was unavailable, so only visual assessment was realized.

Fracture surfaces of ShKh-15 steel samples No. 1–3 are presented in the **Fig. 7**.

Fig. 7. Fracture surfaces of ShKh-15 steel samples No. 1–3

It can be seen in the Fig. 7 that each sample has different fracture. From the first view, grain structure for the samples No. 2 and No. 3 is similar. Grain coarseness of the sample No. 1 is seen apparently, it is maximal in comparison with grain size of other samples.

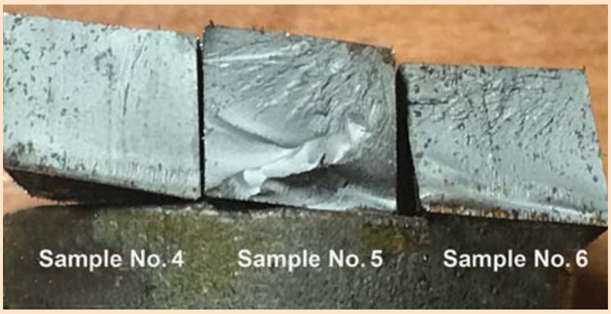

Fig. 8. Fracture surfaces of ShKh-15 steel samples No. 4–6

Fracture surfaces of ShKh15 steel samples No. 4–6 are presented in the **Fig. 8**.

It is difficult to assess the steel internal grain coarseness depending on increase of number of cyclic temperature measurement iterations within the framework of the second TC cycle, based on the Fig. 8. It should be mentioned that fractures of the samples presented in the Fig. 8 are not equal visually, they differ apparently from each other.

Fracture surfaces of ShKh15 steel samples No. 7–9 are presented in the **Fig. 9**.

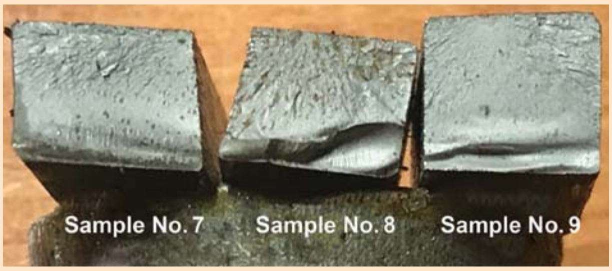

Fig. 9. Fracture surfaces of ShKh-15 steel samples No. 7–9

It can be seen in the Fig. 9 that fracture of the samples becomes more homogenous with increase of number of cycles. The grain structure of the sample No. 7 is evidently more porous in comparison with two other samples.

Hardness measurement of the samples using stationary hardness meter HR-150A

Hardness of the samples was measured in two mutually perpendicular planes using stationary hardness meter HR-150A. The measurements were carried out in GRC units, using diamond tip for a hardness meter. The results are presented in the **Table**.

Dependence between hardness variation of steel samples and number of iterations of temperature cyclic variation for three kinds of TC cycles is presented in the **Fig. 10**.

Growth of hardness of the samples can be seen on the Fig. 10, depending on increase of number of cyclic iterations. For the second and third kinds of TC cycles, hardness variation looks like linear relationship. Maximal hardness was achieved in the third kind of TC cycle with six iterations.

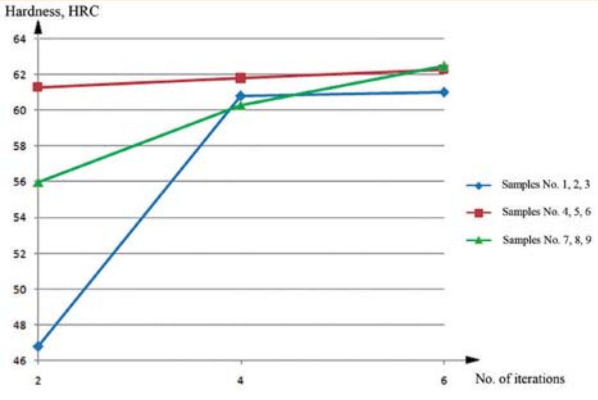

Fig. 10. Dependence between hardness variation of steel samples and number of iterations of temperature cyclic variation

