An approach to calculating the casting temperature of high-manganese austenite steel

S. L. Arapov, *Chief Metallurgist* [1], *Junior Researcher* [2], *e-mail: arapovsl@yandex.ru;*
S. V. Belyaev, *Dr. Eng., Prof., Head of Foundry Department* [2], *e-mail: 244812@mail.ru;*
A. A. Kosovich, *Cand. Eng., Associate Prof., Senior Researcher* [2], *e-mail: akosovich@sfu-kras.ru;*
E. G. Partyko, *Cand. Eng., Associate Prof., Junior Researcher* [2], *e-mail: elforion@mail.ru*

[1] *LLC Engineering Construction Maintenance (Russia, Achinsk)*
[2] *Siberian Federal University (Russia, Krasnoyarsk)*

This study is devoted to influence of the temperature procedures of high-manganese austenite steel casting on formation of the internal structure and properties of castings. An example of a high-manganese austenite steel Fe-1.1C-16Mn-0.8Si-1.3Cr-Mo-Ni is considered, which differs from the generally accepted composition of Hadfield steel (110G13L) by an expanded Mn content and combined alloying with carbide-forming elements. The study applied an approach to choosing the optimal casting temperature, which is implemented using pre-computer modeling of the cast structure by the Cellular Automaton Finite Element method, followed by verification on physical samples. An analysis of the microstructure of the experimental samples obtained at the selected casting temperatures indicates the accuracy of conducted calculation: the discrepancy between grain sizes does not exceed 5 μm (4.4 %). Rational temperature contributes to formation of more fine microstructure and, accordingly, a high level of mechanical properties: pouring the alloy under study at 1390-1410 °C makes it possible to obtain an average grain size of 113-116 μm, minimal mass loss upon contact with the abrasive (1.74-1.81 %) and increased impact strength (28.5-28.3 kgf·m/cm^2). Subsequent approximation of the calculated values and obtaining a regression equation using the Reduced Major Axis method allows in practice to predict reliably (with determination coefficient 0.826) the grain size of the casting at the selected casting temperature without using additional software.

Keywords: Hadfield steel, chemical composition, microstructure, austenite, impact strength, Cellular Automaton Finite Element; casting temperature.
DOI: 10.17580/cisisr.2023.02.07

Introduction

The grade of high-manganese austenite steel 110G13L, in accordance with GOST 977-88 [1], which was developed by R. A. Hadfield, have been widely used since the end of XIX century. This steel, including its different modifications (e.g. 110G13Kh2BRL, 110G13FTL, 130G14KhMFAL, is one of the main materials for fabrication of changing parts for assemblies and devices in machine-building, mining, metallurgical production as well as in railroad infrastructure. Large volume of grade range of such products is caused by the complex of the Hadfield steel properties, i.e. impact strength, wear resistance under the effect of high pressure or impact loads, strain hardening ability. Increased wear resistance during the contact with abrasive particles is connected with forming of thin strengthened layer on a part surface, which is reclaimed in more deep layers in the wearing process during whole operation period [2-4].

At the same time, the global scientific society accumulated substantial laboratorial and industrial experience in different aspects of the Hadfield steel examination. The most research works were concentrated on the problems of quality improvement of castings [5-7], material strengthening [8-11], study of corresponding wearing mechanisms [12-15], optimization of technological processes in order to decrease production cost [16, 17].

The main manufacturing method for products made from Hadfield steel is casting with use of various auxiliary equipment; in this case casting mass can achieve several hundreds of kg. This technological operation directly finalizes in forming the typical internal material structure with austenite grains of different sizes. The last factor has serious influence on the level of mechanical and operating properties.

It is known that overheating of melt up to the temperatures 1500-1550 °C allows to provide sufficient conditions for removal of non-metallic inclusions, despite simultaneous hazard of steel contamination due to high level of gas absorption and aggression to refractory materials of a ladle and mould. Increased casting temperature is also the cause of consequent growth of austenite grain and forming the columnar structure. The castings with such structure are characterized by low impact strength, small cracking resistance, cold brittleness, decrease of wear resistance. In this case, appearing of hot cracks is noted, because grain boundaries in high-manganese steel are often considered as the planes with maximal weakness [6, 18].

