Development of new composition for sHSS steel used for hot rolling mill rolls at Magnitogorsk Iron and Steel Works

***V. M. Kolokoltsev**, Dr. Eng., Prof., President of the University[1], e-mail: kwm@magtu.ru;*
***N. A. Feoktistov**, Cand. Eng., Associate Prof., Head of the Dept. of Casting Processes and Materials Science[1], e-mail: fna87@mail.ru;*
***A. S. Savinov**, Dr. Eng., Prof., Director of the Institute of Metallurgy, Machine-building and Material Processing[1], e-mail: savinov_nis@mail.ru;*
***E. V. Skripkin**, Magister Student[1]*

[1]Nosov Magnitogorsk State Technical University (Magnitogorsk, Russia)

The paper presents the results of the complex scientific and research work directed on development of the new composition of sHSS steel for rolling mill rolls together with Magnito-gorsk Iron and Steel Works (MMK) and Magnitogorsk Mill Rolls Plant (MZPV). The first part includes the review of technical literature in the field of the results of roll steel examination by domestic and foreign researchers, investigation of structure and determination of properties of foreign rolling rolls, which were operated at the MMK hot rolling mill. The minimal level od sHSS steel properties for the working layer of a rolling roll, providing its operation reliability, is also determined.
Laboratorial experiments were conducted at the second stage. The formed massif of ex-perimental data was processed using neural net, and as a result, the optimal chemical composition of the roll steel with high wear resistance and hardness was obtained. After processing of the re-sults of the planned experiment, the regression equation was obtained; it describes influence of the alloy chemical composition on wear resistance and hardness coefficients.
Optimized composition of the alloy was developed at Magnitogorsk Mill Rolls Plant; it wad resulted in manufacture of the pilot roll sleeve in centrifugal machine. This roll sleeve was subjected to heat treatment according to the standard plant procedure.
The final step included laboratorial testing of the pilot roll sleeve which was manufac-tured from steel with optimized chemical composition. It was determined that the developed composition is characterized by wear resistance increased by 27 % in comparison with the re-searched foreign analogue, as well as by similar qualitative parameters of the alloy microstructure.
Key words: rolling roll, sHSS steels, wear resistance, hardness, working layer, neural net, microstructure, heat treatment.
DOI: 10.17580/cisisr.2022.01.05

Introduction

The first rolls from high-speed steel appeared in Japan in the end of 1980-ies. They were used for hot rolling mills. Since the beginning of 1990-ies, cast rolls from semi-high-speed steel (sHSS) were tested. The industrial enterprises of Japan, USA and Europe since 2000-ies have experience of rolls manufacture from the materials which are alternative to conventional ones; tool steels (HP), AS180X steels, semi-high-speed steels (sHSS) and other can be mentioned here [1, 2].

sHSS steel for rolls manufacture with consequent application in wide hot strip mills as well as modern casting-rolling complexes.

C, Cr, V, Mo are the main alloying elements of these steels. The material structure after dual-stage special heat treatment consists of the martensite-bainite matrix including vanadium carbides (VC), molybdenum carbides (Mo_2C), chromium carbides ($Cr_{17}C_3$), as well as mixed car-bides of M_6C type. Hardness is provided by the martensite-bainite matrix, which is alloyed by chromium, vanadium and molybdenum, while special carbides are characterized by very high hardness (up to 3,000 HV) and enable thereby obtaining high wear resistance of the material. This structure can be obtained only via heat treatment [3, 4].

Saving of high hardness in the conditions of operation at the increased temperatures (up to 550 °C), as well as high heat resistance with permanent hardness through the whole depth of the working layer [5-8] are considered as the main advantages of sHSS type steels.

Chemical compositions of sHSS steels for rolling rolls differ seriously in their components concentration depending on various producers. Chromium, molybdenum and tungsten concentra-tions differ from 4 to 10 %, from 2 to 8 % and from 2 to 10 % respectively etc. Each of these alloys has its own cost which can differ from the cost of an equivalent alloy by two and more times. The level of properties varies not substantially at the same time.

In this connection, the aim of this work was formulated as development of sparingly alloyed composition of sHSS steel for rolling rolls, providing the preset level of mechanical and operating properties of rolling rolls.