Possible areas of thermal cycling application

Fine concentrates, natural porous ores, wastes of different production facilities are usually not valid for consequent direct processing of use and are required in agglomeration. Briquetting is considered as one of agglomeration methods,

The results of hardness measurement of samples in two mutual perpendicular planes

No. of TC cycle	No. of sample	First hardness measurement, HRC	Second hardness measurement, HRC	Average hardness value, HRC
1	1	45.5	48.0	46.8
	2	60.5	61.0	60.8
	3	61.5	61.0	61.0
2	4	62.0	60.5	61.3
	5	62.0	61.5	61.8
	6	61.5	63.0	62.3
3	7	54.5	57.5	56.0
	8	59.0	61.5	60.3
	9	62.0	63.0	62.5

and roller presses are among the most widely distributed equipment for briquetting [25–29].

Extrusion units, having several advantages in comparison with roller presses can be also used for briquetting. But extruders can be efficiently used only in operation with rather soft and non-abrasive materials. When operating with hard abrasive materials (steel chips and sawdust, hard abrasive mineral resources etc.), rather quick wear is observed, mainly for a forming head of extruder as well as screw conveyer and internal shell surface [30–36].

Improvement of mechanical properties, such as hardness and wear resistance of forming heads, screw conveyer and internal shell surface of extruders, is one of the possible areas of thermal cycling application, what increases their service life.

Conclusion

Based on the results of conducted experiments and analysis of the obtained data, it was established that use of thermal cycling provides essential effect on steel properties. The final result depends on correct choice of TC cycle. The cycle with deviation by 60 °C above and below the critical point Ac_3 for ShKh-15 steel was recognized as the best fron the researched cycles.

Taking into account the results of hardness measurement for the samples, it was revealed that the first kind of thermal cycling was characterized by the minimal steel hardness value; moreover, the sample No. 1 had maximal grain size and minimal hardness in relation to all other samples.

Maximal hardness value was noted for the sample No. 9, which was processed via the third kind of thermal cycling with deviation by 60 °C above and below the critical point $Ac_3 = 900$ °C. This TC kind allows to obtain steel with most high hardness in comparison with other researched cycles.

Use of thermal cycling provides obtaining more homogenous distribution in internal steel structure, uniform size of material grains, as well as decreasing of internal stresses inside metal.

Thus, steel thermal cycling allows to rise its mechanical properties, in particular hardness and wear resistance, what improve in its turn quality of finished products manufactured from this steel.

