IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

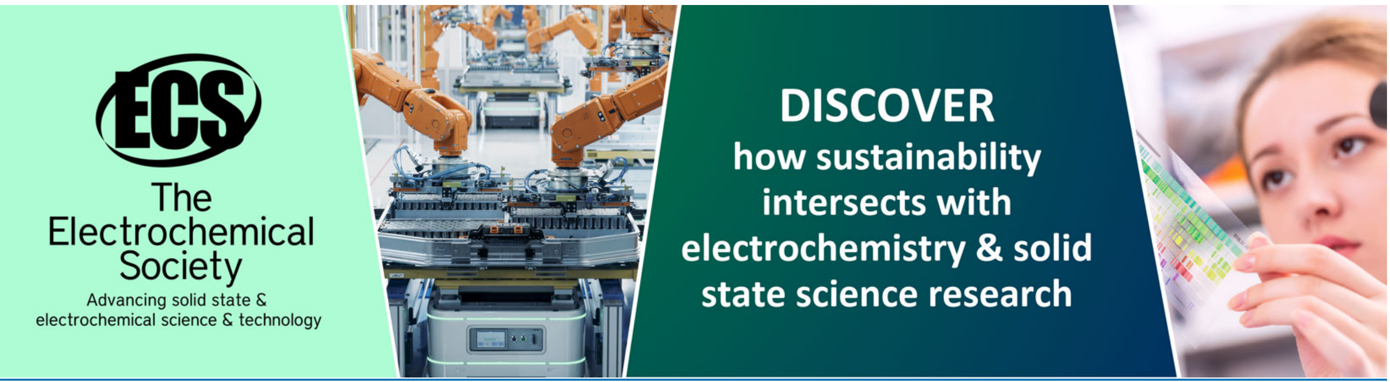
Computer modelling-based selection of accelerated cooling parameters for advanced high-strength structural steel

To cite this article: V G Efremenko *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1037** 012030

View the article online for updates and enhancements.

You may also like

- Advancing a distributed multi-scale computing framework for large-scale high-throughput discovery in materials science
  J Knap, C E Spear, O Borodin et al.
- On Measurement of Electromagnetic Radiation by Computer System in Indoor Electromagnetic Environment
  Xiangguo Dong
- Research on Security Mechanism of Service Interoperability Based on Power Grid Computer System
  Yuling Zhang, Jijun Wang, Wencheng Liu et al.



This content was downloaded from IP address 3.149.254.35 on 05/05/2024 at 16:09

IOP Conf. Series: Materials Science and Engineering 1037 (2021) 012030 doi:10.1088/1757-899X/1037/1/012030

Computer modelling-based selection of accelerated cooling parameters for advanced high-strength structural steel

V G Efremenko [1], D S Zotov[2], V I Zurnadzhy[1], R A Kussa[2], V I Savenko[3], R I Sagirov[2], O A Bocharova[1] and A V Efremenko[1]

[1] Pryazovskyi State Technical University, Universtiteskaya Str. 7, Mariupol, 87555, Ukraine
[2] PJSC "AZOVSTAL IRON & STEEL WORKS", Leporskyi Str. 1, Mariupol, 87555, Ukraine
[3] Kyiv National University of Construction and Architecture, Povitroflotskyi Av. 31, Kyiv, 03037, Ukraine

Corresponding author's email: vgefremenko@gmail.com

Abstract. The article describes the working principles and configuration of the computer system applied for selecting parameters of accelerating water cooling of rolled sheets made of low-carbon advanced strength steel. The system is based on mathematical models using empirical regression equations that describe the interconnections between working parameters of cooling equipment and the technological parameters of thermal processing. The equations are outlined and discussed. The results of computer modelling verification in industrial trials are presented. The case-study involved computer system concerning steel properties and microstructure is described.

