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PREDICTION OF CONDITIONS FOR OBTAINING NANOSTRUCTURED BAINITE BASED ON A COMPREHENSIVE APPROACH

Introduction. Modern resource-efficient engineering requires the production of thick steel plates from advanced high-strength steels (AHSS) of the latest generation with a nanostructured bainitic microstructure that combines high strength and adequate ductility.

Problem Statement. A major challenge is predicting microstructure evolution in heavy plate products subjected to different cooling conditions while accounting for the chemical and structural heterogeneity formed during solidification, which exerts a hereditary influence on subsequent microstructural evolution during hot deformation and heat treatment.

Purpose. To investigate the formation of gradient microstructures in experimental AHSS steels and to optimize cooling rates through prediction of the conditions required for the formation of a nanostructured bainitic microstructure.

Materials and Methods. A comprehensive computational approach has been employed to predict the phase constitution after continuous cooling at rates of 1—97 °C/s, given the experimentally determined microhardness distribution in the as-cast condition of AHSS steels with different chemical compositions.

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Numerical simulations were performed using the QForm, CallPhad, and JMatPro software packages. Microstructural characterization and microhardness measurements have been carried out using standard metallographic techniques.

Results. The relationship between the non-uniform microhardness distribution in the as-cast condition and the microstructural heterogeneity of low-alloy AHSS steels after subsequent hot deformation and heat treatment has been established. An adaptive approach for predicting microstructure evolution while accounting for the hereditary effect of chemical heterogeneity has been developed. The optimum cooling rates required for the formation of nanostructured bainite have been determined, and the predictive capability of the proposed model has been experimentally validated using steels of the investigated compositions.

Conclusions. The proposed approach has enabled optimization of the cooling schedules for AHSS steels to control the formation of gradient microstructures during heat treatment while accounting for the hereditary influence of chemical heterogeneity formed during solidification. The developed methodology has provided an effective tool for predicting the evolution of the final phase constitution in thick-section steel products.

Keywords: modeling, gradient microstructure, thermal processing, heterogeneity, phase transformation, steel.

Heavy steel plate occupies a key position among metallurgical products and is widely used in bridge engineering, shipbuilding, the aerospace industry, and automotive manufacturing. Owing to the increasing demand for improved service performance and extended service life under severe operating conditions, considerable attention has recently been paid to the production of advanced high-strength steels (AHSS) with large cross-sections [1].

This class of steels extends beyond the chemical composition of conventional high-strength low-alloy (HSLA) steels, thereby providing greater potential for simultaneously achieving high strength and ductility. As reported in Refs. [2–6], AHSS are commonly classified into three generations. The first generation includes dual-phase (ferrite–martensite) steels, in which ferrite provides ductility while martensite serves as the strengthening phase, as well as TRIP (Transformation-Induced Plasticity) steels [2], which possess a polygonal ferritic matrix and are strengthened during heat treatment within the $\alpha + \gamma$ two-phase region. The second generation comprises TWIP (Twinning-Induced Plasticity) steels, whose strengthening mechanism is based on deformation twinning promoted by alloying. The third generation includes medium- and low-alloy TRIP steels [4] subjected to quenching and partitioning (Q&P) treatment involving an isothermal transformation process [5], together with nanostructured bainitic steels [3, 6], which develop a stable nanoscale lamellar $\alpha/\text{Fe}_3\text{C}$

structure resembling pearlite but formed through a different transformation mechanism.

In recent years, third-generation AHSS, particularly TRIP steels and nanostructured bainitic steels, have attracted increasing interest in a wide range of engineering applications, including mechanical engineering, shipbuilding, and related industries [7, 8]. This interest is primarily driven by their potential for structural optimization through the use of advanced materials [9], as well as by opportunities for resource conservation through reduced fuel consumption resulting from lighter structures [10]. Consequently, the application of these next-generation steels makes it possible to simultaneously address two major engineering challenges: increasing structural strength while reducing component weight through the use of thinner sections.

However, the production of heavy steel plate from these steels remains technologically challenging, labor-intensive, and costly. These difficulties arise from the need to achieve a homogeneous microstructure and minimal variation in mechanical properties throughout the thickness of products with different geometries while accounting for the effects of hot plastic deformation and cooling conditions. Therefore, the principal materials science challenge is to achieve the required service properties and the desired distribution of microstructural constituents throughout the thickness of heavy steel plate intended for critical structural applications.