REFERENCES

1. Litvinenko V. S., Petrov V. I., Vasilevskaya D. V., Yakovenko A. V., Naumov I. A., Ratnikov M. A. Assessmemt of the state role in management of mineral resources. *Zapiski Gornogo instituta*. 2023. Vol. 259. pp. 95–111. DOI: 10.31897/PMI.2022.100.
2. Litvinenko V. S., Sergeev I. B. Innovations as a Factor in the Development of the Natural Resources Sector. *Studies on Russian Economic Development*. 2019. Vol. 30. No. 6. pp. 637–645. DOI: 10.1134/S107570071906011X.
3. Nedosekin A. O., Reishakhrit E. I., Kozlovskiy A. N. Strategic approach to evaluation of economical stability of the objects of Russian mineral and raw material complex. *Zapiski Gornogo instituta*. 2019. Vol. 237. pp. 354–360. DOI: 10.31897/PMI.2019.3.354.
4. Yurak V. V., Dushin A. V., Mochalova L. A. Against sustainable development: the future scenarios. *Zapiski Gornogo instituta*. 2020. Vol. 242. pp. 242–247. DOI: 10.31897//PMI.2020.2.242.
5. Aleksandrova T. N. Complex and deep processing of mineral raw materials of natural and technogenic origin: state and prospects. *Zapiski Gornogo instituta*. 2022. Vol. 256. pp. 503–504. https://pmi.spmi.ru/index.php/pmi/article/view/16064.
6. Trushko V. L., Trushko O. V. Complex development of iron ore deposits on the base of competitive underground geotechnologies. *Zapiski Gornogo instituta*. 2021. Vol. 250. pp. 569–577. DOI: 10.31897/PMI.2021.4.10.
7. Saginashvili D. G., Ryabova V. D., Zakirova M. I. Analysis of steelmaking industry in Russia. *Vestnik universiteta*. 2021. No. 1 (8). pp. 81–88. DOI: 10.26425/1816-4277-2021-8-81-88.
8. Nikulin S. A. et al. Influence of high temperatures on mechanical properties of steel 22K. *Deformatsiya i razrushenie materialov*. 2020. No. 5. pp. 22–26. DOI: 10.31044/1814-4632-2020-5-22-26.
9. Bazhin V. Yu., Issa B. Influence of heat treatment on microstructure of steel tubing coils in a tubular heating furnace. *Zapiski Gornogo instituta*. 2021. Vol. 249. pp. 393–400. DOI: 10.31897/PMI.2021.3.8.
10. Milyuts V. G., Tsukanov V. V., Pryakhin E. I., Nikitina L. B. Development of manufacturing technology for high-strength shell steel providing decrease of production cycle and high quality of sheets. *Zapiski Gornogo instituta*. 2019. Vol. 239. p. 536. DOI: 10.31897/pmi.2019.5.536.
11. Gordienko V. V. et al. Influence of heat treatment and thermal cycling on mechanical properties of structural steels. *Vestnik grazhdanskikh inzhenerov*. 2018. No. 1. pp. 128–133. DOI: 10.23968/1999-5571-2018-15-1-128-133.
12. Karimov N. K., Ashurov Kh. Kh. Increase of impact toughness of structural steels via thermal cycling. *Natural and technical sciences: the problems of interdisciplinary synthesis. Scientific proceedings of International scientific and practical conference. Belgorod, December 25, 2020.* Agenstvo perspektivnykh nauchnykh issledovaniy (APNI). 2020. pp. 40–43.
13. Kaparov S. A., Zholdoshov B. M., Mamatkadyrova B. B. Thermal cycling of structural steels 30KhGSA and 45Kh. *Mashinovedenie*. 2022. No. 1 (15). pp. 65–71.