In this connection, the quantitative relationships between casting temperature (T) and impact strength (KCU), tensile strength ($\sigma_{\text{В}}$), relative elongation (δ) present definite interest; they were established in the work [19]:

$$KCU = 123\text{-}0{,}07T \quad (1)$$

$$\sigma_{\text{В}} = 220\text{-}0{,}097T \quad (2)$$

$$\delta = 123\text{-}0{,}062T \quad (3)$$

It is seen that increased level of mechanical properties is typical for castings fabricated at the minimal allowable casting temperature, taking into account permanency of other factors (observation of the technology, optimal wall thickness of billets etc.). It can be explained by obtaining the structure with fine austenite grain and minimal weakening in the form of phosphide, oxysulphide and other inclusions, as well as by heterogeneity of chemical composition in the whole material volume. E.g., based on [18] data, conditional cold brittleness threshold moves from -20 to -50 °C during casting temperature reducing from 1470 to 1410 °C.

Nevertheless, the substantiated limiting factors of application of such approach exist. Casting temperature reducing restricts processability of melting, as well as possibilities of furnace and ladle treatment. The melt having relatively low temperature, is characterized by increased toughness, what has negative effect on motion of non-metallic inclusions during ladle treatment and causes their introduction in a casting body.

Based on the above-mentioned regulations, the aim of this research is determination of the optimal temperature procedure for casting from high-manganese austenite steel, using the virtual model of the obtained microstructure and its verification on real samples.

Experimental technique

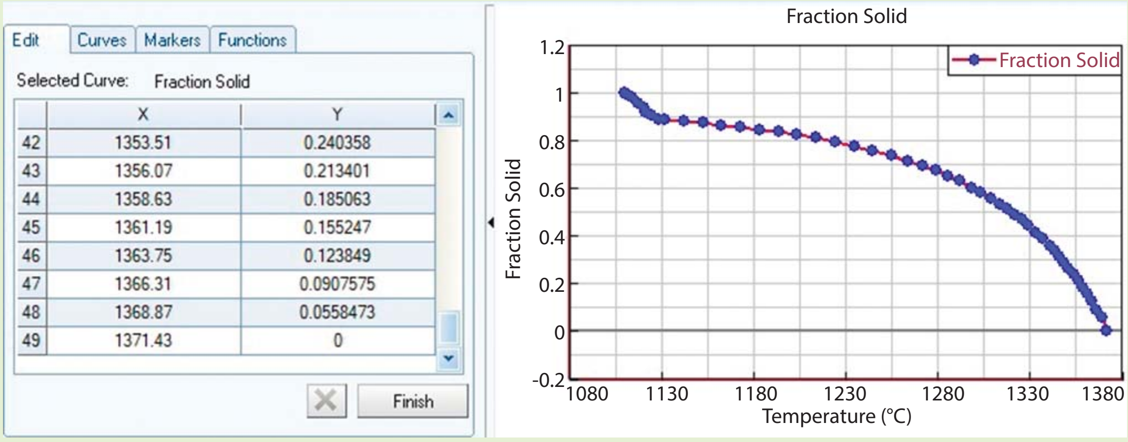
The researched material is presented by the analog of the Hadfield steel with increased Mn content and combined alloying by carbide-forming elements Fe-1.1C-16Mn-0.8Si-1.3Cr-Mo-Ni, which was described by the authors in the previous investigation [20].

The processing model of arising and growth of austenite grains was used at the starting stage; these processes take place during mould filling and casting solidification. As soon as possibility of management of the model parameters for equalizing of the step of calculated cell with the real grain size is required for solving of such tasks, it is insufficient to rely on empiric models of relationships, which are able to predict only microstructural scale of lengths and distances between dendrite branches. Thereby this calculation was realized using the method of "Cellular Automaton Finite Element (CAFÉ)", i.e. using mathematical model in the form of uniform net of simultaneously operated cells, each of them was connected with adjacent definite rules of interaction. Imitation model allows to take into account thermodynamic parameters of preset compositions of the alloy and casting moulds (Green Sand in this case) for the most exact reproduction of temperature fields in concrete conditions [21-23].