In recent years, numerous studies [11–14] have been conducted to establish the mechanisms governing the formation of gradient microstructures throughout the thickness of heavy steel plate under industrial processing conditions. These studies have demonstrated that desirable service properties can be achieved through the formation of appropriate gradients in grain size and microstructure across the plate thickness of experimental steels. It is well recognized that attaining an optimal combination of service properties, particularly in AHSS, requires careful consideration of the effects of alloying systems, the initial microstructural state, mechanical properties, and section geometry. These factors remain among the most important research topics in modern applied materials science.

Achieving superior service performance in AHSS continues to represent a major challenge in applied materials science. Addressing this challenge requires a comprehensive understanding of the influence of alloying systems, microstructural characteristics, mechanical properties, and the geometric profile of steel products.

Next-generation steels combining high strength and high ductility are highly attractive for modern industrial applications. However, the development of high-strength steels is generally accompanied by a reduction in ductility [15–19], which is primarily attributed to a low strain-hardening rate [17, 18]. To overcome this limitation, several strengthening approaches have been proposed while maintaining adequate ductility, including the development of gradient microstructures [19], heterogeneous lamellar architectures [21, 22], and heterogeneous grain structures [23]. Materials with gradient microstructures have attracted considerable attention because of their potential to achieve an exceptional synergy of strength and ductility by adapting their microstructure to service loading conditions [24, 25].

The formation of gradient microstructures is typically achieved through controlled alloying, which promotes localized spatial redistribution of chemical elements. This redistribution influences phase transformations and phase constituents,

thereby improving the microstructure, mechanical properties, and overall service performance of the material [26–28].

This unique combination of properties has stimulated growing interest in these steels and has generated substantial industrial demand, largely because of their suitability for a wide range of service conditions and their potential to improve economic efficiency.

The industrial implementation of these advanced steels has created a demand for energy-efficient technologies capable of consistently achieving the required mechanical properties, which remains a challenging task. One promising solution is to utilize the rolling reheating temperature to develop the desired microstructure directly during thermomechanical processing, thereby eliminating the need for secondary heat treatment while simultaneously retaining the dislocation structure generated during plastic deformation.

The objective of this study is to investigate the formation of gradient microstructural constituents in experimental AHSS grades in order to optimize cooling rates through predicting the conditions required for the formation of a nanostructured bainitic microstructure.

The experimental materials consisted of laboratory-produced steels manufactured using an ITPE-0.01 induction melting unit. Melting was performed by remelting without forced oxidation of impurities. Alloying elements were introduced into the molten steel by immersion in a protective metallic container. The actual chemical composition of the produced steels is presented in Table.

Hot plastic deformation was performed under laboratory conditions using specimens measuring $70 \times 70 \times 80$ mm, machined from the experimental ingots. The specimens were compressed to a 50% reduction in height. Prior to deformation, the specimens were heated to 1260 °C, which closely approximates the rolling temperature employed under industrial processing conditions.

Experimental heat treatment was carried out using a SNOL 1.6/1100 laboratory furnace. Temperature was monitored with a Type K (chromel–

alumel) thermocouple inserted to a depth of 2 mm at the center of each specimen. Cylindrical specimens with dimensions of $\varnothing 10 \times 10$ mm were heat-treated according to schedules established from mathematical modeling and continuous cooling transformation (CCT) diagrams.

The microstructure of the experimental steels was examined using an AxioVert 200M Mat optical microscope in bright-field mode. Metallographic specimens were prepared following standard metallographic procedures using a Struers Labopol-5 grinding and polishing system with diamond suspensions and polishing pastes. The microstructure was revealed by etching with 2% atal. Mechanical characterization focused on the microhardness of individual microstructural constituents, which was measured using an LHV5-1000Z microhardness tester under a 50 g load. The analyzed area measured 2.4×2.4 mm.

Phase diagram calculations were performed using the JmatPro software package with thermodynamic databases. The chemical composition listed in Table 1 was used as the actual alloy composition. To ensure that the simulations closely reproduced industrial processing conditions, the modeling incorporated the results of optical microscopy together with the experimentally measured cooling curves obtained after heat treatment. The simulations were conducted under non-isothermal conditions, assuming that the disordered face-centered cubic (FCC) matrix formed throughout the specimen volume, whereas the remaining phases nucleated and developed predominantly along prior-austenite grain boundaries.