1. Introduction

Advanced high-strength steels (AHSSs) are constructional steels having ultimate strength higher than 550 MPa [1]. AHSSs' sheets are intended for use in automotive and structural applications to reduce construction weight due to higher steel strength [2]. According to standard approach, AHSSs are subjected to heat treatment in order to acquire the necessary mechanical properties [3, 4]. Some of the AHSSs grades are manufactured via the process involved hot rolling (thermo-mechanical controlled processing - TMCP) with consequent accelerated cooling (AC) by water [5]. For this purpose accelerated cooling unit (ACU) is used being installed into the production lines after the hot-rolling mill [6]. ACU combines a rolling conveyor (for sheet transportation) and a cooling water supplying system. «AZOVSTAL IRON & STEEL WORKS» (further «AZOVSTAL» in short) is the only Ukrainian steel producer equipped with ACU. AC technology is energy-saving and environment friendly since the heat treatment is fulfilled without additional heating in fuel furnace. However, AC needs using precise processing parameters which are dependant on steel chemical composition, sheet size/temperature, water flow/temperature, etc. The selection of AC processing parameters should be controlled automatically to avoid the human factor. A computer-based controlling system is one of the most important parts of ACU. As usual, such systems with appropriate software are developed by ACU manufacturer to be installed together with ACU equipment. This software should use the mathematical models that are adequate for specific production conditions.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

2. The approaches to control accelerated cooling parameters

Steel mechanical properties are greatly affected by microstructure status resulted from technological processing. The microstructure results from phase transformation occurring in steel mostly under the cooling from the austenite temperature range. The path of phase transformation depends on steel chemical composition as well as on initial metal temperature before cooling, cooling rate, and the temperature of cooling interruption [7, 8]. As reported by Tang et al. [9] accelerated water cooling of TMCP-processed low-carbon low-alloy constructional steels leads to a fine-grained structure comprising quasi-ferrite, granular bainite and martensite/austenite "islands" ensuring advanced tensile properties in combination with high ductility and high low-temperature impact toughness. In TRIP-assisted AHSSs multi-phase structure forms, consisting of polygonal ferrite, carbide-free bainite and retained austenite which is able to excellent strain hardening under the load [10-12]. The selection of AC regime parameters should be specified regarding time/temperature peculiarities of phase transformation in certain steel grade. The temperature of AC start (T_{start}) defines the starting structural condition which prerequisites the final structure [13]. The proper selection of the temperature of AC finish (T_{finish}) is also of great importance since T_{finish} defines the temperature range of overcooled austenite transformation [9, 13, 14]. Cooling rate (CR) should ensure avoiding austenite transformation in a higher temperature range which could lead to a coarse structure with poor mechanical properties [9, 15]. Thus T_{start}, T_{finish}, and CR are the key processing indicators of steel sheets accelerated cooling. They should be precisely ensured by using appropriate ACU working parameters that presumes involving an automatic controlling system.

Each accelerated cooling unit is mandatorily equipped with a controlling system for automatic regulation of steel processing. The development of such a system and appropriate software should be based on the latest approaches of modelling, simulation, and automation [16-18]. Thus Knapiński et al [19, 20] applied physical simulations and numerical modelling of the plates accelerated cooling to govern the temperature distribution on the cross-section of the cooled plates of X100 grade steel plate. Chen et al [21] developed a basic automation subsystem and process automation subsystem intended for using in device for ultra-fast cooling installed in the steel plate production line. There the cooling schedule is set by process control system using the finite element temperature field model and the temperature homogeneity model. These models are based on a multi-dimensional self-learning strategy [22] which ensures precise calculation of steel strip temperature. The automation system for ACU includes "Programmable Logic Control" (PCL) devices to operate water flow/temperature [21, 23]. Since any metal processing operates in uncertainty conditions of parameter variation [24] a "closed-loop control" concept can applicable to steel sheets accelerating cooling in order to reduce inconsistencies in product properties [25].

Routinely steel sheets are manufactured being collected in separate batches. The batch presumes the sheets of certain size made of steel of specific grade with specific mechanical properties. The on-going manufacturing process is characterized by frequent alteration of sheet batches subjected to AC; thus AC processing indicators are changed as well. Accordingly, ACU working parameters have to be quickly changed to follow the current manufacturing situation. The change could be done manually by the operator or automatically by the controlling system.