Melt preparation in the conditions of industrial experiment was carried out in a 3-phase alternative current electric arc steelmaking furnace with basic lining (MgO > 91 %), and witn mandatory execution of desulpurization and dephosphorization. Used charge materials are presented in the **Table 1**. Control of chemical composition was conducted using DFS-500 spectrometer in the set with argon cleaning

Table 1. **Experimental charge materials [25-31]**

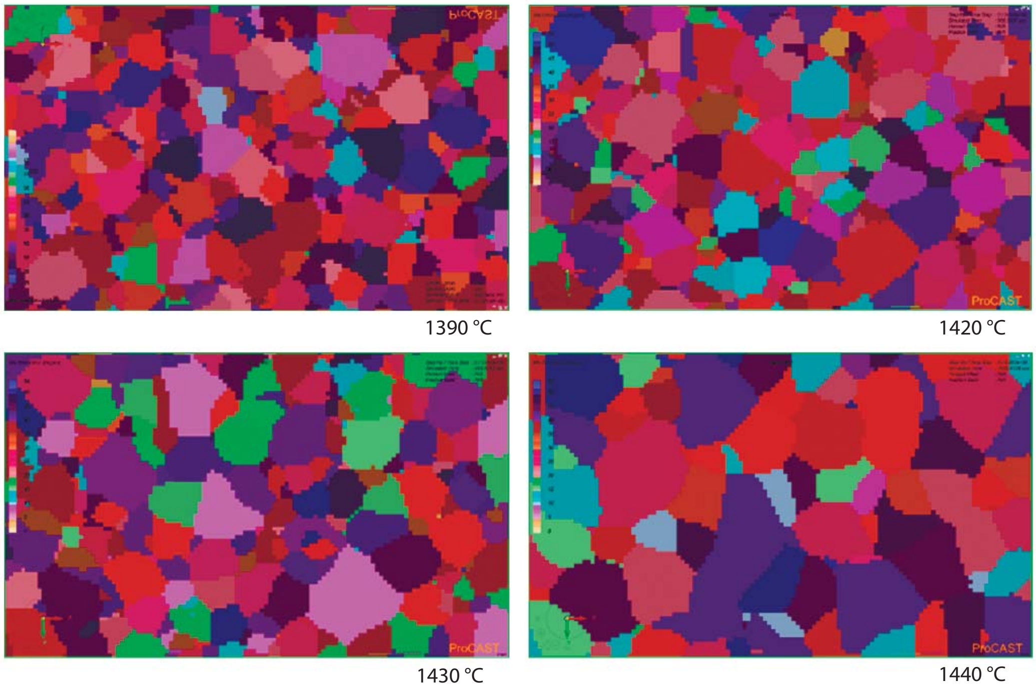
Processes	Material
Metal charging	Carbon steel scrap
Correction of Mn content	FeMn78 (GOST 4755-91), Mn95 (GOST 6008-90)
Introduction of Cr	FeCr010 (GOST 4757-91)
Introduction of Mo	FeMo6 (GOST 4759-91)
Introduction of Ni	H-4 (GOST 849-2018)
Diffusion deoxidation	FeSi65 (GOST 1415-93)
Residual deoxidation	AV91 (GOST 295-98)



Selected Curve: Fraction Solid

	X	Y
42	1353.51	0.240358
43	1356.07	0.213401
44	1358.63	0.185063
45	1361.19	0.155247
46	1363.75	0.123849
47	1366.31	0.0907575
48	1368.87	0.0558473
49	1371.43	0

Fig. 1. Liquidus point of the examined steel Fe-1.1C-16Mn-0.8Si-1.3Cr-Mo-Ni


1390 °C 1420 °C

1430 °C 1440 °C

Fig. 2. Typical models of cast steel microstructure within the temperature range 1390-1440 °C (magnification x100).

stand “SOAR-1” according to the GOST R 54153-2010 [24]. Control of melt casting temperature was executed using the sensor “STAL-4” with switched-on thermoelectric transformer TPR(V)-021.