© Kolokoltsev V. M., Feoktistov N. A., Savinov A. S., Skripkin E. V., 2022

Experimental methods

Melting of experimental alloys was conducted in the conditions of casting laboratory of the Nosov Magnitogorsk State Technical University, in the induction furnaces IST-0,06 and IST-0.002. Pig cast iron P1 (according to the GOST 805-80), steel scrap of 30L grade (according to the GOST 977-75) and the following ferroalloys: ferrochromium FKh 025 (according to the GOST 4757-91), ferrosilicon FS 60 (according to the GOST 1415-78) and ferromanganese FMn70 (according to the GOST 4755-91) as well as aluminium AV 97 (according to the GOST 295-79) were used as charge materials. Another variant of charge included use of ferroniobium FN 655S (according to the GOST 16773-85), ferrotungsten 75 (according to the GOST 17293-93), ferrovanadium 40 (according to the GOST 27130-86), ferromolybdenum FM 60 (according to the GOST 4759-91), nickel NP1 (according to the GOST 492-73), together with the same cast iron P1 and steel scrap 30L.

Metal melt was cast at the temperature 1525 °C in the metallic mould via centrifugal ma-chine which imitates the technological process of rolling rolls manufacture in the conditions of Magnitogorsk Mill Rolls Plant (MZPV).

Chemical composition of cast metal was determined using the SPECTRO optical emission spectrometer, MAXx model.

The cast samples were subjected to heat treatment in the resistance furnace "Nakal". This furnace is equipped by the electronic module allowing to realize the step-by-step procedure of heat treatment.

Homogenization from the temperature 1050 °C with holding time in the furnace for the samples was used as heat treatment. Homogenization was followed by five-time tempering at the temperature 510 °C.

Wear resistance of the alloys was examined in accordance with the GOST 23.208-79 entitled "The method of materials testing for wear resistance during friction with non-rigidly fixed abrasive particles". Hardness was determined using hardness meter EmcoTest M4C 075 G3 according to the GOST 9013-59.

To provide microanalysis, the polished sections were prepared from the sample via the standard technique, using pressing of the samples in «Transoptic» resin at the Simplimet 1000 automatic press in the Buechler sample preparation line. The surface of polished sections was ex-amined after pickling using Axio Observer optical spectrometer, with 100-fold and 1000-fold magnification, and Thixomet PRO system for images computer analysis.

Study of morphological features of microstructural components and determination of carbides composition was conducted using JSM 6490 LV scanning microscope, in secondary electrons with accelerating voltage 20 kV, equipped by the system for energy-dispersive analysis sys-tem INCA Energy 450 x-MAX 50 Premium, with more than 100-fold magnification.

Results and discussion

The conducted review of domestic and foreign researching works displayed that the operating properties of a rolling roll are determined by strength, hardness and red hardness of its working layer material. To provide the a.m. complex of properties, including alloy red hardness, its chemical composition should include the following elements (in addition to the main ones): Cr, Mo, Ni, Nb, V and W [3, 5]. These elements form complex carbides or are contained in a soli solution.

Based on the conducted analysis of compositions of sHSS steels, presented in the works [1-3], the varying limits of chemical elements in the experimental alloy were chosen (**Table 1**).

In addition to determination of the varying intervals of chemical elements in the roll alloy composition, the working layer of the rolling roll, manufactured by one of the foreign producers, was also examined.

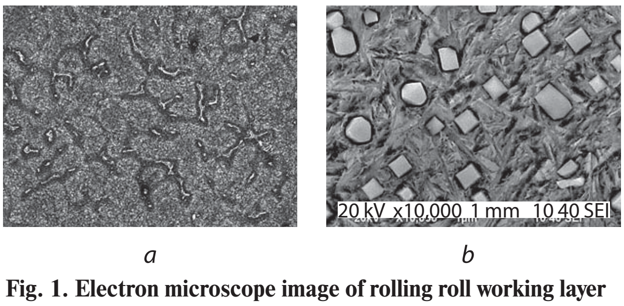
Microstructure of the examined roll steel after pickling includes dispersed martensite, residual austenite which is hardened by rough net of primary (eutectic) carbides along the grain boundaries, and (based on the results of the research) by dispersed secondary carbides inside grains (**Fig. 1**, *a*). Eutectic carbides are presented as MC, M_2C and M_7C_3. Electron microscope examination showed that dispersed secondary carbides with average size 1.27 μm are close to ball form and have distinct quadrangular form (**Fig. 1**, *b*).

Additional research using X-ray spectral microanalysis and mapping displayed that coarse primary carbides contains mainly chromium and less amount of molybdenum and vanadium, besides iron, carbon and silicon. Carbides which have the form of extended plates or irregular poly-hedral form, include niobium additionally to the a.m. elements. Large inclusions with spheroid form are identified by X-ray microanalysis as cementite alloyed by carbide-forming elements (first of all by molybdenum); it leads to rise of its resistance.

Investigations of the alloy properties determined that hardness in the middle of the rolling roll working layer makes 57-58 HRC. At the same time wear resistance coefficient of this steel makes 1.95 units.