To predict the cooling rates required for the formation of the desired microstructure and to determine the distribution of gradient microstructural constituents throughout the thickness of the experimental steels, numerical simulations were performed using the previously developed CAD model [5]. The simulations were conducted using the finite element method (FEM) implemented in the Qform software package. FEM is a numerical technique that transforms a system of differential equations into a system of algebraic equations suitable for numerical solution. In the present study, the numerical implementation of the finite difference formulation of the Fourier heat conduction equation was employed, in which the temperature field, $T(x, y)$, was represented by a grid function, where i and k denote the nodes of the two-dimensional computational mesh. A uniform mesh was used, with identical grid spacing in the x - and y -directions [5].

The finite element simulation of the cooling process for the experimental CAD model consisted of the following stages.

1. *Construction of the geometric model.* The geometry of the experimental CAD model was created in SolidWorks and exported to QForm in the .stp format. The computational domain was then discretized into four-node planar finite elements with an element size of 2 mm. Each node was assigned a single degree of freedom corresponding to temperature.

2. *Specification of the initial conditions.* The initial temperature prior to quenching was set to 820 °C, with a holding time of 1 min per millimeter of section thickness.

Actual Chemical Composition of the Studied Steels

Steel	Element content, % wt.															
	C	Mn	Si	Cr	Ni	Mo	V	Ti	Al	Ca	Nb	S	P	N	Cu	B
1	0.313	0.35	0.384	2.86	2.54	0.451	0.0057	0.0031	0.014	<0.0001	<0.004	0.018	0.011	0.012	0.03	0.002
2	0.329	0.74	1.68	2.26	1.92	0.455	0.153	0.0024	0.024	0.0004	<0.001	0.007	0.004	0.007	0.03	0.001
3	0.321	0.54	0.368	0.81	2.26	0.356	0.148	0.026	0.043	0.003	0.002	0.022	0.02	0.0035	0.03	0.002
4	0.251	0.65	0.284	0.98	1.84	0.317	0.133	0.0012	0.026	0.0003	0.029	0.022	0.022	0.0071	0.271	0.002

3. *Specification of the boundary conditions.* The quenching media considered were water and oil, whose thermophysical characteristics were incorporated into the QForm material library in the .qdat format. Each cooling medium was characterized by its temperature and heat transfer coefficient. The heat transfer coefficient was defined as a temperature-dependent function of the metal surface temperature.

The simulations were performed for the experimental steels with the actual chemical compositions listed in Table 1. For each alloy, the evolution of the microstructure and microhardness during cooling was predicted using the corresponding continuous cooling transformation (CCT) diagram.

4. *Determination of thermophysical and phase transformation properties.* The thermophysical and phase transformation characteristics of the experimental steels were determined using the CALPHAD approach implemented in JMatPro. Based on the chemical composition of each steel, JMatPro was used to predict the evolution of the microstructure during cooling. The following temperature-dependent material properties were incorporated into the thermal model: density, specific heat capacity, and thermal diffusivity.

5. *Specification of numerical solution parameters.* The thermal simulations were performed using the following computational settings: a quasi-static solution scheme, an iterative numerical algorithm, and implicit time integration.

6. *Model calibration and validation.* In the final stage of the simulation, the numerical model was calibrated against the actual process by comparing the predicted values at selected control points with the corresponding experimental measurements, followed by iterative refinement of the model. The simulated temperature distributions at different depths within the model were compared with experimental data derived from the continuous cooling transformation (CCT) diagrams. Whenever significant discrepancies were observed, the numerical model was adjusted accordingly.

The primary outputs of the quenching simulation were the cooling-rate profiles and the corres-

ponding time-dependent microstructural evolution diagrams.

The cooling rates in different regions of the experimental CAD model were determined by solving the transient heat conduction equation (Fourier equation) using the finite element method. Simulations were performed for different quenching media, with temperature data recorded at the center of each representative volume element of the model. The model consisted of cubic elements with edge lengths ranging from 5 to 100 mm. The simulations predicted cooling rates ranging from 0.9 to 67 °C/s for the experimental steels.

The primary objective of this study was to investigate the influence of cooling parameters on the development of gradient microstructures. As a preliminary stage of the investigation, the characteristics of gradient microstructure formation during solidification were evaluated together with the corresponding mechanical properties, specifically the microhardness, in the as-cast condition (Fig. 1).