Fabricated samples were subjected to heat treatment via high-temperature water quenching from the temperature 1150 °C. Microstructure was examined using Carl Zeiss Observer .A1m microscope and AxioVision software according to the GOST 5639-82 [32] with preliminary pickling by a chemical reagent on the base of chlorine ferrum ($FeCl_3 \cdot 6H_2O$), ammonium persulfate ((NH4)2S2O8), hydrochloric acid (HCl) and water.

Impact strength (KCU, kgf·m/cm^2) was determined according to the GOST 9454-78 [33] on the samples with U-shaped concentrator, using pendulum impact testing machine MK-30A. Abrasive wear resistance was evaluated by a sample mass loss, while this sample was placed in automatic grinding and polishing machine ATM SAPHIR 520 under load 100 N. Diamond grinding disk CAMEO PLATINIUM I was used as abrasive tool.

Experimental results and discussion

It was mentioned above that lowering of casting temperature allows to avoid arising of transcrystallization and to obtain more fine grain structure. Respectively, we should base on liquidus line for each alloy during determination of the minimal allowable casting temperature. Calculation of the liquidus point using ProCAST Fraction Solid tool is based on the chemical composition of the examined steel Fe-1.1C-16Mn-0.8Si-1.3Cr-Mo-Ni (**Fig. 1**).

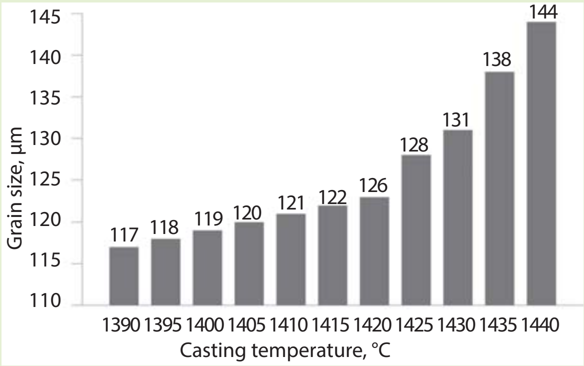


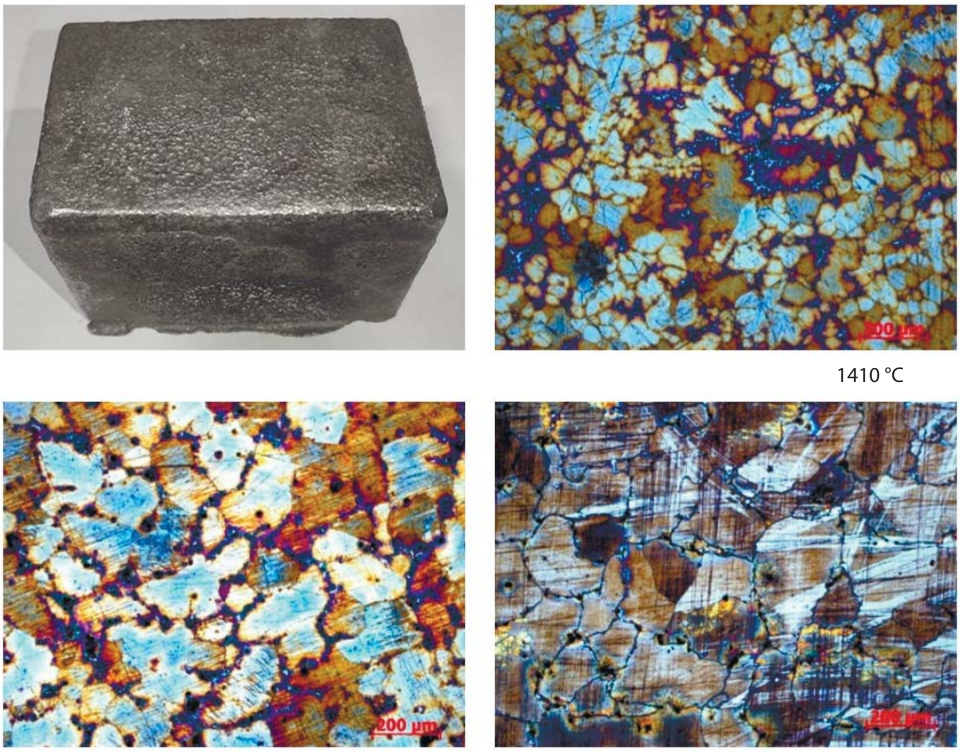
Fig. 3. Calculated grain size within the casting temperature range 1390-1440 °C

According to the executed calculation, the value of the liquidus point for the using material makes 1371 °C. Taking into account the practical experience of fabrication of steel castings, it was decided to increase the temperature mark by 20 °C. Thus, structure simulation (**Fig. 2**) and calculation of predicted grain size (**Fig. 3**) were carried out from the starting point 1390 °C with 5 °C pitch for 11 control points.