Table 1. **Varying limits of chemical elements in compositions of sHSS steel for rolls manufactures by different producers**

C	Si	Mn	Cr	Mo	Ni	W	Nb	V
0.4 – 1.0	0.4 – 0.8	0.4 – 0.8	6.0 – 8.0	1.5 – 3.0	0.2 – 1.0	0.1 – 2.0	≤ 0.5	≤ 0.5



a *b*

Fig. 1. Electron microscope image of rolling roll working layer microstructure from high-speed steel HSS (obtained using scanning electron microscope)

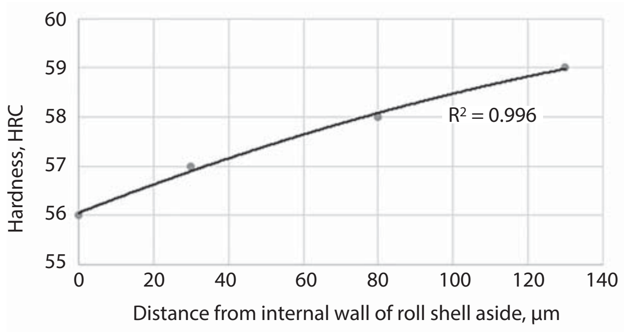


Fig. 2. Diagram of variation of HV_1 hardness from internal wall to the working surface

Table 2. **The ranges of each factor variation**

Value	x_1, %	x_2, %	x_3, %	x_4, %	x_5, %
Minimal (CFE) (-1)	0.4	1.5	0.1	0.6	2
Central (0)	0.6	2.25	0.3	2.05	5
Maximal (CFE) (+1)	0.8	3	0.5	3.5	8
Minimal (composi-tional) (-a)	0.281	1.053	-0.019	-0.264	0.212
Maximal (composi-tional) (+a)	0.919	3.447	0.619	4.364	9.788

CFE – complete factorial experiment

Table 3. **Coefficients of the regression equation with factors in technical units after correction**

Coefficient	Values for the parameter y_{HRC}	Values for the parameter y_{Kwr}
b^*_0	7.187	1.437474
b^*_1	45.210	0.117403
b^*_2	0.374	-0.05944
b^*_3	-8.510	-0.07667
b^*_4	2.803	-0.07333
b^*_5	7.748	-0.10897
b^*_{12}	-1.206	-0.06479
b^*_{13}	2.508	0.053322
b^*_{14}	-0.325	-0.15033
b^*_{15}	1.562321	0.062742
b^*_{23}	-1.6945	-0.0134
b^*_{24}	-0.60435	0.064181
b^*_{25}	-0.4413	0.052445
b^*_{34}	-0.72107	-0.05262
b^*_{35}	1.387116	0.052031
b^*_{45}	-0.32173	-0.06342
b^*_{11}	-35.7202	0.002853
b^*_{22}	1.249942	0.01533
b^*_{33}	2.74313	0.036973
b^*_{44}	0.296829	0.206185
b^*_{55}	-0.44086	0.026714

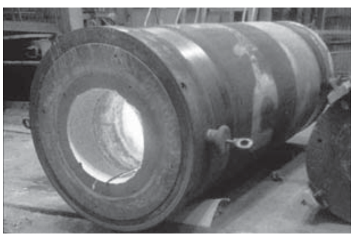


Fig. 3. Pilot roll shell from the developed steel sHSS

It should be mentioned that forming of the working layer in a centrifugal machine and its consequent isothermal holding in the process of core casting as the feature of rolling rolls manufacture [9]. Designated stages of the technological process of rolling rolls manufacture finalize in decrease of material hardness from the contact boundary between melt and mould to rolling roll core. Relationship of hardness variation through the working layer depth was determined during investigations (**Fig. 2**).

Five elements (factors), which have the most effect of the complex of roll steel properties were chosen on the base of literature review of the results of research works and examination of rolling roll material manufactured by the foreign producer. The following elements were included in this list: carbon (X_1), molybdenum (X_2), vanadium (X_3), tungsten (X_4), chromium (X_5) [10, 11]. The ranges of each factor variation in technical units, used during planning and conduction of the experiment, are presented in the **Table 2**.

Based on the chosen elements and taking into account the accepted limits of varying the elements in the steel chemical composition (see Table 2), the matrix of the fractional factorial experiment 5^2 was prepared [12, 13].

A series of experiments was conducted in laboratorial conditions. As a result, 48 experimental cast products were manufactured, which were subjected to the standard heat treatment procedure. The samples were prepared for examination, ad each experimental casting was tested for wear resistance. Their hardness was also determined and metallographic analysis of the alloy microstructure was conducted as well.