Operation of ACU in «AZOVSTAL» revealed the problem which often happens when after the automatic regulation of ACU working parameters the current AC indicators do not meet the required values. In this situation, ACU working parameters are being adjusted further manually by the operator. The adjustment is performed over and over again until AC indicators reach the target level (usually it takes 3-5 «adjusting» sheets for each batch). That means that most «adjusting» sheets may gain inappropriate microstructure and mechanical properties followed by additional mechanical testing or even additional heat treatment. This situation increases manufacturing costs therefore it should be avoided. The mentioned problem appears when ACU controlling system uses inappropriate mathematical models. This is quite a usual situation since standard controlling software can not match all steel grades which are produced all over the world. Therefore some adjustments of the controlling system should be fulfilled focusing on the peculiarities of specific steel production.

The aim of the paper is to develop the mathematical models for automatic selecting ACU working parameters in order to ensure AC processing parameters focusing on hot-rolled sheets made of low-carbon advanced high strength steels produced by «AZOVSTAL».

3. Mathematic models for ACU functioning

Mathematical models for ACU working parameters selection were developed using the database provided by «AZOVSTAL». This database covered three latest years; it consisted of approximately 5.5 thousand records manually registered by ACU operators during the accelerated cooling of steel sheets. The records included the sets of ACU working parameters which were selected by the operators in "manual" regime. All records were divided into the next categories such as:

(a) The parameters of steel sheet batch (steel grade; sheet size (thickness, length));

(b) AC processing indicators (T_{start}, T_{finish}, CR);

(c) ACU working parameters (cooling water temperature, water flow from upper and bottom sides, number of water suppliers, rolling conveyor speed (RCS)).

These records were digitalized to be further processed according to the regression procedure using MS Excel Tables. The regressions were supposed to link ACU working parameters with steel sheet parameters and AC processing indicators. The rolling conveyor speed was chosen as the target working parameter which should be defined under the postulating other parameters/indicators values.

Taking into account the effect of carbon and alloying elements combination on the kinetics of phase transformation and steel mechanical behaviour the regression equations were developed separately for different steel grade groups. For this purpose, all steel grades produced in «AZOVSTAL» and subjected to accelerated cooling were divided into three groups namely: Cr-Si-Ni-Cu (group I), Mn-Si-V-Nb (group II), and Mn-Cr-Ni-Mo-Cu-V-Nb (group III).

The functional scheme of ACU parameters calculation is presented in Fig. 1. On the first stage the total water flow (TWF) is calculated using the data of steel grade, sheet thickness (δ, mm), water temperature (TW, °C), number of water suppliers (NS), and the targeted AC indicators such as T_{start} (°C), T_{finish} (°C) and CR (K/s). Then the total water flow is divided into water flow from upper and water flow from the bottom sides of ACU. On the second stage, the speed of rolling conveyor is calculated based on all above-mentioned parameters and indicators.

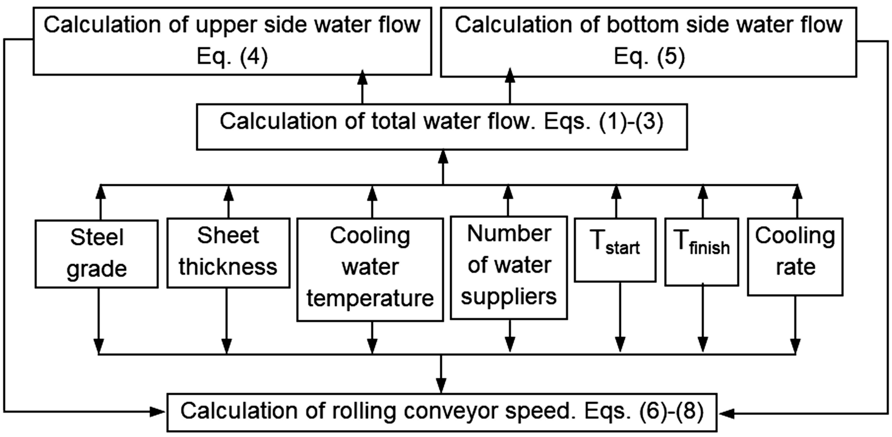


Fig. 1. Functional scheme of ACU parameters calculation

After processing the raw data the following mathematical models were obtained as regression equations (1)-(8) presented below.