Taking into account small difference between predicted grain sizes, which were obtained within the temperature

Table 2. **Chemical composition of the samples, % (Fe – residual).**

Casting temerature, °C	C	Mn	Si	Cr	Mo	Ni	S	P
1390	1.15	16.50	0.83	1.42	0.41	0.46	0.01	0.07
1400	1.15	16.50	0.80	1.42	0.40	0.45	0.01	0.05
1410	1.14	16.47	0.80	1.40	0.40	0.41	0.01	0.05
1420	1.13	16.41	0.78	1.40	0.37	0.40	0.01	0.05
1430	1.11	16.37	0,75	1.36	0.36	0.38	0.01	0.02
1440	1.09	16.18	0.74	1.35	0.33	0.36	0.01	0.02



1410 °C

1430 °C

1440 °C

Fig. 4. General view of a cast sample and typical steel microstructures for different casting temperatures (magnification x100).

range from 1390 °C (117 µm) to 1420 °C (123 µm), which was equal to 6 µm, it was decided to use the casting temperature of physical samples within the temperature range 1390-1440 °C with increased pitch 10 °C. Possibility of practical evaluation and comparison of grain size for real samples is considered here as additional restriction, taking into account the measurement error. At the same time, difference in grain size for the minimal casting temperature and 1430 °C makes 14 µm, what is a detectable intermediate result. The result of calculation (144 µm) for the ultimate examined point (1440 °C) also sparks the interest.

Respectively, verification of a computer model was conducted for 6 demonstrational points via fabrication of 18 physical samples (3 samples for each point) from the prepared melt at the preset casting temperatures. The results of analysis of the averaged chemical composition for these samples are presented in the **Table 2**. Typical metallography of the reference samples made from the examined steel, which were crystallized in the identical cooling conditions, is presented on the **Fig. 4**.

It is known that microstructure with minimal grain size is most preferable for obtaining the high level of properties. This interaction for the alloy Fe-1.1C-16Mn-0.8Si-1.3Cr-Mo-Ni is apparently seen based on the testing results for reference samples in determination of impact strength and abrasive wear resistance (**Table 3**) for different casting temperatures. It should be noted here that these measured results of impact strength correlate with the similar results which were obtained in the previous investigation for the examined steel [20].

Evaluation of convergence of the results of computer simulation and physical experiment is an important stage of this research. The graph reflecting linear relationship between the casting temperature and grain size parameters of

Table 3. **Testing results for the samples**

Casting temperature, °C	Average grain size, µm	Initial mass, g	Final mass, g	Mass loss, g_r	Relative mass variation, %	KCU, kgf·m/cm^2
1390	113	70.23	69.01	1.22	1.74	28.5
1400	114	69.15	67.92	1.23	1.78	28.5
1410	116	69.18	67.93	1.25	1.81	28.3
1420	125	70.62	69.19	1.43	2.02	27.5
1430	134	79.69	78.08	1.61	2.02	26.4
1440	147	71.43	67.53	3.90	5.46	23.3