The authors formed the research base of roll steel compositions in correspondence with the experimental matrix, and then they obtained the regression equations describing interaction of chemical composition with wear resistance (y_{Kwr}) and hardness (y_{HRC}) of high-speed steel. The general image of these equations is presented below (1). The factorial coefficients are reflected in the **Table 3**.

$$\begin{aligned} y^* = {} & b_0^* + b_1^*x_1 + b_2^*x_2 + b_3^*x_3 + b_4^*x_4 + \\ & + b_5^*x_5 + b_{12}^*x_1x_2 + b_{13}^*x_1x_3 + b_{14}^*x_1x_4 + \\ & + b_{15}^*x_1x_5 + b_{23}^*x_2x_3 + b_{24}^*x_2x_4 + \\ & + b_{25}^*x_2x_5 + b_{34}^*x_3x_4 + b_{35}^*x_3x_5 + \\ & + b_{45}^*x_4x_5 + b_{11}^*x_1^2 + b_{22}^*x_2^2 + b_{33}^*x_3^2 + \\ & + b_{44}^*x_4^2 + b_{55}^*x_5^2 \end{aligned} \quad (1)$$

The chosen compositions were checked via chromium and tungsten equivalents, which were recommended by the authors in [14]. These equivalents were calculated according to the following expressions:

$$Cr_{eq} = Cr + 1.5\ Si + Mo = 8.5 – 12.5, \quad (2)$$

$$W_{eq} = W + 2Mo = 6 – 12, \quad (3)$$

The alloy composition after optimization was tested in the conditions of Magnitogorsk Mill Rolls Plant. Pilot roll shell was manufactured from the developed steel (**Fig. 3**), and it was later examined in laboratorial conditions of Nosov Magnitogorsk State Technical University.

The data base of compositions and properties was also processed using neural net; as a re-sult, optimized chemical composition of the alloy with varying intervals for each element were obtained [15]. This optimized composition is presented in the **Table 4**.

Table 4. **Optimized composition of the experimental alloy**
Concentration of the element in the alloy, % (mass.)

C	Si	Mn	P	S	Cr	Ni	Nb	V	Mo	W
0.75 – 0.95	0.4 – 0.6	0.5 – 0.8	up to 0.02	up to 0.015	8.2 – 8.4	0.3 – 0.4	0.3 – 0.4	0.45 – 0.6	3.0 – 3.2	2.2 – 2.6

The conducted testing of the pilot roll shell working layer displayed that the developed alloy id characterized by higher hardness 64-65 HRC (compared with 58 HRC of the rolling roll manufactured by the foreign producer). Besides that, the wear resistance coefficient of the developed alloy K_{wr} is equal to 2.48, what is higher by 27 % than that of the foreign roll.

It was established via metallographic examinations of the pilot roll shell that obtained microstructure is identical with microstructure of the rolling roll manufactured by the foreign producer. It includes martensite, residual austenite and carbides after heat treatment (**Fig. 4**).

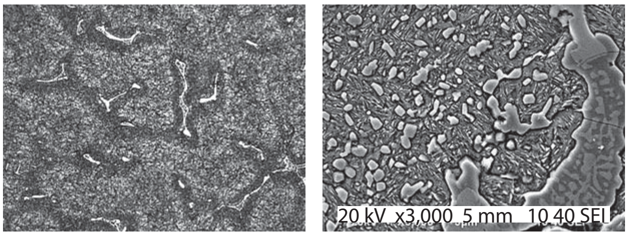


Fig. 4. Optical (× 1000) and electron (× 3000) image of the pilot roll shell microstructure

The particles in the form of polyhedrons were revealed in the alloy microstructure, most often – in the form of quadrangles. They include niobium, vanadium, chromium and tungsten (in addition to iron and carbon); in round (ball-formed) particles molybdenum presence is also observed. It allows to identify them as complex carbides containing the above-mentioned elements; their formula is described in technical literature as (Nb, Cr, V)C, as well as (Mo, Cr, V)C.

Such microstructure provides high operating properties of a rolling roll for a hot rolling mill, as well as its red hardness in the process of contact with hot metal.

Development of technological recommendations for casting of rolling roll core and providing its high-quality welding with the working layer can be considered as the further stage of joint work.

