



Introducing nano-VC precipitates makes ultrafine bainitic steel a better combination of strength, ductility, and toughness

Zhuanqin Liang, Hongguang Li, Cuicui Chen, Huajun Fu, Xiaoyong Feng, Xinliang Gao, Zhinan Yang & Fucheng Zhang

To cite this article: Zhuanqin Liang, Hongguang Li, Cuicui Chen, Huajun Fu, Xiaoyong Feng, Xinliang Gao, Zhinan Yang & Fucheng Zhang (2024) Introducing nano-VC precipitates makes ultrafine bainitic steel a better combination of strength, ductility, and toughness, Materials Research Letters, 12:10, 756-763, DOI: [10.1080/21663831.2024.2386439](https://doi.org/10.1080/21663831.2024.2386439)

To link to this article: <https://doi.org/10.1080/21663831.2024.2386439>



© 2024 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.



[View supplementary material](#)



Published online: 06 Aug 2024.



[Submit your article to this journal](#)



Article views: 1790



[View related articles](#)



[View Crossmark data](#)



Citing articles: 11 [View citing articles](#)

ORIGINAL REPORTS

OPEN ACCESS



Introducing nano-VC precipitates makes ultrafine bainitic steel a better combination of strength, ductility, and toughness

Zhuanqin Liang^a, Hongguang Li^a, Cuicui Chen^a, Huajun Fu^a, Xiaoyong Feng^{b,c}, Xinliang Gao^a, Zhinan Yang^c and Fucheng Zhang^{b,c}

^aNational Engineering Research Center for Equipment and Technology of Cold Strip Rolling, Yanshan University, Qinhuangdao, People's Republic of China; ^bCollege of Metallurgy and Energy, North China University of Science and Technology, Tangshan, People's Republic of China; ^cHebei Iron and Steel Laboratory, North China University of Science and Technology, Tangshan, People's Republic of China

ABSTRACT

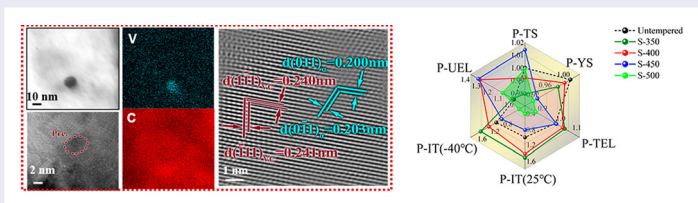
Simultaneously enhancing the strength, plasticity, and toughness of metal materials has been a prominent research objective. In this study, the precipitation of nano-scale vanadium carbide particles at a lower tempering temperature is controlled to achieve three key benefits: reducing lattice distortion in bainitic ferrite, strengthening through precipitation, and enhancing the toughness of bainitic ferrite, while also maintaining the content and stability of retained austenite. The adopted procedure increases the comprehensive mechanical properties of steel by 17%. In particular, the room-temperature impact toughness is increased by 41%. This comprehensive microstructure optimization endows bainitic steel with an excellent combination of mechanical properties.

ARTICLE HISTORY

Received 27 June 2024

KEYWORDS

Bainite ferrite; Nano-scale VC phase; Tempering; Lattice distortion



1. Introduction

Low-carbon ultrafine bainitic steel has been utilized extensively in rails, vehicles, and vessels owing to its advantages of a short preparation cycle, high strength, toughness, and wear resistance [1–3]. The microstructure of this steel is made up of stress field formed by solid-soluble supersaturated carbon in bainitic ferrite and the high-density dislocations is primarily responsible for the high strength of bainitic steel. However, the solid-solution stress field causes several issues, including the generation of residual stress, an increase in sensitivity to hydrogen embrittlement, and a declining work-hardening rate [4]. Furthermore, during service, the high-stress field causes metastable retained austenite to transform, negatively impacting the mechanical characteristics [5]. Therefore, reducing lattice stress in bainite is crucial for improving the overall performance of bainitic steel.

Tempering is a conventional heat treatment procedure that promotes carbon atom diffusion, dislocation redistribution, carbide precipitation, and residual stress release [6–9]. Research has revealed that ‘cluster strengthening’ can occur in the structure after low-temperature tempering [4,10,11]. However, cluster segregation at grain or phase boundaries can lead to local stress concentrations, thereby reducing the plasticity and toughness of the material [12–14]. After high-temperature tempering, the diffusion coefficient of carbon elements and the stability of retained austenite increase, enhancing plasticity and toughness [11,15–18]. However, this procedure may also cause microstructure coarsening, a reduction in dislocation density, martensite/austenite (M/A) island decomposition, and a decrease in solid-solution strengthening, leading to a reduction in the strength of bainitic steel [19–23]. Therefore, enhancing the plasticity and toughness of tempered bainitic

CONTACT Zhinan Yang ✉ zhinanyang@ysu.edu.cn Hebei Iron and Steel Laboratory, North China University of Science and Technology, Tangshan 063210, People's Republic of China

Supplemental data for this article can be accessed online at <https://doi.org/10.1080/21663831.2024.2386439>.

© 2024 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

Table 1. Main chemical composition of sample materials (wt.%).

C	Mn	Si	Al	Cr	Ni	Mo	V	Nb
0.26	1.7	1.3	0.41	0.90	0.15	0.20	0.19	0.03

steel while maintaining its strength is a significant challenge.

The nano-second phase is an effective strengthening phase [4]. A second phase with high coherence with the matrix can improve the strength of the material while maintaining high plasticity, as seen with compounds such as NiAl, AlN, Ni₂AlTi, Cu, and Ni₂AlMn [24–26]. Generally, a higher tempering temperature is necessary for the precipitation of these second phases. Vanadium (V) is a common microalloying element that can increase the hardenability of steel and produce a precipitation-strengthening effect [27,28]. The vanadium carbide (VC) phase, a highly coherent second phase with body-centered cubic Fe (bcc-Fe), precipitates at temperatures ranging from 340°C to 750°C [14,23,29–32]. This prompts the question of whether the tempering temperature can be adjusted to precipitate the nano-VC phase in the bainitic ferrite to reduce lattice distortion by reducing the supersaturated carbon content of the solid solution, thereby producing a strengthening effect in the nano-second phase and ensuring the excellent strength, plasticity, and toughness of the steel.

