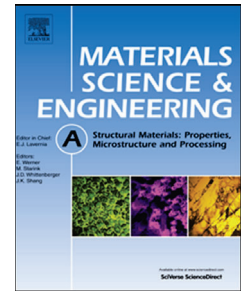


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Phase Transformation Testing and Modeling for Hot Stamping of Boron Steel Considering the Effect of the Prior Austenite Deformation

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Abstract:

Hot stamping of boron steels is a thermal-mechanical and phase transformation coupled process. The phase transformation of boron steels during continuous cooling is a complex process since the phase transformation is tightly coupled with plastic deformation during the hot stamping process. In the present work, the effects of hot deformation amount, deformation temperature, and strain rate on phase transformation are investigated by using a comprehensive set of methods including in-situ isothermal tensile tests combined with dilatometry and ex-situ microstructure characterization. The dilatation curves, phase fraction evolution curves, continuous cooling transformation (CCT), and deformed continuous cooling transformation (DCCT) diagrams are constructed. Finally, based on the testing results, a new non-isothermal kinetic model of phase transformation are proposed to introduce the effect of the austenite deformation on transformation during the continuous cooling. The proposed model is validated by testing Vickers hardness of DCCT specimens and hot stamping W-channel parts. The results demonstrate that the deformation accelerates the diffusive phase transformation, causing the CCT curves to move in the direction of shorter incubation time. But the acceleration of diffusion transformation is rapidly saturated as the plastic strain increases. Lower deformation temperature and

higher strain rate are more favorable to the diffusion phase transformation, and the higher the critical cooling rate of the martensite transformation is needed. The proposed kinetic model not only accurately predicts the final phase fraction and hardness of the DCCT specimen, but also the distribution of mechanical properties of the hot stamping W-channel parts.

Key words: Hot stamping; Phase transformation; Boron steel; Thermomechanical processes; Mechanical properties

1. Introduction

Hot stamping is currently one of the most effective methods to produce ultra-high strength automotive parts to meet increasing requirements for weight reduction and passenger safety[1-3]. During hot stamping, boron steel is austenitized at about 900°C, stamped into a target shape in an austenite state, and then quenched by water cooling die to achieve phase transformation strengthening. The method of die quenching allows steels to achieve a strength greater than 1500 MPa while ensuring high dimensional accuracy [4, 5]. The target strength of final product is assured by a sufficiently high cooling rate above a critical value to make austenite completely transform into high strength martensite, eliminating diffusive transformation, such as ferritic or bainitic transformation.

The hot stamping of Boron steel is a complex process which involves the prior plastic deformation followed by a continuous cooling transformation. The phase transformation during press hardening is affected by many factors, including material content, tool/blank interfacial contact, tool design, etc. [6-8], two factors among which are deserved to be emphasized, one is the pre-deformation just ahead of die quenching, especially at the corner and side wall of the hot stamped part [9], the other is the continuous cooling path during die quenching. In the past ten years, some research has been carried out to study the phase transformation during hot stamping process, in the aspects of experimental methods, kinetic models and property prediction.

In the aspect of experimental methods, isothermal cooling rather than continuous cooling path is commonly adopted for kinetic modeling of phase transformation in practical press hardening due to the difficulty in modeling directly based on CCT curve. Scheil's principle and additivity rule [10] have been frequently applied for the conversion procedure from isothermal to non-isothermal kinetics to consider the incubation period during cooling. However, it has been reported that the non-isothermal kinetics conversing by additivity rule was not appropriate to capture transformation behavior of certain steels under various cooling rates [11]. So the kinetic modeling of phase transformation based on CCT curves is still of urgent demand.

A deformation dilatometer and Gleeble thermal simulator system was used to reproduce the non-isothermal deformation and phase transformation of the boron steel under continuous cooling conditions[12-15]. The isothermal compressive or tensile tests at different deformation temperatures and strain rates were carried out ahead of quenching to study the effect of pre-deformation on both diffusive transformation and martensitic transformation[16-19]. Their results all show that the plastic deformation of austenite can promote the formation of soft phase and accelerate the process of diffusive transformation, and a higher critical cooling rate is necessary for the complete transformation from austenite into martensite, which necessitates the quantitative description on phase transformation kinetics considering pre-deformation.