The results of the microhardness measurements showed that the experimental steels exhibited the following microhardness ranges: Steel 1: 3525—4570 MPa; Steel 2: 3665—4665 MPa; Steel 3: 2390—3274 MPa; and Steel 4: 2760—3670 MPa. Based on these results and previously published data, the principal microstructural constituents were identified as nanostructured bainite, lath martensite containing regions of retained austenite [29], and microstructures formed through diffusion-controlled transformation (Steels 3 and 4).

It should be noted that Steels 1 and 2 have exhibited average microhardness values approximately 23—27% higher than those of Steels 3 and 4. In contrast, Steel 4 has demonstrated a more uniform hardness distribution, with only an isolated decrease in microhardness to approximately 1890 MPa.

Analysis of the microstructure and microhardness distribution in Steel 1 has revealed a pronounced but uniformly distributed segregation pattern. Although this segregation has not significantly affected the overall microhardness distribution, localized increases in microhardness have indicated the presence of local chemical inhomogeneities.

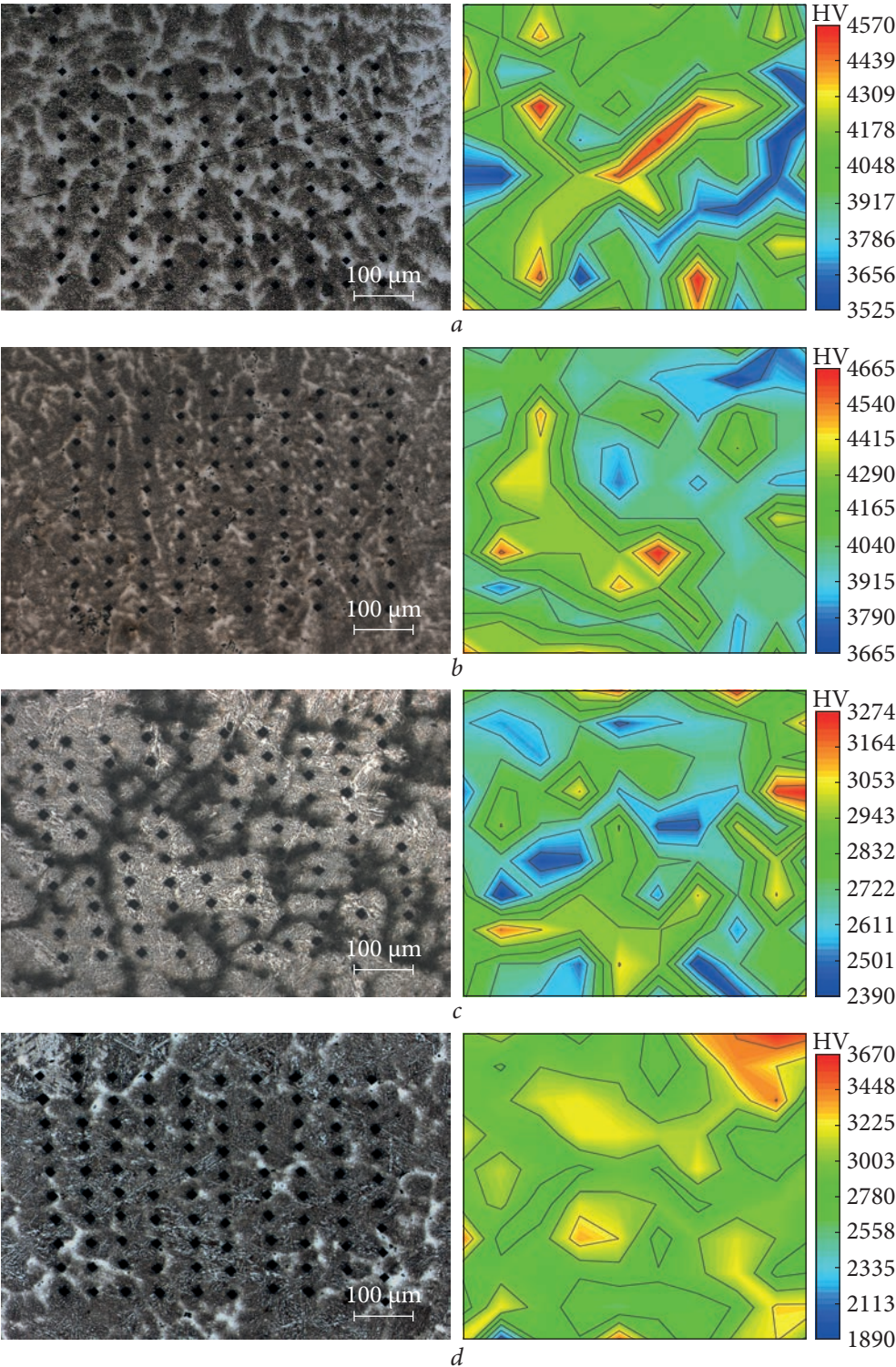


Fig. 1. Microstructures and microhardness distributions of the microstructural constituents in experimental steels 1 (a), 2 (b), 3 (c), and 4 (d) in the as-cast condition after solidification