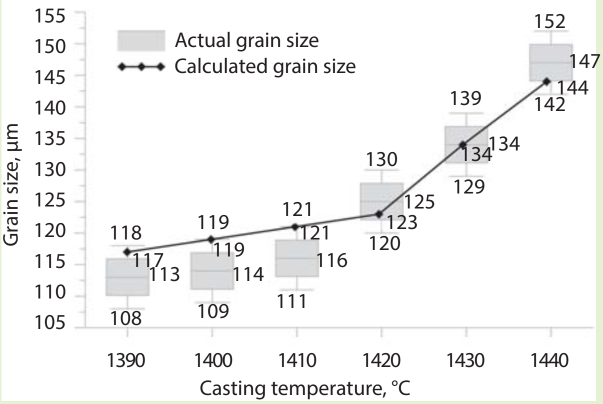


Fig. 5. Comparison between calculated and actual sizes of austenite grain

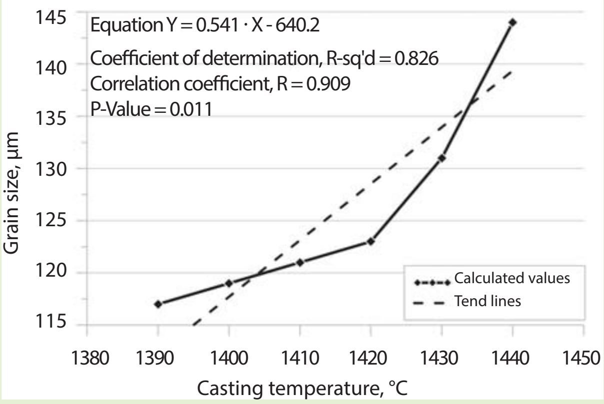


Fig. 6. Approximation of calculated values of grain size

microstructure was built for visual comparison of the results (**Fig. 5**); average grain size with inherent dispersion is displayed.

Difference between the values of average grain size, which were obtained via direct measurement on samples, and those calculated using CAFÉ module, does not exceed 4.4 %. Taking into account dispersion of the measured values (±5 µm), this difference does not exceed 11.5 %. Respectively, calculated data can be considered as reliable within the selected temperature range. At the same time it is possible to conduct approximation of the values via graphical method (**Fig. 6**) and to derive the regression equation of the type $y = f(x)$ (expression 4).

$$d_{gs}=0,541\cdot T\text{-}640,2 \qquad (4)$$

where d_{gs} – grain size (µm), T – casting temperature (°C).

The tend line on the Fig. 6 was built using the Reduced Major Axis (RMA) method, which means tuning of the linear regression model to the data via minimization of square sum of perpendicular distance between each data point and regression line, taking into account possible measuring error for one of the variables. Deviation of the values, which were calculated according to the expression (4), from CAFÉ models makes less than 4.7%, as well it is within the range 0.4-5.4 % for actual average grain size and it does not exceed 9.5 % taking into account dispersion of measurements (±5 µm).

Thus, the obtained mathematical relationship allows to predict grain size in castings made from the examined steel Fe-1.1C-16Mn-0.8Si-1.3Cr-Mo-Ni with high probability (R^2=0.826), within the temperature range 1390-1440 °C. Practically it means that we can determine calculated parameters of the structure and evaluate the level of mechanical properties of product without use of complicated software, via placing the current melt temperature in the formula.

Conclusion

Based on the presented data, expedience of using the above-described method for casting temperature calculation of high-manganese austenite steels can be concluded. Deviation between the average grain size of cast structure for the predicted CAFÉ model and physical samples does not exceed 5 µm (4.4 %). It was confirmed experimentally that the rational temperature of the examined melt promotes forming the most fine microstructure, which makes positive effect on the casting properties. So, metal casting at the temperature 1390-1410 °C allows to obtain the average grain size 113-116 µm, minimal mass loss after contact with an abrasive tool (1.74-1.81 %) and high impact strength (28.5-28.3 kgf·m/cm^2). At the same time, temperature rise will lead to reverse proportional variation of these data.

The obtained regression equation describes quantitatively the relationship between casting temperature of the steel

Fe-1.1C-16Mn-0.8Si-1.3Cr-Mo-Ni in temporary moulds (within the temperature range 1390-1440 °C) and obtained grain size in a casting; it allows to predict this grain size with high reliability, deviation does not exceed 9.5 %.

This experience can be also used for other high-manganese steels, taking into account their features during casting in temporary moulds. Holding the lower liquid metal temperature can lead to reducing of electric power consumption and wear of lining materials.

The research was carried out within the State scientific order of the Siberian federal university, the project No. FSRZ-2020-0013.