According to the above analysis, vanadium-containing bainitic steel was designed in this study, with the aim of controlling the precipitation of the nano-scale VC phase by regulating the tempering temperature. The microstructure was characterized through electron microscopy, and the relationship between multiphase microstructure evolution and mechanical properties was investigated. This study revealed the strengthening, plasticizing, and toughening mechanisms of the VC phase, aiming to improve the plasticity and toughness of bainitic steel while maintaining its high strength.

2. Materials and methods

The chemical composition of the sample steel is shown in Table 1. The steel after austenitizing treatment was obtained through a two-stage isothermal treatment and then tempered at temperatures of 350–500°C. According to preliminary research results [33], the tempering time in this study was set to 18,000 s. Samples subjected to isothermal bainitic transformation and tempering at 350°C, 400°C, 450°C, and 500°C were labeled as untempered sample, S-350, S-400, S-450, and S-500, respectively.

The microstructure was examined via transmission electron microscopy (TEM, FEI-Talos F200S, Thermo Fisher Scientific, USA) and electron backscatter diffraction

microscopy (EBSD, S9000X, Oxford Instruments, UK). X-ray diffraction (XRD, Rigaku Smartlab-9KW, Co-K α , Rigaku Corporation, Japan) was used to calculate the retained austenite content (V_{RA}), carbon content (C_{RA}), dislocation density in the matrix (ρ), and mechanical stability evaluation values (K) of the different tempered samples. The tensile properties of the round rod-shaped samples with a parallel section gauge of 25 mm and a diameter of 5 mm were evaluated using an MTS material tensile testing machine (Eden Prairie, USA). Toughness tests were conducted at both 25°C and –40°C utilizing a pendulum impact tester (JB-300J, Jinan Shiguang Test Instrument Co., Ltd., China). Each test was performed at least three times, and the average value and error of the detection results were calculated to confirm the accuracy and re-testability of the test results.

3. Results and discussion

Figure 1 illustrates the TEM microstructure of various tempered samples. The microstructure of the tempered sample consisted of bainitic ferrite laths and retained austenite (Figure 1(a,b)). The size of the lath was estimated using Equation (1) ((reference attachment)). The dimension of the untempered sample was 112 ± 8 nm, while S-350 was coarsened to 129 ± 8 nm. As the temperature increased to 400°C, the thickness of the lath only increased to 133 ± 9 nm. Further increasing the temperature to 450°C resulted in almost no change in thickness, which measured 135 ± 3 nm. Detailed observation of the microstructure revealed that the microstructure of S-400 contained a large number of spherical particles with an equivalent diameter of 7 ± 1 nm, and most of the particles were distributed at dislocations and grain boundaries (Figure 1(c)). This distribution was largely due to the significant difference in lattice parameters between the ferrite and precipitated phases, and heterogeneous nucleation on defects was beneficial for reducing strain energy [4]. The precipitates were detected via high-angle annular dark-field imaging, energy spectrum analysis, high-resolution TEM (HRTEM), and inverse fast Fourier transform (IFFT), as illustrated in Figure 1(c₁)–(c₃). The results revealed a substantial enrichment of carbon and vanadium in the precipitated phase (Figure 1(c₁)). The HRTEM image displayed interference fringes of the precipitated phase, which indicated the presence of internal defects. Through two-dimensional Fourier transform analysis, the phase was identified as