The microhardness distribution in Steel 2 has exhibited isolated hardness peaks exceeding 4415 MPa, suggesting local microstructural heterogeneity associated with the formation of acicular microstructural regions resulting from the localized non-uniform distribution of slowly dissolving alloying elements.

For Steel 3, both microstructural observations and microhardness measurements have confirmed pronounced structural heterogeneity. The darker regions have most likely corresponded to interdendritic areas, representing former liquid microvolumes enriched in alloying elements during solidification. However, the microhardness measured at the centers of the former dendrite arms (light regions) has remained comparable to that of the darker regions, averaging approximately 2822 MPa, whereas reduced microhardness has been observed primarily at the interfaces between these regions.

Steel 4 has contained light regions with a distinct acicular morphology, indicating the presence of martensite with microhardness values reaching 3225 MPa.

Overall, the results have demonstrated that the investigated alloying systems promote pronounced chemical segregation during solidification, which subsequently influences the final microstructure and mechanical properties. These findings have therefore provided an essential basis for predicting the evolution of gradient microstructures and for assessing the influence of inherited solidification features on the development of the final microstructure.

Analysis of the mathematical simulation performed using the CAD model and the specified input parameters demonstrated that the microstructures of Steels 1 and 2 (Fig. 2, *a*), within the investigated cooling-rate ranges of 1–67 °C/s and 1–97 °C/s, respectively, are predominantly composed of martensite and retained austenite. In contrast, simulation of Steels 3 and 4 (Fig. 2, *b*) over the cooling-rate range of 0.9–93.7 °C/s predicted the formation of martensite, bainite, and retained austenite without the occurrence of lo-

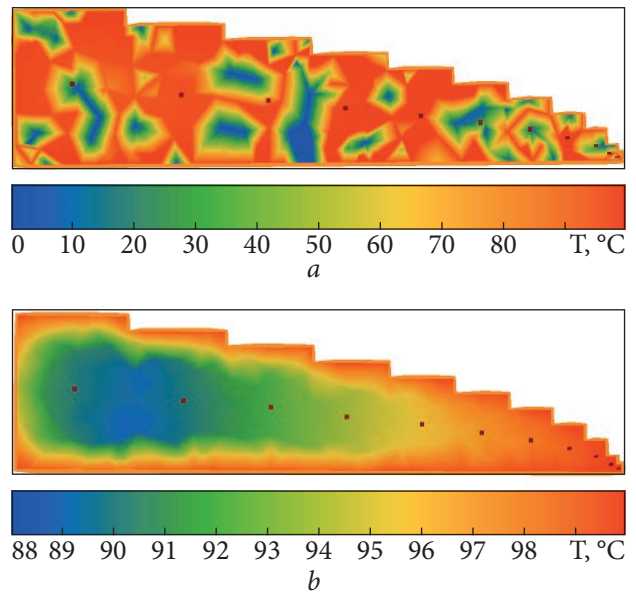


Fig. 2. Predicted distribution of the martensitic phase in Steel 2 (*a*) and Steel 4 (*b*) across the cross-section of the experimental model, based on the experimentally determined properties of the as-cast condition (Fig. 1), after water quenching (cooling rate: 4.5–97 °C/s and 4.5–93 °C/s, respectively)

calized regions of phase heterogeneity that could indicate the influence of chemical segregation within the framework of the simulation.

The results obtained from the mathematical model (Fig. 2) further demonstrate that incorporating experimental data on chemical and structural heterogeneity, represented by the measured microhardness distribution of the structural constituents (Fig. 1), makes it possible to predict the persistence of the hereditary relationship between chemical heterogeneity in the as-cast condition and the final microstructure after subsequent heat treatment.

Therefore, the obtained results provide preliminary evidence supporting the adequacy of the proposed mathematical modelling approach, which incorporates experimentally determined material characteristics, for predicting potential structural heterogeneity. Consequently, the proposed method enables simulation-based assessment of the hereditary influence of the initial microstructure on the final phase constitution after heat treatment.