The kinetic model of phase transformation is critical to the prediction of mechanical properties for the hot stamped parts[20]. There has been a long history of study on kinetic model of phase transformation, and some classical phase transformation models have been proposed (e.g., Johnson and Mehl [21]; Avrami [22, 23]; Kolmogorov (JMAK model) [24]; Kirkaldy and Venugopalan (K-V model) [25]; Victor Li (Li model) [26]; Åkerström and Oldenburg (A-O model) [27]). Behrens and Olle [28] applied the JMAK model to the prediction of diffusive transformation in hot stamping process earlier, and realized the thermo-mechanical-metallurgical coupled simulation. Bok et al.[29] compared the accuracy of K-V, Li and A-O models in predicting the microstructure evolution of hot stamping parts of boron steel, and

found that there was still a large deviation between the predicted and testing results. To obtain higher prediction accuracy and wider application range of phase transformation model, Hippchen et al.[30] introduced a retardation coefficient for each phase and extended the model parameter to a cooling rate dependency. Some other scholars[31,32] have also modified the K-V model. The idea of the modification is to introduce more model parameters to improve the prediction accuracy.

In spite of these great efforts in prediction accuracy improvement on phase transformation of boron steel, there is still a lack of simple and reliable models to predict the phase transformation behavior of pre-deformed austenite. To introduce deformation effect into the traditional kinetic model of phase transformation, some scholars have made different attempts. Serajzadeh [33] established the relationship between plastic deformation and incubation time, that is, incubation time is proportional with $(1-\epsilon)^2$. Based on this proportional relationship, the traditional JMAK model was modified by introducing deformation effect. This kinetic model of phase transformation was also numerically implemented by Åkerström et al. [34] and integrated into the MAT_244 material card of LS-DYNA. Bok et al. [35] modified the K-V model from the microscopic mechanism of plastic deformation promoting diffusive transformation. The relationship between grain size, dislocation density, and recrystallization volume fraction was established. The grain size was used as an intermediate variable to introduce the effect of deformation on phase transformation. However, Bok's model contains a large number of parameters for describing the evolution of dislocation density and recrystallization, which is difficult to test and identify. Bambach et al. [2] and Hart-Rawung et al.[36] introduced strain-dependent activation energy to modify the kinetic model of phase transformation. But only the effect of the strain on phase transformation under the deformation temperature of 700 °C and cooling rate of 31.5 °C/s was tested. The activation energy is only a piecewise linear function of strain. Similarly, Omer et al. [37] used hardness as the evaluation index to optimize the activation energy parameters of the kinetic model at the strain of 20%. The linear interpolation method was then used to calculate the activation energy for any engineering strain ranges from 0% to 20%. The influence of

deformation temperature and strain rate on phase transformation was not considered in the above model. Therefore, whether it is suitable for all deformation and cooling conditions remains to be verified.

In this paper, the more accurate CCT (continuous cooling transformation) and DCCT (Deformed continuous cooling transformation) experiments covering a wider range of hot stamping process conditions have been performed on a Gleeble system. The influences of plastic strain, deformation temperature, and strain rate on phase transformation are studied by combining dilation test with microstructure observation. Then a new non-isothermal kinetic model of phase transformation is established, and the effect of the strain, strain rate and deformation temperature are introduced into the proposed phase transformation model through the concept of virtual cooling rate. The phase fraction and Vickers hardness of CCT and DCCT specimens are predicted by using the proposed model and compared with the experimental results. Finally, the proposed model is applied to hot stamping of the W-channel part for the prediction of the microstructure and mechanical properties.

2. Experiments and data analysis

2.1 Materials and testing method

The regular bare sheet of B1500HS with a thickness of 1.4 mm is used in this study. The chemical composition is given in Table 1. The microstructure of the as-received steel is 78% ferrite and 22% pearlite.

Table 1 Chemical composition of B1500HS boron steel in wt%

Value	C	Si	Mn	P	S	Al	Ti	B	Cr+Mo+Nb
Reference	0.2-0.25	≤0.5	1.0-1.5	≤0.025	≤0.010	0.01-0.06	≤0.05	≤0.005	≤0.5
Test	0.23	0.25	1.35	0.015	0.006	0.03	0.04	0.003	0.19+0.04+0.00

To study the phase transformation of boron steel under hot stamping conditions, the tests have been carried out in a Gleeble 3500 thermomechanical simulation testing

machine for its excellent ability of controlling the temperature and deformation. The volume fraction of phase transformation is monitored by a dilatometer with the width change of specimen due to thermal and transformational dilation from austenite to ferrite, pearlite, bainite or martensite. Once the material undergoes an austenite decomposition, the turning points appear on the dilation curves, which makes it applicable of dilatometry in phase amount calculation.

