Łukasz RAUCH, Rafał GOŁĄB

AGH, Akademia Górniczo-Hutnicza, Wydział Inżynierii Metali i Informatyki Przemysłowej

Roman KUZIAK, Valeriy PIDVYSOTS'KYY

Instytut Metalurgii Żelaza im. St. Staszica

Maciej PIETRZYK

AGH, Akademia Górniczo-Hutnicza, Wydział Inżynierii Metali i Informatyki Przemysłowej

APPLICATION OF THE EXPERT COMPUTER SYSTEM TO DESIGN THE HOT STRIP ROLLING TECHNOLOGY IN THE LPS LINE

Application of computer systems in industry becomes more and more frequent, in particular in those companies which are exposed to fast changes in the market due to the changing needs of products consumers. In the metals processing industry, these changes concern mainly the properties of semiproducts and products. Usually series of costly experimental trials are performed to meet these requirements. Therefore, there is a need for computer systems, which will aid design of the technology and allow decreasing the number of experimental trials. Details of the expert system applied to the analysis and optimization of the hot strip rolling technology in the semi-industrial rolling line (LPS) are described in the paper. Constructional multi-phase (CP) steel was selected for the analysis. Material models, developed for the investigated steel on the basis of experimental tests carried out at the Institute for Ferrous Metallurgy, were implemented in the system. Results of performed numerical simulations using the system are presented.

Key words: *expert system, hot strip rolling, technology design, constructional steel*

ZASTOSOWANIE KOMPUTEROWEGO SYSTEMU EKSPERCKIEGO DO PROJEKTOWANIA TECHNOLOGII WALCOWANIA NA GORĄCO BLACH W LPS

Zastosowanie systemów komputerowych w przemyśle jest coraz częstsze, co szczególnie jest widoczne w przedsiębiorstwach nastawionych na bezpośredni kontakt ze zmieniającymi się potrzebami klientów. W przetwórstwie metali ma to przede wszystkim odzwierciedlenie w zapotrzebowaniu klientów na specyficzne własności półproduktów i wyrobów finalnych. Aby sprostać tym wymaganiom, zwykle konieczne jest podjęcie wielu kosztowych analiz doświadczalnych, które metodą prób i błędów dają oczekiwany rezultat. Dlatego potrzebne są systemy komputerowe oferujące funkcjonalność hybrydową, łączącą symulacje numeryczne, optymalizację i wiedzę ekspercką wspomagającą projektowanie technologii. W artykule przedstawiono szczegóły projektu oraz implementacji systemu, który został wykonany dla wspomagania projektowania technologii z wykorzystaniem Linii Półprzemysłowej Symulacji (LPS). Możliwości systemu przedstawiono na przykładzie stali konstrukcyjnej CP. W systemie zaimplementowano modele dla tej stali opracowane na podstawie badań wykonanych w IMŻ. W artykule zaprezentowano wyniki symulacji numerycznych wykonanych z wykorzystaniem zaproponowanego systemu.

Słowa kluczowe: *system ekspertowy, walcowanie na gorąco, projektowanie technologii, stal konstrukcyjna CP*

1. INTRODUCTION

The objectives of the thermo-mechanical rolling are very complex. The rolling parameters have to be carefully and precisely controlled to obtain required microstructure after rolling and after accelerated cooling. This task is even more difficult when manufacturing of Advanced High Strength Steels with multiphase microstructures is considered. Physical simulations are usually performed to determine the optimal rolling parameters. LPS line was installed at IMZ Gliwice to investigate hot rolling processes. Physical experiments are costly, therefore, numerical simulations are used to support experimental analysis and to decrease the number of necessary experiments. The computer system, which supports experimental rolling on the LPS, was developed at the AGH University of Science and Technology. The objective of this paper is to demonstrate capabilities of this system as far as design of rolling and cooling technology for the CP multiphase steel is considered.

2. MATERIAL MODELS

Constructional CP steel with the chemical composition given in Table 1 was selected for the analysis. Flow stress and microstructure evolution model for this steel were developed on the basis of experiments performed at IMZ Gliwice on the thermomechanical simulator Gleeble 3800. Plastometric tests for axisymmetrical samples were performed to identify the flow stress model and stress relaxation tests were performed to identify the microstructure evolution model for hot deformation.