The models for the total water flow (liters/min):

(a) for Cr-Si-Ni-Cu steels:

$$TWF_I = 56.7 \cdot T_W - 92.8 \cdot N_S + 34.5 \cdot \delta + 0.4 \cdot (T_{start} - T_{finish}) + 25.5 \cdot CR \ (R^2=0.99) \quad (1)$$

(b) for Mn-Si-V-Nb steels:

$$TWF_{II} = 9.2 \cdot T_W - 15.8 \cdot N_S + 30.6 \cdot \delta + 8.3 \cdot (T_{start} - T_{finish}) + 47.2 \cdot CR + 0.5 \cdot \delta^2 - 0.03 \cdot (T_{start} - T_{finish})^2 - 2.2 \cdot CR^2 + 0.01 \cdot N_c \cdot (T_{start} - T_{finish}) \cdot CR - 4.4 \cdot 10^{-9} \cdot \delta^2 \cdot (T_{start} - T_{finish})^2 \cdot CR^2 \quad (R^2=0.97) \tag{2}$$

(c) for Mn-Cr-Ni-Mo-Cu-V-Nb steels:

$$TWF_{III} = 37.6 \cdot T_W + 60.6 \cdot N_S + 36.3 \cdot \delta + 0.02 \cdot (T_{start} - T_{finish}) + 23.1 \cdot CR \quad (R^2=0.90) \tag{3}$$

Total water flow is divided into water flow from upper side (WFU) and water flow from bottom side (WFB) as:

$$WFU = TWC/(1+ x) \tag{4}$$

$$WFB = x \cdot WFU \tag{5}$$

where “x” depends on steel grades to be in the range of 2.0 – 3.0.

The models for the rolling conveyor speed (RCS, m/s):
(a) for Cr-Si-Ni-Cu steels:

$$RCS_I = 0.006 \cdot T_W + 0.1 \cdot N_C - 0.2 \cdot \delta - 0.003 \cdot (T_{start} - T_{finish}) + 0.06 \cdot CR + 3.9 \cdot 10^{-4} \cdot WFU + 3.8 \cdot 10^{-5} \cdot WFB \quad (R^2=0.99) \tag{6}$$

(b) for Mn-Si-V-Nb steels:

$$RCS_{II} = 0.003 \cdot T_W + 0.09 \cdot N_C - 0.2 \cdot \delta - 0.003 \cdot (T_{start} - T_{finish}) + 0.06 \cdot CR + 9.5 \cdot 10^{-4} \cdot WFU + 9.0 \cdot 10^{-5} \cdot WFB \quad (R^2=0.99) \tag{7}$$

(c) for Mn-Cr-Ni-Mo-Cu-V-Nb steels:

$$RCS_{III} = -0.01 \cdot T_W + 0.2 \cdot N_C - 0.1 \cdot \delta - 0.008 \cdot (T_{start} - T_{finish}) + 0.07 \cdot CR - 3.9 \cdot 10^{-4} \cdot WFU + 7.2 \cdot 10^{-4} \cdot WFB \quad (R^2=0.99) \tag{8}$$

As seen, the determination coefficient for all equations is rather high (not less than 0.90) indicating the adequacy of regression models.