REFERENCES

1. GOST 977-88. Steel castings. General specifications. Introduced: 01.01.1990.
2. Sinitskiy E. V., Nefedyev A. A., Akhmetova A. A., Ovchinnikova M. V., Khrenov I. B., Deryabin D. A. Review of the results of investigations aimed at improvement of properties of castings made from high manganese steel. *Teoriya i tekhnologiya metallurgicheskogo proizvodstva*. 2016. No. 2. pp. 45-57.
3. Okechukwu C., Dahunsi O. A., Oke P. K., Oladele I. O., Dauda M. Prominence of Hadfield Steel in Mining and Minerals Industries: A Review. *IJET*. 2017. Vol. 3. No. 2. pp. 83-90. DOI: 10.19072/IJET.299068.
4. Alimov V. I., Shtykhno A. P., Bairova I. I. Improving the production of steel parts 110G13L for crushing and grinding equipment. *Resursosberegayushchie tekhnologii proizvodstva i obrabotki davleniem materialov v mashinostroenii*. 2021. No. 3. pp. 50-60.
5. Ten E. B., Bazlova T. A., Likholobov E. Yu. Effect of ladle treatment on the structure and mechanical properties of steel 110G13L. *Metallovedenie i termicheskaya obrabotka metallov*. 2015. No. 3. pp. 26-28.
6. Chaikin A. V., Chaikin V. A., Lozov V. S., Kasimgazinov A. D., Karman Y. V., Bykov P. O. Comparative analysis of the quality indices of the 110G13L steel produced with various modifiers and deoxidizing agents. *Vestnik Magnitogorskogo gosudarstvennogo tekhnicheskogo universiteta im. G. I. Nosova*. 2018. Vol. 16. No. 1. pp. 19-25. DOI: 10.18503/1995-2732-2018-16-1-19-25.
7. Arapov S. L., Belyaev S. V., Kosovich A. A., Partyko E. G., Stepanenko N. A., Yuriev P. O., Mansurov Y. N. Application of Mathematical Statistics to Improve Hadfield Steel Casting Impact Strength. *Metallurgist*. 2023. Vol. 66. No. 9-10. pp. 1083-1091. DOI: 10.1007/s11015-023-01421-7.
8. Zhang F. C., Lu B., Wang T. S., Zheng C. L., Zhang M., Luo H. H., Liu H., Xu A. Y. Explosion hardening of Hadfield steel crossing. *Materials Science and Technology*. 2010. Vol. 26. No. 2. pp. 223-229. DOI: 10.1179/174328408X363263.
9. Najafabadi V., Amini K., Alamdarlo M. Investigating the effect of titanium addition on the wear resistance of Hadfield steel. *Metallurgical Research & Technology*. 2014. Vol. 111. No. 6. pp. 375-382. DOI: 10.1051/metal/2014044.
10. Zhbanova E. N., Saitgareev L. N., Skidin I. E., Bialik G. A. An electrophysical method for increasing the wear resistance of castings from steel 110G13L during crystallization. V*estnik Gomelskogo gosudarstvennogo tekhnicheskogo universiteta im. P. O. Sukhogo*. 2017. No. 3. pp. 24-28.
11. Vdovin K., Pesin A., Feoktistov N., Gorlenko D. Surface Wear in Hadfield Steel Castings DOPED with Nitrided Vanadium. *Metals*. 2018. No. 8. pp. 845. DOI: 10.3390/met8100845.
12. Abbasi M., Kheirandish S., Kharrazi Y., Hejazi J. On the comparison of the abrasive wear behavior of aluminum alloyed and standard Hadfield steels. *Wear*. 2010. Vol. 268. No. 1-2. pp. 202-207. DOI: 10.1016/j.wear.2009.07.010.
13. Bolobov V. I., Batalov A. P., Bochkov V. S., Chupin S. A. Wear resistace of steel 110G13L in different abrasive media. *Zapiski Gornogo instituta*. 2014. Vol. 209. No. 17. pp. 17-22.
14. Kolokoltsev V. M., Vdovin K. N., Chernov V. P., Feoktistov N. A., Gorlenko D. A., Dubrovin V. K. Study of abrasive and impact and abrasive wear mechanisms of high manganese steel. *Vestnik Magnitogorskogo gosudarstvennogo tekhnicheskogo universiteta im. G. I. Nosova*. 2017. Vol. 15. No. 2. pp. 54-62. DOI: 10.18503/1995-2732-2017-15-2-54-62.