Hansel-Spittel equation [1] with coefficients determined on the basis of plastometric tests was used as flow stress model:

$$\sigma_p = 5189.3\varepsilon_i^{0.267}\exp(-0.343\varepsilon_i)\dot{\varepsilon}_i^{0.112}\exp\left(\frac{-3.32T}{1000}\right) \quad (1)$$

Microstructure evolution model was based on the works of Sellars [2] with coefficients determined on the basis of experimental tests, and was composed of the following equations:

- Kinetics of static recrystallization

$$X_{st} = 1 - \exp\left[\ln(0.5)\left(\frac{t}{t_{0.5}^{st}}\right)^{n_{st}}\right] \quad (2)$$

where: n_{st} = 0.72254 for $T < 1000^{\circ}$C and n_{st} = 0.8355 for T ≥ 1000°C

- Time for 50% recrystallization

$T < 1000^{\circ}$C

$$t_{0.5}^{st} = 1.60092\cdot10^{-9}\varepsilon^{-0.30545}\dot{\varepsilon}^{-0.44279}D_0^{0.624834}\exp\left(\frac{150713}{RT}\right)$$

$T \geq 1000^{\circ}$C

$$t_{0.5}^{st} = 1.76771\cdot10^{-19}\varepsilon^{-3.12712}\dot{\varepsilon}^{-0.23129}D_0^{0.624834}\exp\left(\frac{375926}{RT}\right)$$

(3)

- Grain size after static recrystallization

$$D_{st} = 23.3783\varepsilon^{-0.07278}D_0^{0.1368}\exp\left(-\frac{6521.8}{RT}\right) \quad (4)$$

- Kinetics of metadynamic recrystallization

$$X_{md} = 1 - \exp\left\{\ln(0.5)\left[\frac{t}{22.339Z^{-0.8187}\exp\left(\frac{241449}{RT}\right)}\right]^{1.2}\right\}$$

(5)

- Grain size after metadynamic recrystallization

$$D_{md} = 62.0115Z^{0.0303} \quad (6)$$

- Grain growth

$$D_{gr}^{10} = D_{st}^{10} + 2.24692\cdot10^{28}t\exp\left(-\frac{437000}{RT}\right) \quad (7)$$

where:

X_{st}, X_{md} – static and metadynamic recrystallized volume fraction,

T – temperature in K,

$\varepsilon, \dot{\varepsilon}$ – effective strain and strain rate,

D_0 – austenite grain size prior to deformation.

Phase transformation is, in general, based on the Avrami type equation:

$$X = 1 - \exp(-kt^n) \quad (8)$$

Details of this model are given in [3]. Briefly, theoretical considerations show that a constant value of coefficient n in equation (8) can be used. These coefficient were included in vector a as optimization variables a_4, a_{15} and a_{24} respectively for ferritic, bainitic and bainitic transformations. On contrary, value of the coefficient k must vary with temperature. A modified Gaussian function was proposed in [4] and is used for the ferritic transformation in the present project:

$$k = \frac{a_5}{D_\gamma}\exp\left[-\left(\frac{T - Ae_3 - \frac{400}{D_\gamma} + a_6}{a_8}\right)^{a_7}\right] \quad (9)$$

where:

D_γ – austenite grain size.

Incubation times τ_p and τ_b are introduces and simpler equations describing k are used for the pearlitic and bainitic transformations:

- Pearlitic:

$$\tau_p = \frac{a_9}{(Ae_1 - T)^{a_{11}}}\exp\left[\frac{a_{10}\cdot10^3}{R(T+273)}\right]$$
$$k = \frac{a_{14}}{D_\gamma^{a_{16}}}\exp\left(a_{12}\frac{T}{100} + a_{13}\right) \quad (10)$$

- Bainitic:

$$\tau_b = \frac{a_{17}k_b}{(T_b - T)^{a9}}\exp\left[\frac{a_{18}\cdot10^3}{R(T+273)}\right]$$
$$k = a_{23}\exp\left(-a_{21}\frac{T}{100} + a_{22}\right) \quad (11)$$

Bainite start temperature B_s and martensite start M_s temperature are calculated as:

$$B_S\ [^{\circ}\text{C}] = a_{20} - 425[\text{C}] - 42.5[\text{Mn}] - 31.5[\text{Ni}] \quad (12)$$

$$M_S\ [^{\circ}\text{C}] = a_{25} - a_{26}c_\gamma \quad (13)$$

where: c_γ – carbon concentration in the austenite.