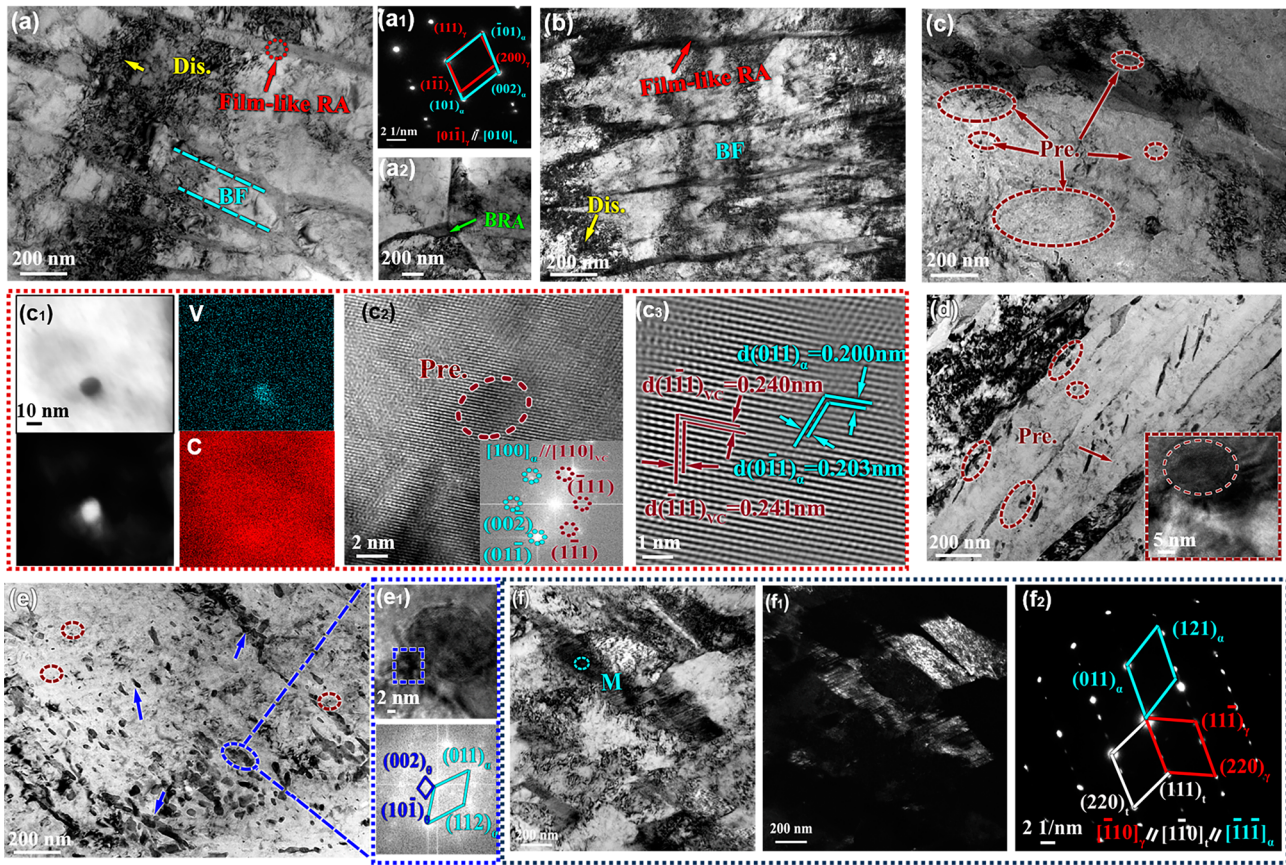


Figure 1. TEM microstructure diagram: (a) untempered sample, (a₁) corresponding selected-area electron diffraction, (a₂) TEM image of BRA, (b) S-350, (c) S-400, (c₁) bright-field diagram, dark-field diagram, elemental energy spectrum analysis of the precipitated phase, (c₂) HRTEM diagram of the precipitated phase, (c₃) the corresponding IFFT diagram of the precipitated phase in the (c₂) diagram, (d) S-450, (e) S-500, (e₁) HRTEM image of cementite and its corresponding IFFT image, (f) bright-field phase of martensite, (f₁) dark-field phase of martensite, and (f₂) corresponding selected-area electron diffraction. Note: dis., Pre., BF, and BRA represent dislocations, nano-scale carbide precipitation, bainitic ferrite laths, and blocky retained austenite, respectively.

VC, with an orientation relationship with the matrix of $[100]_{\alpha} // [110]_{VC}$ (Figure 1(c₂)). In addition, the crystal plane spacing of $(011)_{\alpha}$ and $\begin{pmatrix} 0 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}_{\alpha}$ was approximately 0.200 and 0.203 nm, respectively, while the crystal plane spacing of nano-scale VC corresponding to $\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}_{VC}$ and $\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}_{VC}$ planes was approximately 0.241 and 0.240 nm, respectively (Figure 1(c₃)). The mismatch between VC and the bainitic ferrite matrix was calculated as $2.6 \pm 0.3\%$ using Equation (2) (reference attachment), indicating good coherence. With the rise in tempering temperature, the driving force for element diffusion increased owing to the combined effect of tube diffusion and bulk diffusion. This facilitated the aggregation and nucleation of carbon and alloy elements at precipitated carbides and caused the coarsening of the nano-scale VC. The equivalent diameter of the VC in S-450 was 16 ± 4 nm (Figure 1(d)), while S-500 was coarser at 20 ± 3 nm (Figure 1(e)). However, the increase in the

size of the VC led to increased lattice distortion between the matrix and the precipitated phase, further enhancing the surrounding elastic stress field and increasing interaction with dislocations. In addition, the microstructure of S-500 contained some short rod cementite (indicated by the blue arrow in Figure 1(e)) and twin martensite (Figure 1(f-1f₂)). This is mainly owing to the precipitation of carbides in the microstructure, which significantly reduces the carbon concentration in the retained austenite, lowering its chemical stability. Therefore, during the cooling process after tempering, the retained austenite with low chemical stability enters the martensitic transformation, resulting in the formation of twin martensite.

Figure 2(a) and (b) illustrate the engineering stress-strain curves and related property values of various tempered samples. While the tensile strength (TS) remained stable, the yield strength (YS) decreased as the tempering temperature increased. However, at 400°C, the YS increased to 1086 ± 34 MPa. According to Figure 2(c), with increasing temperature, the total elongation