The schematic and the equipment of the testing system are shown in Fig. 1. In this paper, phase transformation observation on CCT and DCCT processes is carried out based on this system respectively.

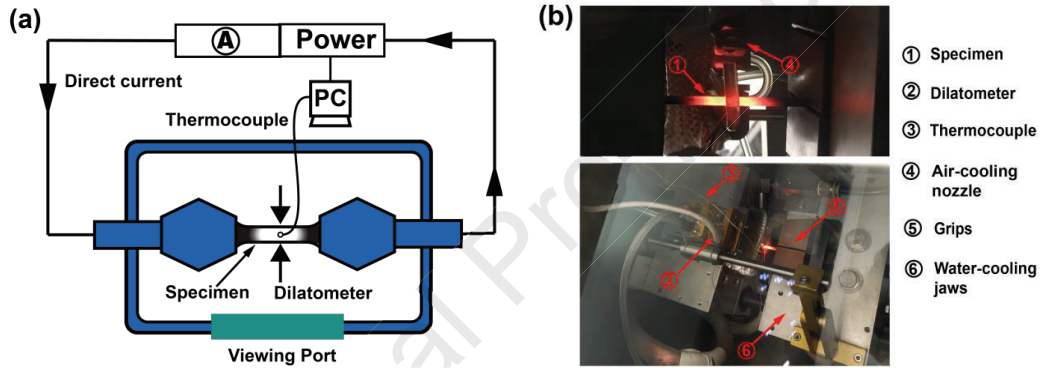


Fig. 1. Phase transformation testing system. (a) schematic diagram and (b) testing device.

2.2 Testing program

2.2.1 Thermal and mechanical cycles design

The thermal and mechanical cycles are designed in two manners of CCT and DCCT respectively for the purpose of simulating the real hot stamping process. For CCT manner, as shown in Fig. 2(a), the specimens are heated at a speed of 10°C/s to the austenitization temperature of 900°C , soaked for 5 min, and then cooled under different rates from 0.5 to 50°C/s . The high-capacity argon cooling system is used to realize the rapid cooling process.

In current experiment, DCCT manner is adopted to study the effect of prior deformation on phase transformation, which is a key issue for process optimization and mechanical property evaluation of hot stamping. A set of appropriate thermal cycles are designed as shown in Fig. 2(b) to ensure that the prior deformation be

implemented in the austenitic state. The specimens are heated to 900 °C and soaked for 5 min, then cooled to different deformation temperatures (650°C, 725°C and 800°C) with a cooling rate of 75 °C/s, followed by tensile deformation up to different strokes of 2, 4 and 6 mm, and at different velocity of 2, 20 and 200 mm/s respectively. To study the transformation kinetics, the aforementioned deformed specimens are continuously cooled to room temperature with various rates between 20°C/s and 75°C /s. The dilation curves are recorded to obtain the phase transformation information.

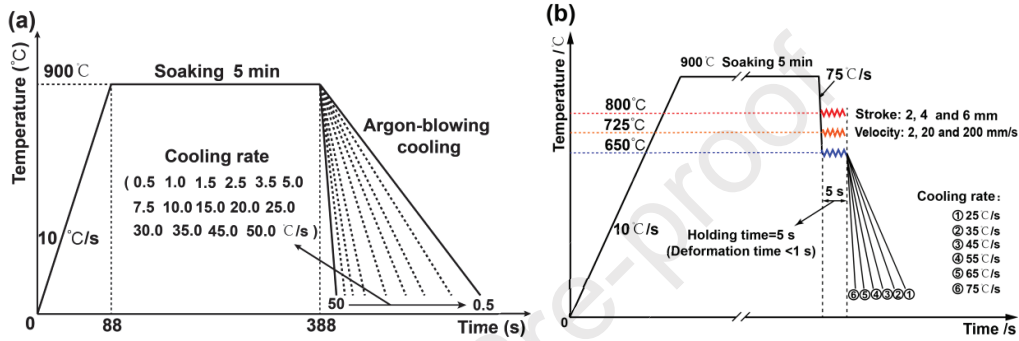


Fig. 2 The thermal and mechanical cycles for (a) CCT and (b) DCCT testing.

2.2.2 Testing specimens design

For traditional strip specimens, there is always a temperature gradient across the width direction, which results in a measurement error in phase transformation due to the non-isothermal distribution induced non-uniform dilation. Therefore, a double-slot specimen as shown in Fig. 3(a) is designed for static CCT to attain an isothermal distribution in the plane of specimen.