Fraction of austenite, which transforms into martensite is calculated as [5]:

$$X_m = 1 - \exp[-0.011(M_S - T)] \quad (14)$$

Equation (13) represents volume fraction of martensite with respect to the whole volume of austenite, which was remaining at the temperature M_s. The volume fraction of martensite with respect to the whole volume of the material is:

$$F_m = (1 - F_f - F_p - F_b)\{1 - \exp[-0.011(M_S - T)]\} \quad (15)$$

Table 1. Chemical composition of the investigated multi-phase (CP) steel, wt%

Tablica 1. Skład chemiczny analizowanej stali wielofazowej (CP), w % masowych

C	Mn	Si	P	S	Cr	Ni	Cu	V	Ti	$Al_{met.}$	O (ppm)	N (ppm)
0.09	1.55	0.40	0.010	0.010	0.31	0.21	0.20	<0.005	0.12	0.04	8	27

Table 2. Coefficients in the phase transformation model for the investigated multi-phase (CP) steel

Tablica 2.Współczynniki modelu przemian fazowych dla analizowanej stali wielofazowej (CP)

a_4	a_5	a_6	a_7
0.956	0.999	215.4	86.38
a_8	a_9	a_{10}	a_{11}
2.968	24.51	41.41	0.0627
a_{12}	a_{13}	a_{14}	a_{15}
0.07049	3.13	0.001	2.083
a_{16}	a_{17}	a_{18}	a_{19}
0.0326	192.97	51.63	2.837
a_{20}	a_{21}	a_{22}	a_{23}
710.1	0.795	2.728	0.6315
a_{24}	a_{25}	a_{26}	
0.766	446.8	119.5	

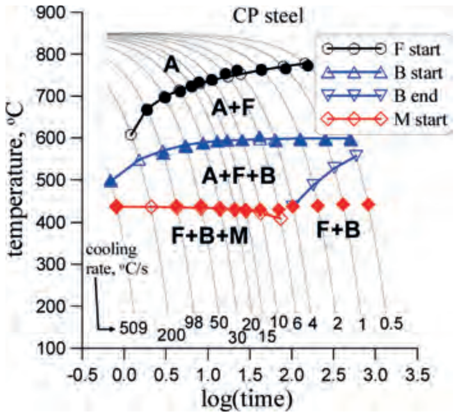

Fig. 1. Comparison of the measured (filled symbols) and calculated (open symbols with lines) start and end temperatures for transformations

Rys. 1. Porównanie zmierzonych (pełne symbole) i obliczonych (puste symbole z liniami) temperatur początku i końca przemian

where:

F_f, F_p, F_b – fraction of ferrite, pearlite and bainite with respect to the whole volume.

The model contains coefficients, which were determined using inverse analysis of the dilatometric tests. Results of the inverse calculations are given in Table 2. Comparison of the measured and calculated start and end temperatures for transformations is shown in Figure 1.

3. EXPERT SYSTEM

3.1. LPS DESCRIPTION

LPS line installed at IMZ Gliwice was investigated in the project. The line is composed of heating furnace, descaler, reverse rolling stand, controlled cooling systems after odd passes and after rolling, furnace for heat treatment after rolling and bath cooling tank. Detailed description can be found in [6]. All these elements of LPS were analyzed in details and equipment parameters, having the highest influence on the forming process and material properties, were selected. On the basis of the results obtained from this analysis, the particular models were designed, implemented and presented to final users on the Graphical User Interface, GUI (figure 2).

3.2. IMPLEMENTATION DETAILS

The main component diagram is presented in figure 3, where five main functional packages are distinguished: Tools, Calculations, Data and Logic Layers, and Window App.