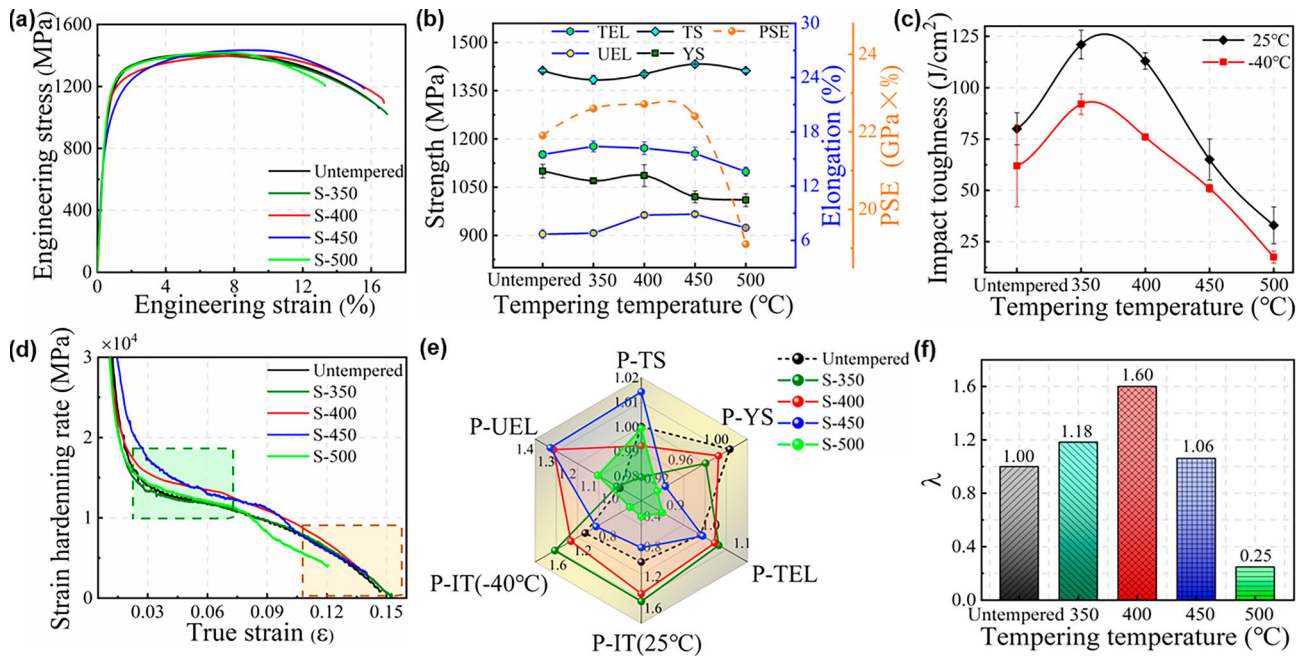


Figure 2. Engineering stress–strain curve (a), corresponding mechanical properties (b), impact toughness change curve (c), and strain hardening curve (d) of the test steel at different tempering temperatures; (e) (color line) comparison of the performances of samples from five dimensions: TS, YS, TEL, UEL, and impact toughness (IT) (25°C and –40°C); (f) corresponding area ratio. Note: P-M represents the proportion of M.

(TEL), uniform elongation (UEL), product of strength and elongation (PSE), and impact toughness of the sample first increased and then decreased, maintaining a high level at 400°C. Compared with untempered sample, S-400 exhibited 4.5%, 31.3%, 3.7%, 41%, and 13% higher TEL, UEL, PSE, room-temperature impact toughness, and low-temperature impact toughness, respectively. The strain hardening rate curves of various samples decreased monotonically with strain (Figure 2(d)). Both S-400 and S-450 exhibited higher work-hardening abilities. To assess the overall performance of bainitic steel, the comprehensive performances of various tempered samples were compared and normalized according to the properties and area of untempered sample (Figure 2(e)–(f)). A comparison of the properties of samples revealed that the outermost layer exhibited the highest mechanical properties, while the inner layers exhibited lower performance (Figure 2(e)). The various characteristics of the same sample were sequentially connected to form a closed graph. The area ratio was used to evaluate the comprehensive mechanical properties of different samples, which were normalized according to the area of untempered sample. The area ratio was defined as the comprehensive performance evaluation coefficient (λ). Figure 2(f) illustrates the variation in the comprehensive performance evaluation coefficient λ with the tempering temperature. A higher λ (the comprehensive

performance evaluation coefficient) value indicates better overall performance for a sample. S-400 exhibited the highest λ value, followed by S-350, while S-500 exhibited the lowest value. These results suggest that introducing the VC with a low-mismatch coherent interface and small size into bainitic steel can significantly improve its overall performance.

Among the samples, S-400 exhibited the most outstanding comprehensive mechanical properties (Figure 2). To further clarify the mechanisms of strength, plasticity, and toughness of steel, the microstructure evolution of various tempered samples was investigated.

Figure 3 displays the inverse pole figures and geometrically necessary dislocation (GND) maps for untempered sample and S-400. As depicted in Figure 3(a) and (b), each bainite packet was divided by a bainite block in the same direction. Compared with the untempered sample ($14.5 \pm 7 \mu\text{m}$), S-400 ($24.9 \pm 13 \mu\text{m}$) exhibited an approximately 10 μm higher block width. In general, the block is the smallest substructure with high angle grain boundaries (misorientation angle $\geq 15^\circ$) in bainite and its width is usually used to describe the effective grain size of bainite [34–37]. During tempering, due to the decrease of grain boundary energy, the grain boundary migration rate increases, resulting in the increase of block size [38]. As depicted in Figure 3(c) and (d), tempering reduced the presence of GNDs and further