4. Models verification and software industrial trial approbation

Models reliability has been verified by comparison of calculated RCS values with the values taken from the registration journal for the same set of working parameters/indicators values. The comparison is shown in Fig. 2 for different steel grades. As seen, the variation of calculated RCS values well follows the variation of actual values of rolling conveyor speed. It was found that the difference between predicted and actual RCS values (shown as red line) in 90-92 % of cases does not exceed 0.25 m/s, which is acceptable for AC processing. Moreover, the cases exceeding 0.5 m/s account only 1% of the total number of measurements. These results allowed to conclude that above mentioned mathematical models are adequate for the production conditions of «AZOVSTAL».

The next stage of research was a trial approbation of developed models in real manufacturing situations. For this purpose, the software «Controlled Cooling Calculator» was developed basing on the models (1)-(8). It was written in the language C# with the adoption of WPF system. The software consists of the «Calculation unit» and «Correction unit». The first one contains the input fields for the selection of steel grade and for inserting assigned working parameters and process indicators. In «Calculation unite» the calculated values of water flow (upper and bottom) and rolling conveyor speed appear. These three values are input by the operator into ACU before the start of AC processing of the coming up sheet batch. The «Correction unite» is intended for quick correction of working parameters if some of the processing indicator (CR or T_{finish}) is out of the required range after the initial calculation.

The cooling rate is corrected by RCS alteration with corresponding water flow correction. The temperature of AC finish is corrected by water flow tuning while the initial RCS remains unchanged.

Model-based software «Controlled Cooling Calculator» was approbated upon industrial trial held in the sheet-rolling shop of «AZOVSTAL». The software was used for computer selection of ACU working parameters under manufacturing of 31 batches of steel sheet of 17.5-50 mm thick made of different steel grades. The calculated ACU working parameters (WCU, WCB, RTS) were input into ACU before the start of processing each sheet batch. The reached values of AC indicators (T_{finish}, CR) were registered accordingly.