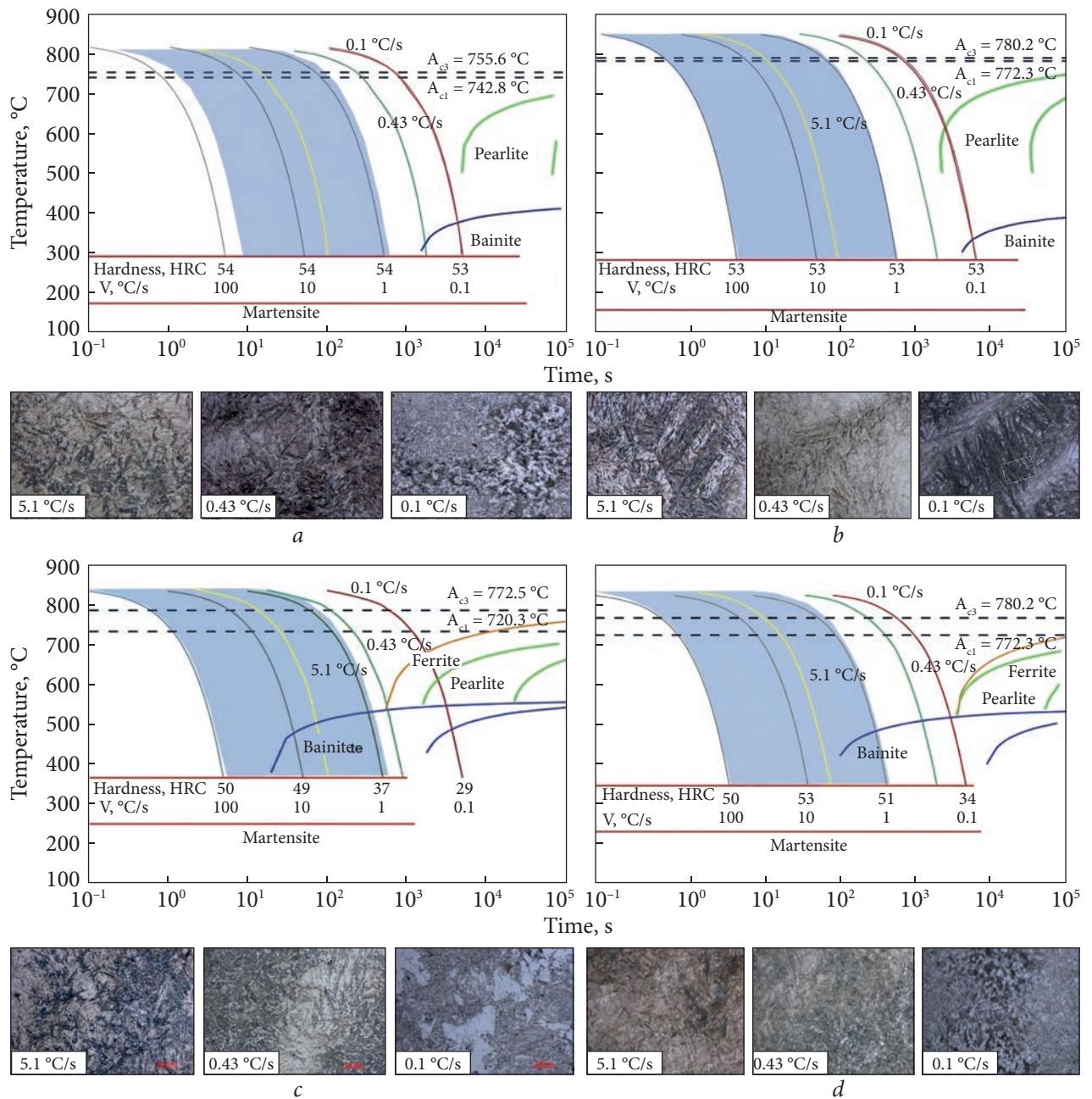


Fig. 3. Continuous cooling transformation (CCT) diagrams of the experimental Steels 1 (a), 2 (b), 3 (c), and 4 (d) with the cooling-rate ranges predicted by mathematical modeling (blue region: 1–67 °C/s, 1–97 °C/s, 0.9–93.7 °C/s, and 0.9–93.7 °C/s, respectively) and the cooling rates employed during the experimental heat treatment: red — 0.1 °C/s, green — 0.43 °C/s, and yellow — 5.1 °C/s

Figure 2 presents the results of the mathematical simulation incorporating the initial structural heterogeneity through the use of experi-

mentally determined mechanical properties and microstructural characteristics of the as-cast condition.