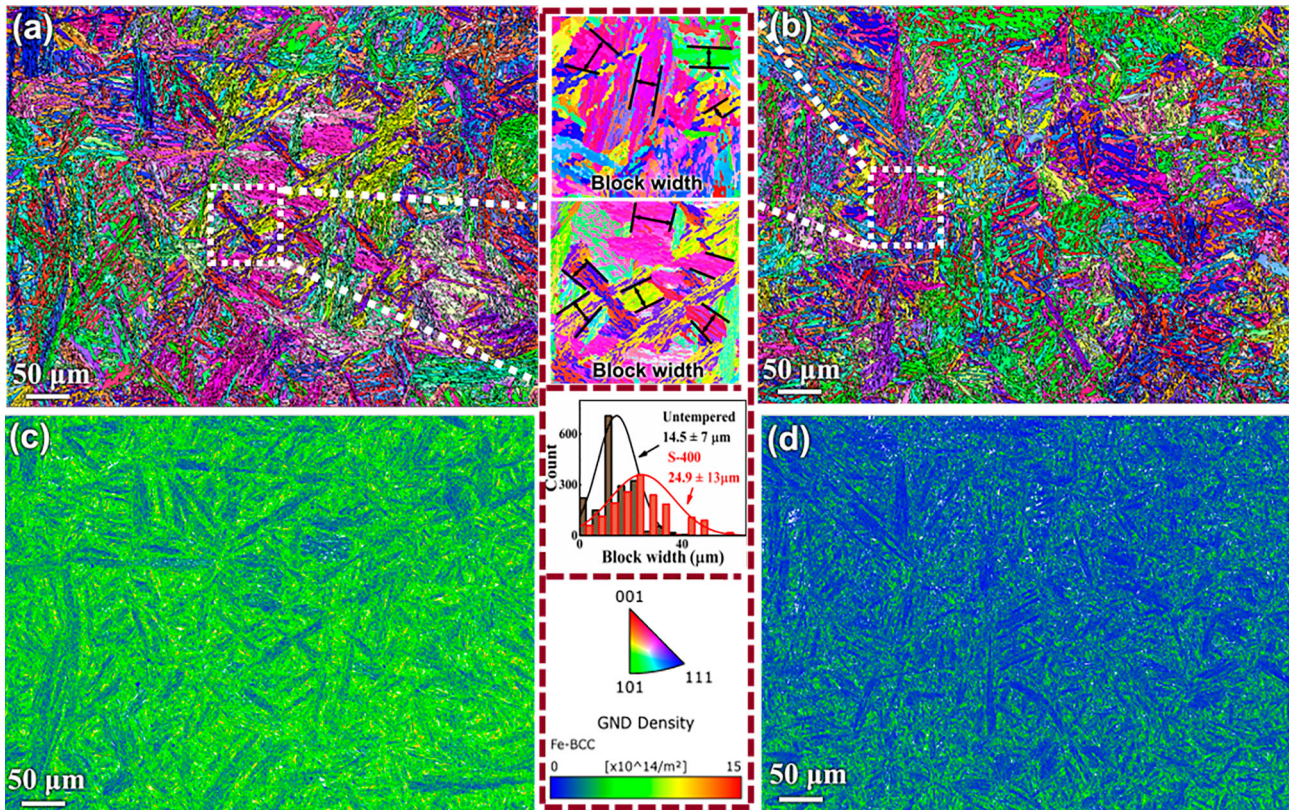


Figure 3. EBSD microstructure of samples: (a) and (b) inverse pole figures; (c) and (d) geometrically necessary dislocation (GND) maps; (a) and (c) untempered sample; (b) and (d) S-400.

alleviated residual stress in the sample steel, which prevented fractures at the precipitate–matrix interface. The bainitic ferrite within the microstructure of ultrafine bainitic steel exists at the nano-scale and is characterized by carbon supersaturation, resulting in significant fine-grain strengthening and solid-solution strengthening. Moreover, bainitic ferrite features a high dislocation density, resulting in a certain dislocation-strengthening effect [4]. This suggests that bainitic steel exhibits substantial strength. According to the classical Hall–Petch equation and the Taylor strengthening equation [39], the strength of bainitic steel progressively reduces with a decrease in dislocation density and the coarsening of grain size. However, S-400 exhibited a higher YS than the untempered sample (Figure 2). Therefore, precipitation-strengthening had a considerable effect on strength. The calculated precipitation strengthening contribution value of S-400 is 92 MPa (the detailed calculation process is shown in the supplementary materials). When the VC phase, which was highly coherent with the matrix, precipitated in the microstructure, the interaction between the coherent interface of the VC phase and the matrix, as well as the dislocation stress field, effectively inhibited dislocation movement, thereby improving the work-hardening effect of the material (Figure 2(a)). This phenomenon

largely compensated for the strength loss of tempered bainitic steel.

During tempering, carbon redistribution resulted in a modification of lattice distortion in bainitic ferrite laths. Generally, changes in the full width at half-maximum (FWHM) of the XRD diffraction peak can be employed to define the lattice strain of the nano-scale phase and the inhomogeneous lattice strain near lattice defects [40]. In the ferrite peak, the low-index crystal plane $(200)_\alpha$ exhibited distinct structural features, strong diffraction intensity, ease of measurement, and high accuracy, making it an effective indicator of changes in carbon content in ferrite. Thus, the $(200)_\alpha$ peak was selected to analyze the effect of tempering temperature on FWHM. Figure 4(a) illustrates the diffraction angle of the $(200)_\alpha$ peak, which notably increased with rising tempering temperature. This trend indicates that the solid solution concentration of carbon in the matrix continuously decreased with an increase in the tempering temperature. The intensity of the diffraction peak was analyzed in detail (Figure 4(b)). As the tempering temperature increased, the FWHM of the $(200)_\alpha$ peak gradually reduced from 1.138° to 0.881° . The microstrain and dislocation density in the matrix followed a similar trend. As tempering temperatures increased, the microstrain and dislocation