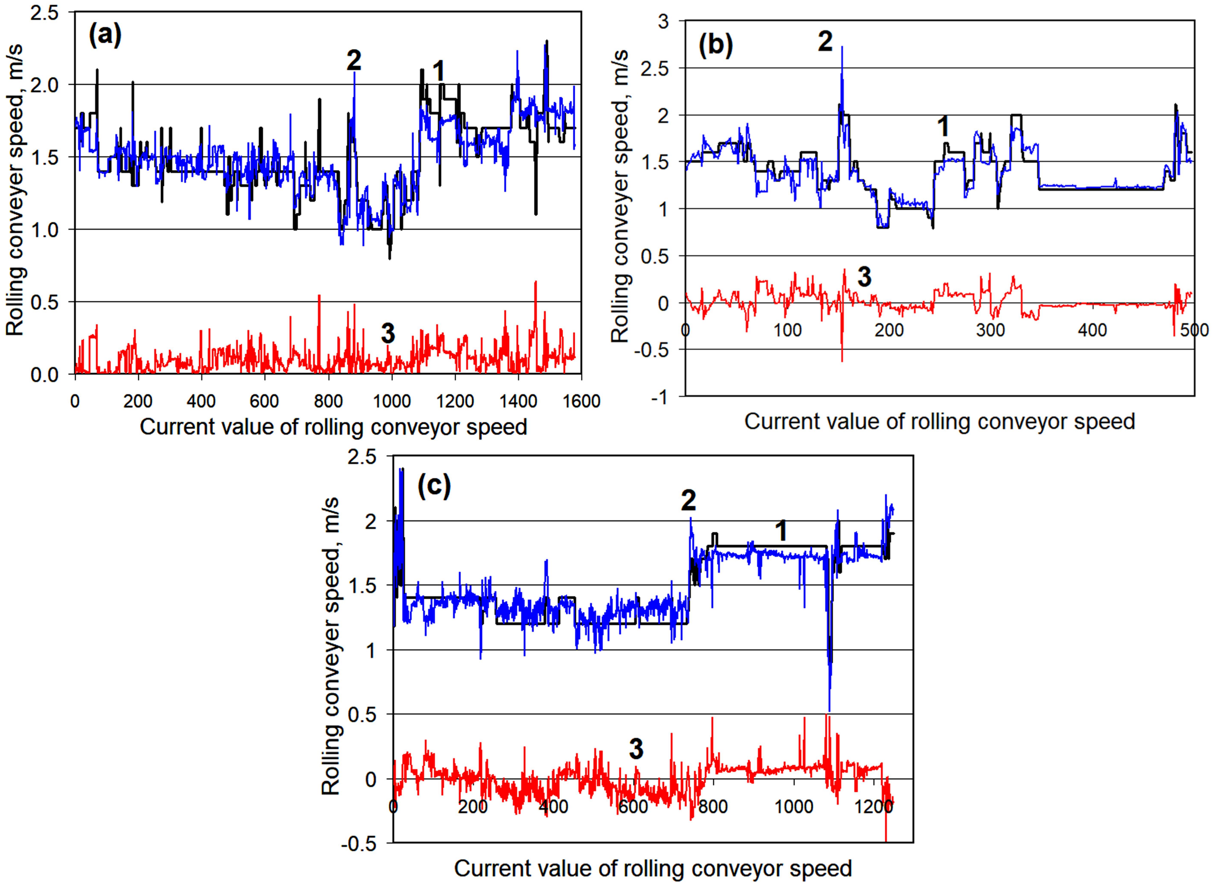


Fig. 2. The comparison of calculated RCS values and actual RCS values for steel grades (a) Cr-Si-Ni-Cu, (b) Mn-Si-V-Nb and (c) Mn-Cr-Ni-Mo-Cu-V-Nb (1 – actual values (taken from the database), 2 – calculated values, 3 – the difference).

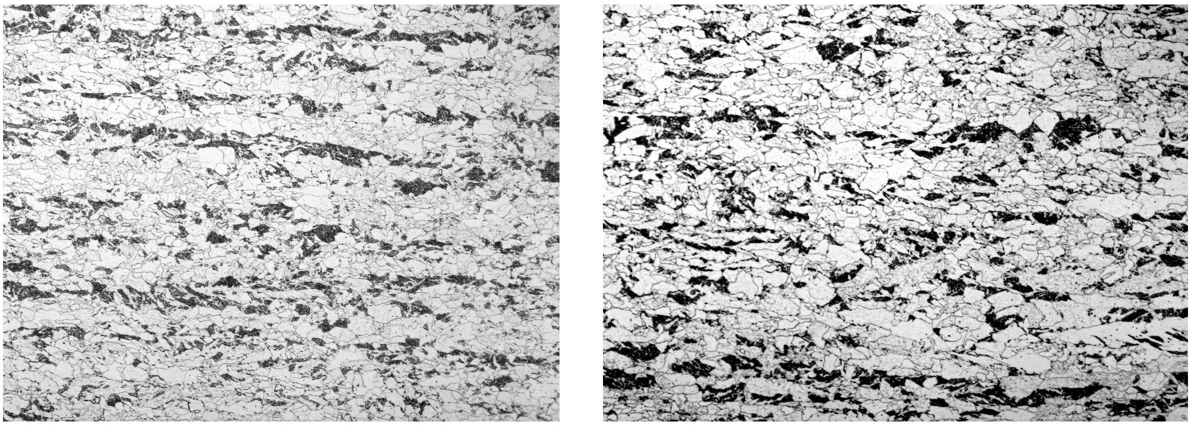
The results showed that under «Controlled Cooling Calculator» guiding the required AC processing indicators (with acceptable deviation in the range of ±25 °C for T_{finish} and ±2 K/s for CR) were obtained in 96.7 % of batches on the first-second sheet of the batch. Moreover, the target indicators values were obtained mostly on the first sheet of the batch: in 73.3 % cases for T_{finish}, and in 76.7 % for CR. Only in one batch (3.3 %) the required CR value was gained on the third sheet. These results revealed the acceptable adequacy of the models (attaining target indicators on the first sheet) as well as the workability of correction unite.