14. Shmatov A. A. Thermal cycling methods for volumetric strengthening of steel tools. *Mezhdunarodnyi zhurnal prikladnykh i fundamentalnykh issledovaniy*. 2021. No. 7. pp. 56–60.
15. Yusupov A. A., Fazilov D. S., Abdukarimova F. A., Berdiev D. M. Thermal cycling technologies for increase of wear resistance. *Central Asian Journal of Theoretical and Applied Science*. 2023. No. 4 (4). pp. 15–19. DOI: 10.17605/OSF.IO/RY8GN.
16. Berdiev D. M., Faizullaev S. S. Wear resistance increase for gear wheels via thermal cycling. *Universum: tekhnicheskie nauki*. 2023. No. 1–2 (106). pp. 15–18.
17. Afanasyev V. K., Popova M. V. Use of thermal cycling deformation for improvement of low carbon steel operating properties. *Metallovedenie i termicheskaya obrabotka metallov*. 2022. No. 12. pp. 3–9. DOI: 10.30906/mitom.2022.12.3-9.
18. Zhao X. et al. The effect of thermal cycling on direct laser-deposited gradient H13 tool steel: Microstructure evolution, nanoprecipitation behaviour, and mechanical properties. *Materials Today Communications*. 2020. Vol. 25. p. 101390. DOI: 10.1016/j.mtcomm.2020.101390.
19. Oñoro M. et al. Mechanical properties and stability of precipitates of an ODS steel after thermal cycling and aging. *Nuclear Materials and Energy*. 2020. Vol. 24. p. 100758. DOI: 10.1016/j.nme.2020.100758.
20. Lan L., Shao G. Morphological evolution of HAZ microstructures in low carbon steel during simulated welding thermal cycle. *Micron*. 2020. Vol. 131. p. 102828. DOI: 10.1016/j.micron.2020.102828.
21. Gordienko V. et al. Structural changes in structural steels during thermal cycling. *Architecture and Engineering*. 2021. Vol. 6. No. 2. pp. 70–76.
22. Liu Q. et al. Effect of thermal cycling on the corrosion behaviour of stainless steels and Ni-based alloys in molten salts under air and argon. *Solar Energy*. 2022. Vol. 238. pp. 248–257.
23. Ghaemifar S. et al. Improved properties of dual-phase steel via pre-intercritical annealing treatment and thermal cycling. *Materials Science and Technology*. 2020. Vol. 36. No. 15. pp. 1663–1670. DOI: 10.1080/02670836.2020.1818511.
24. Hu W. et al. Improving the cycle fatigue life of spring steel by a novel thermal cycling process. *Materials Research Express*. 2021. Vol. 8. No. 5. p. 056516. DOI: 10.1088/2053-1591/ac006c.
25. Fernández-González D., Ruiz-Bustinza I., Mochón J., González-Gasca C., Verdeja L. F. *Iron ore sintering: Process. Mineral Processing and Extractive Metallurgy Review*. 2017. Vol. 38. No. 4. pp. 215—227.
26. Urbanovich N. I., Korneev S. V., Volosatikov V. I., Komarov D. O. Analysis of composition and processing technologies for dispersed iron-containing wastes. *Lityo i metallurgiya*. 2021. No. 4. pp. 66–69. DOI: 10.21122/1683-6065-2021-4-66-69.
27. Kim K. M., Bae J. H., Han J. W. Effect of Aspect Ratio on Iron-Ore Briquettes DuringTwin-Roll Briquetting. *Archives of Metallurgy and Materials*. 2020. Vol. 65. No. 4. pp. 1335—1339.
28. Khalifa A. A., Bazhin V. Yu., Ustinova Ya. V., Shalabi M. E. Kh. Research on the reduction of iron oxide from red mud pellets using coke. *Obogashchenie rud*. 2021. No. 4. pp. 46–51.
29. Aleksandrova T. N., Nikolaeva N. V., Artamonov I. S. Optimization of composition of fuel briquettes. *Gornyi informatsionno-analiticheckiy byulleten*. 2022. No. 6–2. pp. 149–160. DOI: 10.25018/0236_1493_2022_62_0_149.
30. Kurunov I. F., Bizhanov A. M. Brexes as the new stage in agglomeration of raw materials for blast furnaces. *Metallurg*. 2014. No. 3. pp. 49–53.
31. Kurunov I. F., Chizhikova V. M., Bizhanov A. M. The best acceptable technologies in production of agglomerated raw materials for blast furnaces. *Chernaya metallurgiya, Byulleten nauchno-tekhnicheskoy i ekonomicheskoy informatsii*. 2018. Vol. 1. No. 4. pp. 62–66.
32. Bizhanov A. M., Podgorodetskiy G. S. on motion of briquetting mass in extruder. Exact solutions. Message 1. *Izvestiya vysshikh uchebnykh zavedeniy. Chernaya metallurgiya*. 2020. Vol. 63. No. 1. pp. 7–12.
33. Bizhanov A. M. Synergy of agglomeration and briquetting in blast furnace practice. *Metallurg*. 2021. No. 7. pp. 20–28.
34. Bizhanov A. M., Zagainov S. A. Testing of briquettes for mechanical strength. *Metallurg*. 2021. No. 3. pp. 11–18.
35. Mikhailov A. V., Fedorov A. S. Analysis of parameters of a die of screw press for 3D extrusion of peat pieces of tubular type. *Zapiski Gornogo instituta*. 2021. Vol. 249. pp. 351–365. DOI: 10.31897/PMI.2021.3.4.
36. Kuskov V. B., Ilyin E. S. Study of agglomeration process via extrusion for different kinds of raw materials. *Gornyi informatsionno-analiticheckiy byulleten*. 2022. No. 6–1. pp. 279–289. DOI: 10.25018/0236_1493_2022_61_0_279.