Conclusion

The new composition of sHSS steel for the working layer of rolling mill rolls was developed as a result of joint complex work of Magnitogorsk Iron and Steel Works, Magnitogorsk Mill Rolls Plant and Nosov Magnitogorsk State Technical University, based on examination of the foreign analogue and using neural net. The conducted testing of the experimental alloy displayed that the wear resistance coefficient of the developed alloy exceeds the same value of the foreign roll by 27 %. Microstructure of the pilot roll shell includes martensite and special carbides, what stipulates high values of operation stability. CIS

REFERENCES

1. Lecompe-Becker J., Chu-Fang Chiundzhan J., Pirard E. et al. Development of new high-speed steel with optimized carbide composition for rolls. *Stal.* 2003. No. 2. pp. 88-92.
2. Steimer D., Uijtdebroeks H., Liquet D. et al. Development of HSS roll in hot strip mill of Cockerill Sambre. Inernational. *Conference on Newly Developed Metallurgical Process Technology, Duseldorf.* 1999. pp. 269-277.
3. Gulakov A. A., Tukhvatullin I. Kh., Potapov M. G. Experience of production of centrifugal cast sheet rolling rolls for hot rolling mills in the conditions of Kushvinsky Mill Roll Plant. *Chernaya metallurgiya. Bulleten nauchno-tekhnichesloy i ekonomicheskoy informatsii.* 2018. No. 5. pp. 75-81.
4. Gimaletdinov R. Kh., Gulakov A. A., Tukhvatullin I. Kh. Influence of chemical composition on properties *of the working layer of centrifugal cast indefinite rolling rolls. Vestnik Magnitogorskogo gosudarstvennogo tekhnicheskogo universiteta imeni G. I. Nosova.* 2016. Vol. 14. No. 3. pp. 78-89.
5. Deng G. Y., Zhu H. T., Tieu A.K., Su L.H., Reid M. Theoretical and experimental investigation of thermal and oxidation behaviours of a high speed steel work roll during hot rolling. *International Journal of Mechanical Sciences.* 2017. August 12. pp. 811–826.
6. Deng G. Y., Zhu Q., Tieu K., Zhu H.T., Reid M. et al. Evolution of microstructure, temperature and stress in a high speed steel work roll during hot rolling: *Experiment and modeling. Journal of Materials Processing Technology.* 2017. Vol. 240. pp. 200–208.
7. Jing Guo, Bo Liao, Li-Gang Liu, Qiang Li, Xen-Jun Ren, Qing-Xiang Yang. Forging limit of a novel high-speed-steel cold work roll based on ductile fracture criteria by finite element model. *Materials and Design.* 2013. Vol. 52. pp. 1027–1034.
8. Deng G. Y., Tieu A.K., Su L.H., Zhu H. T., Reid M., Zhu Q. Characterizing deformation behaviour of an oxidized high speed steel: Effects of nanoindentation depth, friction and oxide scale porosity. *International Journal of Mechanical Sciences.* 2019. Vol. 155. May. pp. 267-285.
9. Vdovin K. N., Feoktistov N. A., Gorlenko D. A., Mikhalkina I. V. et al. Simulation of crystallization and structure forming processes for rolling roll from hyper-eutectoid steel. *Teoriya i tekhnologiya metallurgicheskogo proizvodstva.* 2020. No. 1 (32). pp. 18 – 25.
10. Feoktistov N. A., Chernov V. P., Savinov A. S. et al. Evaluation of carbon influence on operating properties and microstructure of a roll steel. *Izvestiya Volgogradskogo gosudarstvennogo tekhnicheskogo universiteta.* 2021. No. 7 (254). pp. 35-40.
11. Feoktistov N. A.,Vdovin K. N., Savinov A. S., Skripkin E. V. Study of cast structure forming process for roll steel. *Izvestiya Volgogradskogo gosudarstvennogo tekhnicheskogo universiteta.* 2020. No. 7 (242). pp. 36-40.
12. Parsunkin B. N., Bushmanova M. V., Andreev S. M. et al. Statistical research and simulation of economical and technological metallurgical processes. Magnitogorsk: Izdatelstvo Magnitogorskogo gosudarstvennogo tekhnicheskogo universiteta, 2007. 315 p.
13. Parsunkin B. N., Bushmanova M. V., Andreev S. M. Calculation of the automatic optimization systems for management on technological processes in metallurgy. Magnitogorsk: Izdatelstvo Magnitogorskogo gosudarstvennogo tekhnicheskogo universiteta, 2003. 267 p.
14. Boccalini M. (Jr.), Sinatora A. Microstructure And Wear Resistance of High Speed Steels For Rolling Mill Rolls. *6th International tooling conference,* 2013. pp. 509-524.
15. Denisova A. V., Dadykin S. Yu. Possibilities of neural nets use in analysis and simulation of production systems. *Proceedings of the II All-Russian scientific-technical conference "Prospec-tive scientific developments" (PNR-2020).* 2020. pp. 37-38.