The appropriateness of the computer-based modelling were illustrated for one batch of 30 mm-thick sheets made of steel X70 grade which belongs to Mn-Cr-Ni-Mo-Cu-V-Nb steels. This steel grade is intended for large-diameter pipe lines for gas transportation under the high-pressure thus it belongs to high-importance products. Therefore it implies the improved combination of the mechanical properties. The target AC indicators for this batch were appointed as T_{start} is 765 °C, T_{finish} is 590 °C, CR is 16 K/s.

Using software «Controlled Cooling Calculator» the ACU working parameters were calculated as: (a) water flow upper is 401 liters/min, (b) water flow bottom is 962 liters/min, and (c) rolling conveyor speed is 1.84 m/s. These parameters were generated under the water temperature is 20 ^{o}C, and the number of water suppliers is 14.

These parameters ensured actual AC indicators being in required limits, specifically: T_{start} is 766.6±2.4 ^{o}C, T_{finish} is 593.4±3.7 ^{o}C, CR is 15.8±0.4 K/s. Accordingly, steel gained advanced mechanical properties such as: yield strength (YS) of 555±8 MPa, ultimate tensile strength (UTS) of 682.5±8 MPa, elongation of 23.5±1 %. Notably, an improved low-temperature (–20 ^{o}C) impact toughness was reached as well: fracture energy (KV) of 206.5±2 J, drop weight test (DWTT) of 84.7±2 %. Mentioned values fully met the standard requirements for X70 grade which are: YS ≥ 505 MPa, UTS ≥ 595 %, elongation ≥ 22 %, KV_{-20} ≥ 125 j, $DWTT_{-20}$≥ 85 %.

These properties have resulted from optimal microstructure obtained by computer-based selection of ACU working parameters. The microstructure consists of fine-grained quasi-polygonal ferrite of 10-11 number, granular bainite and a minor amount of pearlite bands oriented along rolling direction (Fig. 3). Such structural status is beneficial for an improving complex of strength, ductility and impact toughness of the steel, intended for exploitation (as a pipe-line) at subzero temperature [7, 26].



(a) (b)

Fig. 3. The microstructure of 30 mm steel sheet of X70 grade heat treated using «Controlled Cooling Calculator» software: (a) at ¼ of sheet thickness, (b) in sheet axis zone. Magnification is x500.

Summing up, the use of «Controlled Cooling Calculator» software allows shortening the number of «adjusting» sheets at least 3 times thus reducing additional production expenses in order of 25-40 $ per every sheet batch. The developed models and software prove to be perspective for full implementation into the rolled sheets manufacturing process in «AZOVSTAL IRON & STEEL WORKS».

5. Conclusion

Mathematical models were developed to calculate the working parameters of water cooling equipment in order to ensure an appropriate steel sheet heat treatment (accelerated cooling after thermo-mechanical controlled processing). The models are regression equations including sheet size, the required technological indicator (T_{start}, T_{finish}, cooling rate) and ACU working parameters (number of water suppliers, water flow upper, water flow bottom, rolling conveyor speed). The models were verified to be adequate for the manufacturing of advanced high strength steels at «AZOVSTAL IRON & STEEL WORKS».

The models were used as a basement for developing software «Controlled Cooling Calculator» (C++, WPF) for the selection of ACU working parameters focusing on target indicators of accelerated cooling for steel sheets of different thickness and steel grades (advanced high strength steels). The software was successfully tested under manufacturing of 31 batches of steel sheet of 17.5-50 mm thickness made of X70 grade. It allowed producing high-quality steel sheets reducing the additional manufacturing costs caused by adjusting the working parameters to the target values. The cost reduction may amount to 25-40 $ per every sheet batch.