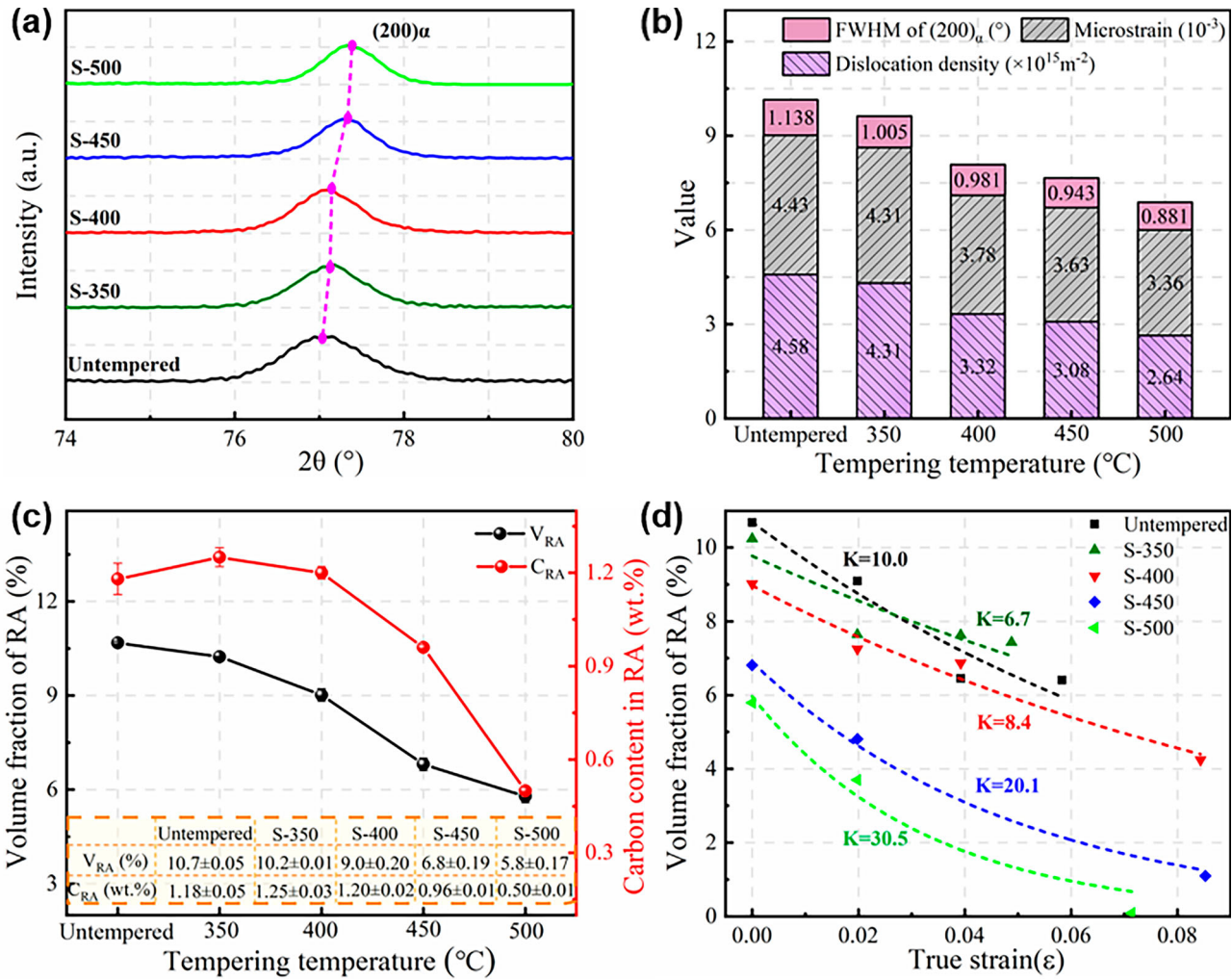


Figure 4. Parameter values in different tempered samples: (a) $(200)\alpha$ peak, (b) FWHM of $(200)\alpha$ peak, dislocation density, and microstrain in the matrix, (c) volume fraction of retained austenite (V_{RA}) and carbon content (C_{RA}), and (d) fitting calculation K value.

density decreased from 4.43×10^{-3} and $4.58 \times 10^{15} \text{m}^{-2}$ to 3.36×10^{-3} and $2.64 \times 10^{15} \text{m}^{-2}$, respectively. The carbon atoms in the interstitial solid solution induced asymmetric lattice distortion ($c/a > 1$) in bainitic ferrite, which led to an uneven stress field. With increasing tempering temperatures, the precipitation of nano-scale VC in bainitic ferrite reduced lattice distortion. Moreover, both microstrain and dislocation density decreased. However, the combined effect of these characteristics achieved the self-toughening of ferrite, enhancing the plasticity and toughness of bainitic steel.

The retained austenite in bainitic steel also had a significant impact on the plasticity and toughness. The volume fraction and carbon content of the retained austenite were calculated using Equations (2)–(4) (reference attachment), and the results are depicted in Figure 4(c). The volume fraction of retained austenite steadily decreased from $10.7 \pm 0.05\%$ in untempered sample to $5.8 \pm 0.17\%$ in S-500. The carbon content of retained

austenite increased from $1.18 \pm 0.05 \text{ wt.}\%$ in untempered sample to $1.25 \pm 0.03 \text{ wt.}\%$ in S-350 before gradually decreasing to $0.5 \pm 0.01 \text{ wt.}\%$ in S-500. This change was mainly associated with the diffusion of carbon atoms, phase transformation, and the precipitation of the VC in the structure. The mechanical stability of retained austenite (K) was assessed using Equation (5) (reference attachment), and is illustrated in Figure 4(d). Generally, the greater the K value, the lower the stability of retained austenite. According to the fitting curve, as tempering temperatures increased, the stability of retained austenite initially increased and then decreased. The retained austenite in S-400 was highly stable. In the later stage of deformation, the transformation-induced plasticity (TRIP) effect persisted over a broader strain range, which promoted ongoing work-hardening and delayed the onset of necking (Figure 2(c)). This further improved the plasticity and toughness of the S-400. Notably, when the tempering temperature reached 450°C or higher,

the stability of retained austenite significantly decreased, causing some of the austenite to decompose into cementite (Figure 1(e)). This decomposition resulted in stress concentration at the phase interface, which could easily lead to crack initiation, thereby reducing plasticity and toughness.

According to the previous analysis, the dislocation density in the microstructure was reduced (Figure 4(a) and (b)) during tempering. Similarly, the VC is precipitated in the supersaturated bainitic ferrite, reducing the lattice distortion of ferrite, thus progressively softening the bainitic ferrite. This indicates that during plastic deformation, greater stress was transmitted to the retained austenite, resulting in the TRIP effect. The combined effect of these three makes the material maintain high plasticity and toughness. Meanwhile, small-scale precipitates could effectively alleviate the microscopic elastic strain around the strengthening phase and reduce elastic interaction with dislocations [24], enhancing the ability of the material to undergo uniform plastic deformation. Consequently, the introduction of the VC, with high coherence with the matrix and small size, into the microstructure at a lower tempering temperature further enhanced the comprehensive mechanical properties of the bainitic steel. In addition, the interaction between the stress field formed by the mismatch strain between the precipitated phase and the matrix and the elastic stress field generated by dislocations impeded dislocation movement [4]. Moreover, the finer precipitated phase was intersected by dislocations, which led to a stronger precipitation-strengthening effect [24]. Therefore, the strength loss of tempered bainitic steel was somewhat compensated. In addition, small-scale precipitates could effectively alleviate the microscopic elastic strain around the strengthening phase and reduce elastic interaction with dislocations [24], enhancing the ability of the material to undergo uniform plastic deformation. Consequently, the introduction of the VC, with high coherence with the matrix and small size, into the microstructure at a lower tempering temperature further enhanced the comprehensive mechanical properties of the bainitic steel.