The mathematical simulations have shown that the microstructures of Steels 1 and 2 (Figs. 3, *a—b*, respectively) have consisted predominantly of lath martensite with the formation of fine acicular packets together with retained austenite over the investigated range of cooling rates. These results indicate that the developed Steels 1 and 2 are comparable to advanced steels employed in ballistic protection applications [30].

For Steels 3 and 4 (Figs. 3, *c—d*), the simulations have predicted microstructures composed primarily of martensite, bainite, and retained austenite throughout the investigated cooling-rate range. According to published studies, this type of gradient microstructure has demonstrated considerable potential for shipbuilding applications because of its favorable combination of strength and toughness [31].

Based on the simulation results, heat treatment using cooling rates in the range of 0.1—5.1 °C/s has been recommended for subsequent experimental validation.

The simulation results enabled prediction of the optimum cooling rates required to achieve the target microstructures during subsequent heat treatment. Based on the results of the mathematical modeling, experimental heat treatments were performed using different cooling media to reproduce cooling rates representative of those expected across the thickness of heavy plate products under industrial processing conditions. Considering the dimensions of the laboratory specimens, the recommended cooling rates were achieved under the following conditions: furnace cooling (0.1 °C/s), cooling under a heat-resistant insulating blanket (0.43 °C/s), and cooling in still air (5.1 °C/s).

Experimental heat treatment performed using the recommended cooling rates demonstrated that the microstructure of Steel 1 (Fig. 3, *a*) cooled at 0.1 °C/s consisted predominantly of bainite together with troostitic–sorbite transformation products. It should be noted that these constituents were distributed non-uniformly throughout the metallographic section, indicating the inherited influence of chemical segregation on the final microstructure.

Increasing the cooling rate to 0.43 °C/s resulted in a microstructure composed primarily of upper and lower bainite, accompanied by a small fraction of acicular martensite and retained austenite, suggesting a non-uniform distribution of slowly dissolving alloying elements inherited from melting and solidification. At a cooling rate of 5.1 °C/s, the microstructure consisted mainly of highly alloyed martensite with different levels of dispersion together with retained austenite.

Microstructural analysis of Steel 2 after cooling at rates between 0.1 and 5.1 °C/s (Fig. 3, *b*) showed that the microstructure consisted predominantly of martensite with different morphologies and dispersions (the martensite becoming finer at 5.1 °C/s) together with regions of retained austenite. The retained austenite regions most likely corresponded to areas previously affected by chemical segregation observed in the as-cast condition (Fig. 1, *b*).

Microstructural examination of Steel 3 revealed that cooling at 0.1 °C/s produced a microstructure composed mainly of ferrite and pearlite with different degrees of dispersion, together with small amounts of bainite and retained austenite. Increasing the cooling rate to 0.43 °C/s resulted in the formation of bainite and troostite, accompanied by isolated laths of fine martensite and retained austenite. The presence of these isolated martensitic regions indicates localized chemical heterogeneity that influenced the final microstructure. After cooling at 5.1 °C/s (Fig. 3, *c*), the microstructure consisted predominantly of martensite together with isolated regions of nanostructured bainite and fine pearlite, while the dispersion of the martensitic phase increased.

Microstructural analysis of Steel 4 (Fig. 3, *d*) after cooling at 0.1 °C/s showed a microstructure consisting of carbide-free bainite, ferrite, and troostitic–sorbite pearlite. Increasing the cooling rate to 0.43 °C/s resulted in the formation of nanostructured bainite together with fine multidirectional martensitic laths. After cooling at 5.1 °C/s, the microstructure consisted predominantly of quenched martensite with a small fraction of nanostructured bainite.

Overall, the results demonstrate that the investigated steels exhibit a pronounced tendency to form nanostructured bainite under relatively slow cooling conditions, accompanied by the development of a homogeneous multidirectional arrangement of alternating $\alpha/\text{Fe}_3\text{C}$ lamellae.

CONCLUSIONS

1. Based on the results of the mathematical modeling and experimental heat treatment, the characteristics of gradient microstructure formation in the experimental steels intended for heavy plate applications were identified over a cooling-rate range of 0.1–97 °C/s.