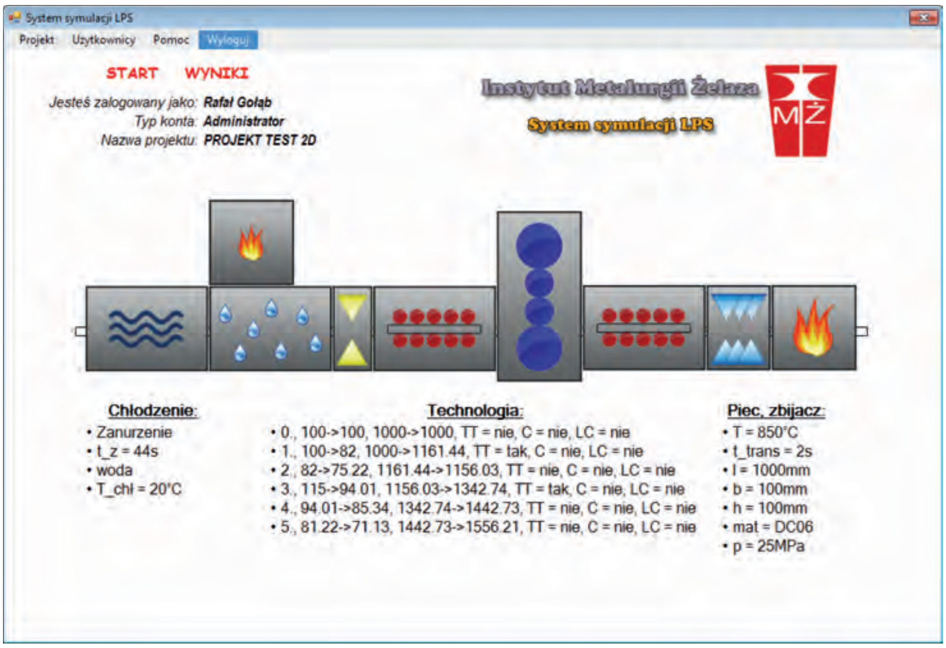

Fig. 2. Graphical User Interface of the computer system supporting design of rolling technology for manufacturing of flat and long products

Rys. 2. Graficzny Interfejs Użytkownika system wspomagającego projektowanie technologii wytwarzania wyrobów płaskich i długich