15. Chen C., Lv B., Ma H., Sun D., Zhang F. Wear behavior and the corresponding work hardening characteristics of Hadfield steel. *Tribology International*. 2018. Vol. 121. pp. 389-399. DOI: 10.1016/j.triboint.2018.01.044.
16. Dement T. V., Popova N. A., Kurzina I. A. The effect of varying the concentration of Mn on the phase composition and intragrain structure of the Fe-Mn-C alloy (1.2 wt.% C). *Fundamentalnye problemy sovremennogo materialovedeniya*. 2016. Vol. 13. No. 4. pp. 421-426.
17. Pyatykh A., Savilov A., Timofeev S. Investigation of Hadfield Steel Machinability in Milling Operations. 2022. *KEM*. Vol. 910. pp. 123-128. DOI: 10.4028/p-8p4ud2.
18. Davydov N. G., Lyamzin V. A. Features of tapping and teeming of high-manganese steel of of 110G13L grade. *Teoriya i tekhnologiya metallurgicheskogo proizvodstva*. 2016. No. 2. pp. 32-34.
19. Shulte Yu. A., Korneichuk A. I., Sherstyuk A. A., Speranskiy B. S. Influence of pouring temperature on mechanical properties and cold brittleness of high-manganese steel G13L. *Metallurgicheskaya i gornorudnaya promyshlennost*. 1971. No. 2. pp. 48-50.
20. Arapov S. L., Belyaev S. V., Kosovich A. A., Partyko E. G. Digital experiment as a method for improving the mechanical properties of Hadfield steel. *Chernye Metally*. 2022. No. 10. pp. 45-51.
21. Hou Y., Li S., Cheng G. Effect of Nb Addition on Dendrite Growth and Equiaxed Grain Ratio of Fe-20 Pct Cr High-Purity Ferritic Stainless Steel. *Metall. Mater. Trans. A*. 2018. Vol. 49. pp. 5445–5457. DOI: 10.1007/s11661-018-4838-2.
22. Ridgeway C. D., Gu C., Ripplinger K., Detwiler D., Ji M., Soghrati S., Luo A. A. Prediction of location specific mechanical properties of aluminum casting using a new CA-FEA (cellular automaton-finite element analysis) approach. *Materials & Design*. 2020. Vol. 194. 108929. DOI: 10.1016/j.matdes.2020.108929.
23. Yan X., Xu Q., Tian G., Liu Q., Hou J., Liu B. Multi-scale modeling of liquid-metal cooling directional solidification and solidification behavior of nickel-based superalloy casting. *Journal of Materials Science & Technology*. 2021. Vol. 67. pp. 36-49. DOI: 10.1016/j.jmst.2020.06.051.
24. GOST R 54153–2010. Steel. Method of atomic emission spectral analysis. Introduced: 01.01.2012.
25. GOST 4755–91. Ferromanganese. Specification and conditions of delivery. Introduced: 01.01.1997.
26. GOST 6008–90. Metallic manganese and nitrated manganese. Specifications. Introduced: 01.07.1991.
27. GOST 4759–91. Ferromolybdenum. Specification and conditions of delivery. Introduced: 01.01.1993.
28. GOST 4757–91. Ferrochromium. Specification and conditions of delivery. Introduced: 01.01.1993.
29. GOST 849–2018. Primary nickel. Specifications. Introduced: 01.06.2019.
30. GOST 1415–93. Ferrosilicium. Specification and conditions of delivery. Introduced: 01.01.1997.
31. GOST 295–98. Aluminium for deoxidation, manufacture of ferroalloys and aluminothermy. Introduced: 01.07.2001.
32. GOST 5639–82. Steels and alloys. Methods for detection and determination of grain size. Introduced: 01.01.1983.
33. GOST 9454–78. Metals. Method for testing the impact bending strength at low, room and high temperature. Introduced: 01.01.1979.