2. A computational model was developed and calibrated using an integrated physics-based and mathematical approach, enabling prediction of phase transformation mechanisms throughout the cross-section of the CAD model while accounting for the initial chemical heterogeneity during continuous cooling. The proposed model can be applied to determine the optimum heat-treatment parameters for heavy plate products required to achieve the target microstructure and hardness distribution across the section as a function of the steel chemical composition.

3. The understanding of the austenite decomposition kinetics in the investigated steels under cooling conditions representative of industrial processing has been further advanced. It was established that the experimental steels containing 0.31 wt.% C, 0.35 wt.% Mn, 0.38 wt.% Si, 2.86 wt.% Cr, 2.54 wt.% Ni, 0.45 wt.% Mo, and 0.0016 wt.% B (Steel 1); 0.32 wt.% C, 0.54 wt.% Mn, 0.36 wt.% Si, 0.81 wt.% Cr, 2.26 wt.% Ni, 0.35 wt.% Mo, and 0.14 wt.% V (Steel 3); and 0.25 wt.% C, 0.65 wt.% Mn, 0.28 wt.% Si, 0.98 wt.% Cr, 1.84 wt.% Ni, 0.317 wt.% Mo, 0.13 wt.% V, and 0.002 wt.% B (Steel 4) predominantly formed a nanostructured bainitic microstructure with a small fraction of pearlite of varying fineness when cooled at 0.1 °C/s. Increasing the cooling rate to 0.43 °C/s promoted austenite decomposition through a mixed diffusional–displacive transformation mechanism.

4. The kinetics of austenite decomposition in the experimental steel containing 0.32 wt.% C, 0.74 wt.% Mn, 1.68 wt.% Si, 2.26 wt.% Cr, 1.92 wt.% Ni, 0.45 wt.% Mo, 0.15 wt.% V, and 0.0014 wt.% B (Steel 2) were determined. Within the investigated cooling-rate range of 0.1–5.1 °C/s, the microstructure consisted predominantly of uniformly oriented martensitic laths, while the fineness of the martensitic structure increased with increasing cooling rate up to 5.1 °C/s.

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ПРОГНОЗУВАННЯ УМОВ ОТРИМАННЯ НАНОСТРУКТУРНОГО БЕЙНІТУ НА ОСНОВІ КОМПЛЕКСНОГО ПІДХОДУ

Вступ. Для вирішення сучасних задач ресурсозбереження у машинобудуванні є потреба у виробництві листового прокату великого перерізу з вдосконалених високоміцних сталей (AHSS) останнього покоління зі структурою наноструктурного бейніту.

Проблематика. При цьому потребує вирішення проблема прогнозування структури масивного прокату залежно від умов охолодження з урахуванням хімічної та структурної неоднорідності, що формується під час кристалізації і впливає на подальше структуроутворення після гарячого деформування та термічного оброблення.

Мета. Дослідження особливостей формування градієнтних структурних складових в дослідних AHSS сталях з метою адаптації вибору швидкостей охолодження на основі прогнозування умов досягнення структури наноструктурного бейніту.

Матеріали й методи. Застосовано комплексний підхід до прогнозування фазового складу після безперервного охолодження з швидкостями 1—97 °C/с з урахуванням фактичного розподілу мікротвердості у литому стані сталей AHSS різного хімічного складу з використанням моделювання у програмних середовищах *QForm*, *CallPhad*, *JmatPRO*. Аналіз мікроструктури та визначення мікротвердості проведено за стандартними методиками.

Результати. Встановлено зв'язок між нерівномірністю розподілу мікротвердості в литому стані та мікроструктурною неоднорідністю економнолегованих сталей після наступного деформування і термічного оброблення. Розроблено адаптивний підхід до прогнозування структуроутворення у економнолегованих AHSS сталях з врахуванням неоднорідності. Визначено рекомендовані швидкості охолодження для формування наноструктурного бейніту та експериментально підтверджено адекватність удосконаленої моделі на сталях дослідного складу.

Висновки. Запропонований підхід дозволяє адаптувати режими охолодження AHSS сталей для керування формуванням градієнтної структури під час термічного оброблення з урахуванням спадкового впливу неоднорідності, сформованої на етапі кристалізації.

Ключові слова: моделювання, градієнтна мікроструктура, термічна обробка, неоднорідність, фазові перетворення, сталь.