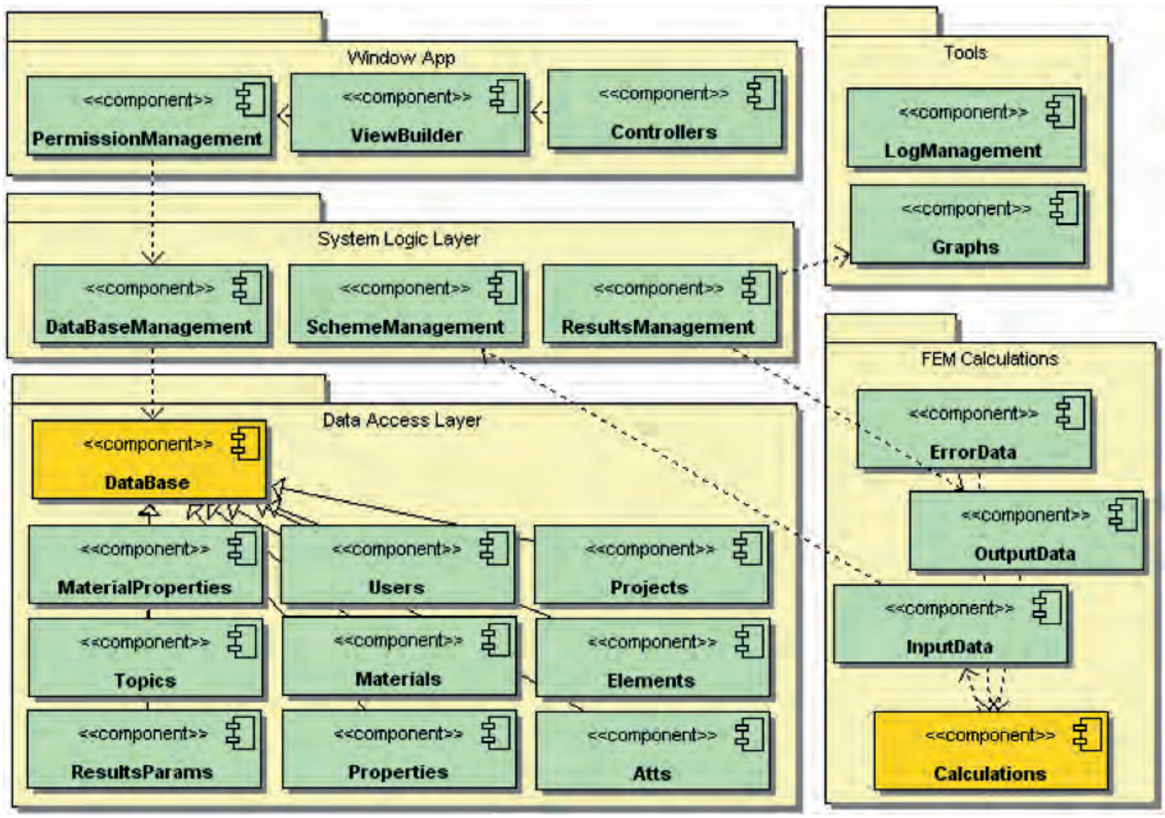

Fig. 3. Diagram of components implemented in the system [7]
Rys. 3. Diagram elementów zaimplementowanych w systemie [7]

The Window App package is responsible for the presentation of windows forms and data to end-users on GUI. Components of controllers and view builders are dedicated to this functionality. Additional components for user identification and authorization were implemented to validate user's permissions to access and copy data gathered in the system. The Window App package is strongly connected to the System Logic Layer, which is the most important part of the system joining all the packages together. It retrieves all the information from the centralized database and, according to users requirements, it passes these data to FEM calculations. Finally, the obtained results are presented to the user by Windows App package with so called helpers implemented within Tools package. The expert system is implemented in SchemeManagement component being the most important part of System Logic Layer. This component was connected to the optimization module, which allowed flexible modeling and optimization of rolling processes [8]. This approach was used to design the optimal rolling and cooling technology for the CP steel in this paper.

4. RESULTS

Expert system with the flow stress model and microstructure evolution model was used for the design of the rolling technology for the investigated DP steel. The flat sample with the cross section 24×100 mm was used as input. The objective was to obtain 4 mm thick strip with the multiphase structure composed of 30% of ferrite, 50 % of bainite and 20% of martensite. This objective was reached by application of the reverse hot rolling in 6 passes followed by 3 stages of the controlled cooling. The rolling technology and main calculated parameters are given in Table 3, where: h – thickness, F – rolling force, r – reduction. Rolling velocity was 1.5 m/s in all passes. Austenite grain size of 15 μm was obtained after rolling. Three-stage cooling schedule after rolling was applied to obtain the required volume fractions of phases. The schedule was composed of accelerated cooling (26°C/s) to 500°C, followed by slow cooling (2°C/s) to 450°C and fast cooling in water. Changes of the temperature during rolling are shown in Figure 4. Changes of the austenite grain size during rolling are shown in this figure, as well. Changes of the temperature and kinetics of transformations during optimal cooling after rolling are shown in Figure 5. Selected microstructures of recrystallized material obtained in the laboratory tests at 1000ºC and 900ºC are shown in Figure 6.

Table 3. Rolling schedule
Tablica 3. Schemat walcowania

h mm	r	F kN
24	-	-
16.6	0.31	790
11.8	0.29	695
8.6	0.27	609
6.4	0.25	546
5.0	0.225	501
4.0	0.2	482

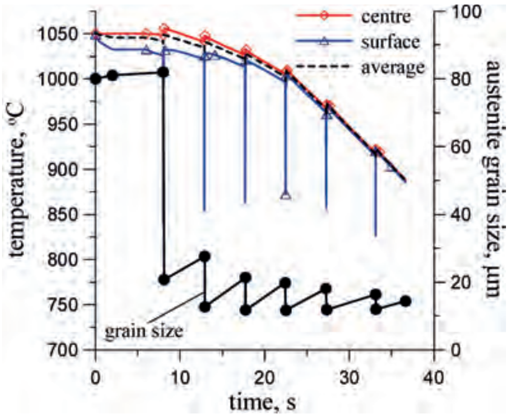

Fig. 4. Changes of the temperature and austenite grain size during 6 pass hot rolling according to the schedule in Table 3

Rys. 4. Zmiany temperatury i wielkości ziarna austenitu w sześcioprzepustowym schemacie walcowania zgodnym z tablicą 3