6. References

[1] Da Silva E A, Malerba F, L F V., De Jesus Silva, J W., Ribeiro R B., Dos Santos Pereira M 2016 *IOSR Journal of Mechanical and Civil Engineering*. **13(5)** 21-27
[2] Bleck W, Guo X and M Y 2019 Steel Research International **88(10)** 1700218
[3] Bublíková D, Jeníček Š, Vorel I and Mašek B 2017 *IOP Conf. Series: Materials Science and Engineering*. **179** 012009
[4] Zurnadzhy V I, Efremenko,V G., Wu K M, Azarkhov A Yu, Chabak Yu G, Greshta V L, Isayev O B and Pomazkov M V 2019 *Mater. Sci. Eng., A*. **745** 307-318
[5] Nakata N and Endo S 2014 *JFE GIHO*. **33** 1–6
[6] Xiangwei K and Liangyun L 2014 *Procedia Eng*. **81** 114-119
[7] Hu J, Du L-X, Wang J-J, Gao C-R, Yang T-Z, Wang A-Y and Misra R D K 2013 *Metall. Mater. Trans. A*. **44(11)** 4937-4947
[8] Kim S, Lee S, Lee B S 2003 *Mater. Sci. Eng., A*. **359** 198–209
[9] Tang S, Liu Z Y, Wang G D and Misra R D K 2013 *Mater. Sci. Eng., A*. **580** 257-265
[10] Efremenko V, Shimizu K, Pastukhova T, Chabak Yu, Brykov M, Kusumoto K and Efremenko A 2018 *Int. J. Mater. Res.* **109(2**) 147-156.
[11] Rykavets ZM, Bouquerel J, Vogt J-B, Duriagina Z A, Kulyk V V, Tepla T L, Bohun LI. and Kovbasyuk T M 2019 *Uspehi Fiziki Metallov*. **20(4)** 620–633
[12] Efremenko V G, Zurnadzhi V I, Chabak Y G, Tsvetkova O V and Dzherenova A V 2017 *Materials Science*. **53(1)** 67-75
[13] Matrosov Y I, Kholodnyi A A, Matrosov M Y, Popov E S, Konovalov G N and Sosin S V 2015 *Metallurgist*. **59** 60–68
[14] Hu Z, Xu Z, Xu G, Yang H, Zhang C and Yu R 2014 *J. Mater. Eng. Perform.* **23(12)** 4216-4222
[15] Chabak Yu G, Fedun V I, Pastukhova T V, Zurnadzhy V I, Berezhnyy S P and Efremenko V G 2017 *Probl. At. Sci. Technol., Ser.: Plasma Phys.* **110(4)** 97-102
[16] Hong L, Han C., Chang C and Hongchao Y 2019 *Int. J. Heat Mass Transfer*. **143** 118342
[17] Qian X, Zhenyi H, Qingyu H, Long Z and Jiajia C 2019 *ISIJ International*. **59(1)** 113-121
[18] Markov O E, Gerasimenko O V, Kukhar V V, Abdulov O R and Ragulina N. V 2019 *J. Braz. Soc. Mech. Sci. Eng.* **41** 310
[19] Knapiński M, Dyja H, Kawałek A, Kwapisz M and Koczurkiewicz B 2013 *Solid State Phenom.* **199** 484–489
[20] Laber K B, Knapiński M, Kawałek A and Kwapisz M 2013 *Solid State Phenom*. **199** 478–483
[21] Chen X L, Wang B X, Tian Y, Yuan G, Wang Z D, Wang G D 2012 *Advanced Materials Research*. **605–607** 1836–1840
[22] Chen D, Li Z-L, Li Y-J and Guo Y 2019 *ISIJ International*. **60(1)** 136-142
[23] Hamzah M A, Rasha F, Nadhim K and Raheem A 2018 *IIER International Conference*, 99-104
[24] Kukhar V V, Grushko A V and Vishtak I V 2018 *Solid State Phenom.* **284** 408–415
[25] Allwood J M, Duncan S R, Cao J, Groche P, Hirt G, Kinsey B, Kuboki T, Liewald M, Sterzing A and Tekkaya A E 2016 *CIRP Annals*. **65(2)** 573-596
[26] Koval' A D, Efremenko V G, Brykov M N, Andrushchenko M I, Kulikovskii R A and Efremenko A V 2012 *Journal of Friction and Wear*. **33(2)** 153–159