4. Conclusion

In summary, this research introduced the nano-scale VC phase, highly coherent with the matrix, into the ultrafine bainitic steel to leverage its precipitation-strengthening effect. Moreover, the precipitation of VC reduced lattice distortion, contributing to the self-toughening of ferrite. Moreover, the enhanced stability of retained austenite increased the samples' resistance to plastic deformation.

The combined effect of these factors significantly optimized the mechanical properties, achieving outstanding strength, plasticity, and toughness. This paves the way for the development of high-performance bainitic steel, offering a new direction for advancements in the field.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by National Key R & D Program Young Scientists Project [grant number 2021YFB3703500], the National Natural Science Foundation of China [grant numbers 52122410, 52374406], and the Hebei Natural Science Foundation [grant number E2023203259].

Date availability

Date will be made available on request.

References

- [1] Kumar A, Blessto B, Singh A. Development of a low-carbon carbide-free nanostructured bainitic steel with extremely high strength and toughness. *Mater Sci Eng A*. 2023;877:145186.
- [2] Rezende AB, Fonseca ST, Fernandes FM, et al. Wear behavior of bainitic and pearlitic microstructures from microalloyed railway wheel steel. *Wear*. 2020;456-457: 203377.
- [3] Liu C, Sun D, Chen C, et al. Constructing multi-scale retained austenite makes bainitic steel better-mechanical properties by introducing weak chemical heterogeneity. *Mater Res Lett*. 2024;12(9):653-660. doi:10.1080/21663831.2024.2366875
- [4] Xiong Z, Timokhina I, Pereloma E. Clustering, nano-scale precipitation and strengthening of steels. *Prog Mater Sci*. 2021;118:100764. doi:10.1016/j.pmatsci.2020.100764
- [5] Hasan SM, Ghosh M, Chakrabarti D, et al. Development of continuously cooled low-carbon, low-alloy, high strength carbide-free bainitic rail steels. *Mater Sci Eng A*. 2020;771:138590.
- [6] Sun X, Wang Y, Sun D, et al. Microstructure and mechanical properties of Si-rich H13 steel processed via austempering and tempering. *Mater Sci Eng A*. 2022;834:142616.
- [7] Wang B, Zhou L, Cao Y, et al. Analysis of residual stress relief for Ti62A alloy welded joints by post weld heat treatment considering creep effect. *J Mater Res Technol*. 2023;24:7462-7474. doi:10.1016/j.jmrt.2023.05.057
- [8] Li Y, Yuan G, Li L, et al. Ductile 2-GPa steels with hierarchical substructure. *Science*. 2023;379(6628):168-173. doi:10.1126/science.add7857
- [9] Hu J, Li X, Meng Q, et al. Tailoring retained austenite and mechanical property improvement in Al-Si-V containing medium Mn steel via direct intercritical rolling. *Mater Sci Eng A*. 2022;855:143904.
- [10] Pereloma E, Timokhina I. Clustering and precipitation in ferritic microalloyed steels. *Encyclop Mater Metals Alloys*. 2022;2:12-25. doi:10.1016/B978-0-12-819726-4.00027-2