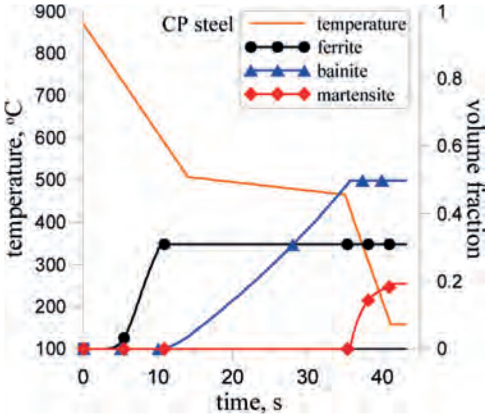

Fig. 5. Changes of the temperature and kinetics of transformation during cooling after hot rolling

Rys. 5. Zmiany temperatury i kinetyki przemiany podczas chłodzenia po walcowaniu na gorąco

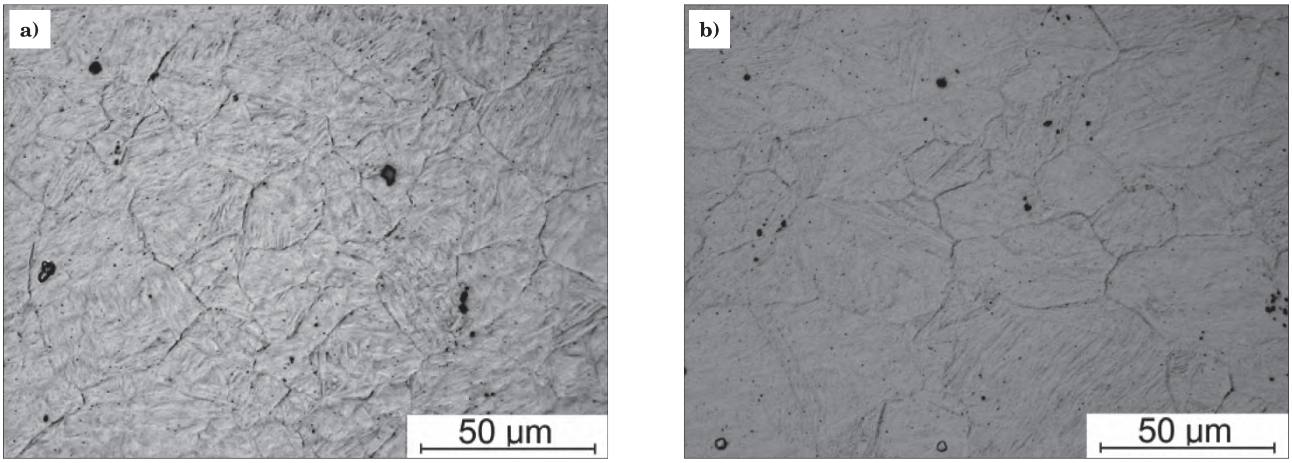

Fig. 6. Selected microstructures after recrystallization for ε = 0.3 and T = 1000°C (a) and 900°C (b)

Rys. 6. Wybrane mikrostruktury po rekrystalizacji dla ε = 0.3 i T = 1000°C (a) i 900°C (b)

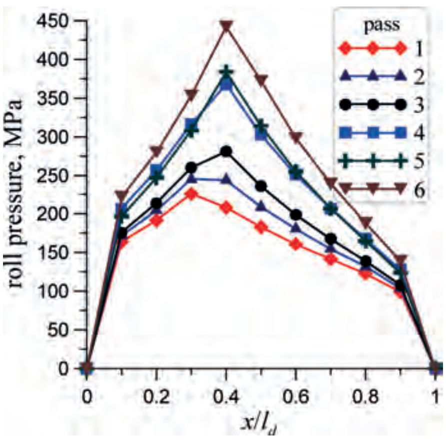

Fig. 7. Distribution of the roll pressure along the arc of contact calculated by the system

Rys. 7. Rozkłady nacisków podczas walcowania wzdłuż krzywizny kontaktu, obliczone przez system

The system calculates all force and power parameters during rolling, including roll pressure, torques, motor power and current. Distribution of the roll pressure along the arc of contact in all passes is presented in Figure 7 as an example (x – coordinate, l_d – length of the arc of contact).

5. CONCLUSIONS

Application of the computer system developed for LPS line installed in the IMZ Gliwice was shown in the paper. The system was used for the design of the optimal rolling and cooling technology for the CP steel. Optimal parameters of the cooling schedule to obtain 30% of ferrite, 50% of bainite and 20% of martensite were determined as accelerated cooling (26°C/s) to 500°C, followed by slow cooling (2°C/s) to 450°C and fast cooling in water

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