- [11] Wang J, Li H, Wang Q, et al. Effect of rapid tempering at high temperature on microstructure, mechanical properties and stability of retained austenite of medium carbon ultrafine bainitic steel. *J Mater Res Technol.* **2024**;28:3144–3154. doi:[10.1016/j.jmrt.2023.12.238](https://doi.org/10.1016/j.jmrt.2023.12.238)
- [12] Hasan HS, Peet MJ, Avettand-Fènoël M-N, et al. Effect of tempering upon the tensile properties of a nanostructured bainitic steel. *Mater Sci Eng A.* **2014**;615:340–347. doi:[10.1016/j.msea.2014.07.097](https://doi.org/10.1016/j.msea.2014.07.097)
- [13] Wang X, Zhang X, Fang Q, et al. Effect of tempering on stability of retained austenite and tensile properties of nanostructured bainitic steel. *Mater Sci Eng A.* **2022**;856:143958.
- [14] Liu X, Han Y, Wei J, et al. Effect of tempering temperature on microstructure and mechanical properties of a low carbon bainitic steel treated by quenching-partitioning-tempering (QPT) process. *J Mater Res Technol.* **2023**;23:911–918. doi:[10.1016/j.jmrt.2023.01.061](https://doi.org/10.1016/j.jmrt.2023.01.061)
- [15] Zhang X, Miyamoto G, Toji Y, et al. Role of cementite and retained austenite on austenite reversion from martensite and bainite in Fe-2Mn-1.5Si-0.3C alloy. *Acta Mater.* **2021**;209:116772.
- [16] Zou Y, Xu YB, Hu ZP, et al. Austenite stability and its effect on the toughness of a high strength ultra-low carbon medium manganese steel plate. *Mater Sci Eng A.* **2016**;675:153–163. doi:[10.1016/j.msea.2016.07.104](https://doi.org/10.1016/j.msea.2016.07.104)
- [17] Zhou Q, Qian L, Tan J, et al. Inconsistent effects of mechanical stability of retained austenite on ductility and toughness of transformation-induced plasticity steels. *Mater Sci Eng A.* **2013**;578:370–376. doi:[10.1016/j.msea.2013.04.096](https://doi.org/10.1016/j.msea.2013.04.096)
- [18] Avishan B, Yazdani S, Hossein Nedjad S. Toughness variations in nanostructured bainitic steels. *Mater Sci Eng A.* **2012**;548:106–111. doi:[10.1016/j.msea.2012.03.098](https://doi.org/10.1016/j.msea.2012.03.098)
- [19] Zorgani M, Garcia-Mateo C, Jahazi M. Microstructural evolution during tempering of an ausformed carbide-free low temperature bainitic steel. *Mater Des.* **2021**;210:110082.
- [20] Jia C, Liu Y, Liu C, et al. Precipitates evolution during tempering of 9CrMoCoB (CB2) ferritic heat-resistant steel. *Mater Charact.* **2019**;152:12–20. doi:[10.1016/j.matchar.2019.04.006](https://doi.org/10.1016/j.matchar.2019.04.006)
- [21] Li W, Cai M, Wang D, et al. Studying on tempering transformation and internal friction for low carbon bainitic steel. *Mater Sci Eng A.* **2017**;679:410–416. doi:[10.1016/j.msea.2016.10.053](https://doi.org/10.1016/j.msea.2016.10.053)
- [22] Jiang Z, Li Y, Yang Z, et al. The tempering behavior of martensite/austenite islands on the mechanical properties of a low alloy Mn-Ni-Mo steel with granular bainite. *Mater Today Commun.* **2021**;26:102166.
- [23] Liu F, Chen K, Kang C, et al. Effects of V–Nb microalloying on the microstructure and properties of spring steel under different quenching-tempering times. *J Mater Res Technol.* **2022**;19:779–793. doi:[10.1016/j.jmrt.2022.05.043](https://doi.org/10.1016/j.jmrt.2022.05.043)
- [24] Jiang S, Wang H, Wu Y, et al. Ultrastrong steel via minimal lattice misfit and high-density nanoprecipitation. *Nature.* **2017**;544(7651):460–464. doi:[10.1038/nature22032](https://doi.org/10.1038/nature22032)
- [25] Xiaojie Z, Zhinan Y, Fucheng Z, et al. Acceleration of bainitic transformation by introducing AlN in medium carbon steel. *Mater Sci Technol.* **2019**;35:147–154. doi:[10.1080/02670836.2018.1543107](https://doi.org/10.1080/02670836.2018.1543107)
- [26] Yoo CHLM, Chan JW, Yoo CH, et al. M2 C precipitates in isothermal tempering of high Co-Ni secondary hardening steel. *Metall Mater Trans.* **1996**;27A:3466.
- [27] Siwecki T, Eliasson J, Lagneborg R, et al. Vanadium microalloyed bainitic hot strip steels. *ISIJ Int.* **2010**;50(5):760–767. doi:[10.2355/isijinternational.50.760](https://doi.org/10.2355/isijinternational.50.760)
- [28] Wang Z, Hui W, Chen Z, et al. Effect of vanadium on microstructure and mechanical properties of bainitic forging steel. *Mater Sci Eng A.* **2020**;771:138653.
- [29] Xie ZJ, Han G, Zhou WH, et al. Study of retained austenite and nano-scale precipitation and their effects on properties of a low alloyed multi-phase steel by the two-step intercritical treatment. *Mater Charact.* **2016**;113:60–66. doi:[10.1016/j.matchar.2016.01.009](https://doi.org/10.1016/j.matchar.2016.01.009)
- [30] Sun J, Wei S, Lu S. Influence of vanadium content on the precipitation evolution and mechanical properties of high-strength Fe–Cr–Ni–Mo weld metal. *Mater Sci Eng A.* **2020**;772:138739.
- [31] Wang X, Li Z, Zhou S, et al. Precipitation behavior of Ti–Nb–V–Mo quaternary microalloyed high strength fire-resistant steel and its influence on mechanical properties. *Mater Sci Eng A.* **2021**;807:140865.
- [32] Hashemi SG, Eghbali B. Analysis of the formation conditions and characteristics of interphase and random vanadium precipitation in a low-carbon steel during isothermal heat treatment. *Int J Miner Metall Mater.* **2018**;25:339–349. doi:[10.1007/s12613-018-1577-8](https://doi.org/10.1007/s12613-018-1577-8)
- [33] Liang Z, Wang J, Li H, et al. Microstructure evolution of V-containing low carbon ultra-fine bainitic steel during medium-temperature tempering and strengthening-toughening mechanism. *Mater Sci Eng A.* **2024**;901:146566. doi:[10.1016/j.msea.2024.146566](https://doi.org/10.1016/j.msea.2024.146566)
- [34] Chen H, Zeng T, Shi Q, et al. Microstructure evolution and mechanical properties during long-term tempering of a low carbon martensitic stainless bearing steel. *J Mater Res Technol.* **2023**;25:297–309. doi:[10.1016/j.jmrt.2023.05.239](https://doi.org/10.1016/j.jmrt.2023.05.239)
- [35] Wei X, Zhang Z. Achieving superior low-temperature toughness in highstrength low-carbon steel via controlling lath boundary segregation. *J Mater Res Technol.* **2023**;24:1524–1536. doi:[10.1016/j.jmrt.2023.03.110](https://doi.org/10.1016/j.jmrt.2023.03.110)
- [36] Luo H, Wang X, Liu Z, et al. Influence of refined hierarchical martensitic microstructures on yield strength and impact toughness of ultra-high strength stainless steel. *Mater Sci Technol.* **2020**;51:130–136. doi:[10.1016/j.jmst.2020.04.001](https://doi.org/10.1016/j.jmst.2020.04.001)
- [37] Shibata A, Nagoshi T, Sone M, et al. Evaluation of the block boundary and sub-block boundary strengths of ferrous lath martensite using a micro-bending test. *Mater Sci Eng A.* **2010**;527(29–30):7538–7544. doi:[10.1016/j.msea.2010.08.026](https://doi.org/10.1016/j.msea.2010.08.026)
- [38] Tsuchiyama T, Natori M, Nakada N, et al. Conditions for grain boundary bulging during tempering of lath martensite in ultra-low carbon steel. *ISIJ Int.* **2010**;50(5):771–773. doi:[10.2355/isijinternational.50.771](https://doi.org/10.2355/isijinternational.50.771)
- [39] Taylor GI. The mechanism of plastic deformation of crystals. *Proc Royal Soc London.* **1934**;145(855):362–387.
- [40] De AK, Murdock DC, Mataya MC, et al. Quantitative measurement of deformation-induced martensite in 304 stainless steel by X-ray diffraction. *Scr Mater.* **2004**;50(12):1445–1449. doi:[10.1016/j.scriptamat.2004.03.011](https://doi.org/10.1016/j.scriptamat.2004.03.011)