The geometry of the tensile specimens for DCCT is illustrated in Fig. 3(b), which has a longer gauge length than that for CCT to measure the effect of deformation on transformation. The C-shaped contact dilatometer is used to measure the width changes of the specimen, so as to calculate the phase amount indirectly. The clamping position of the dilatometer is kept in a straight line with the welding point of the thermocouple to ensure the coincidence between the sections of temperature and dilation measurement.

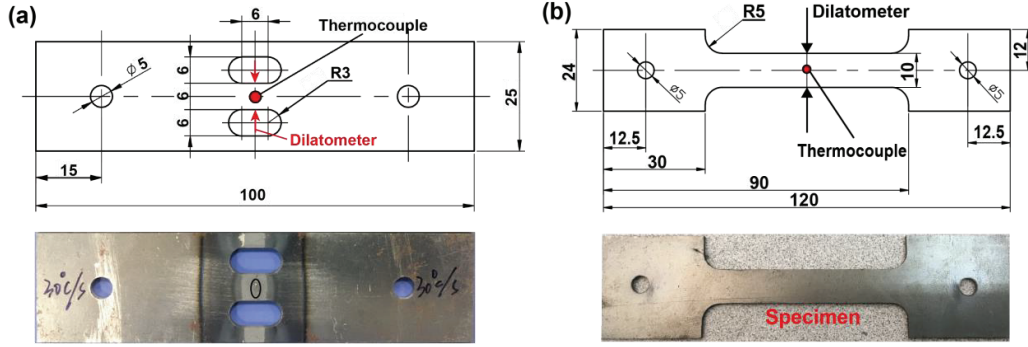


Fig. 3 Specimen geometry for (a) CCT and (b) DCCT testing.

2.3 Strain analysis of prior deformation

Commonly, the longitudinal strain within the gauge is thought to be uniform and quantified by the average strain based on tension stroke. However, the non-uniform deformation induced by the temperature gradient along gauge length exists inevitably in Gleeble system. Therefore, it makes no sense to quantify the local strain at certain point with this average longitudinal strain based on tension stroke. That's why we adopt the width change measured by dilatometer to calculate the local longitudinal strain indirectly, as shown in Fig. 4. The engineering strain in the width direction is written as

$$\varepsilon_{yE} = \frac{w - w_0}{w_0} \quad (1)$$

According to incompressibility of materials, the longitudinal true strain and stress of the clamping section can be expressed as

$$\varepsilon_x = -2\varepsilon_y = -2\ln(1 + \varepsilon_{yE}) = -2\ln\left(\frac{w}{w_0}\right) \quad (2)$$

$$\sigma_x = \frac{F}{t_0 w_0} \exp(\varepsilon_x) \quad (3)$$

where ε_{yE} is the engineering strain in y-direction. ε_x and ε_y are the true strain in x- and y-direction respectively. σ_x is the true stress in x-direction. w_0 and t_0 represent the initial width and thickness, while w is the width after deformation. F is the tensile force applied by the jaws of Gleeble.

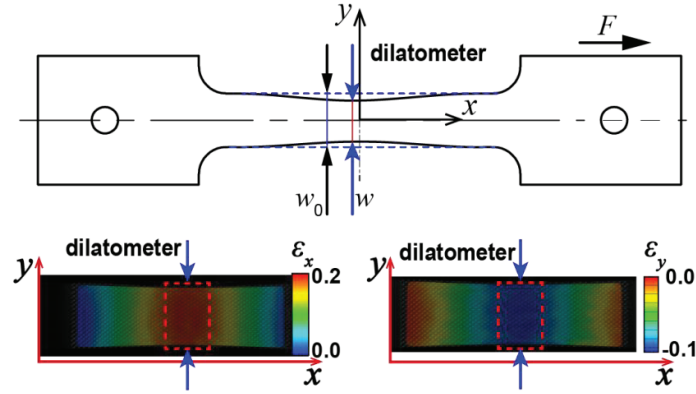


Fig. 4. Schematic diagram of strain calculating with the width variation.

The stress-strain curves under different deformation conditions, including deformation temperatures, strain rates and tension strokes, can be illustrated based on experimental data processing with Eq.(1) to Eq.(3), as shown in Fig. 5. After pre-deformation up to a certain tension stroke, the specimens are unloaded and then cooled at different cooling rates to simulate the phase transformation process, which are recorded by the system and shown as a significant decreasing trends in Fig. 5.

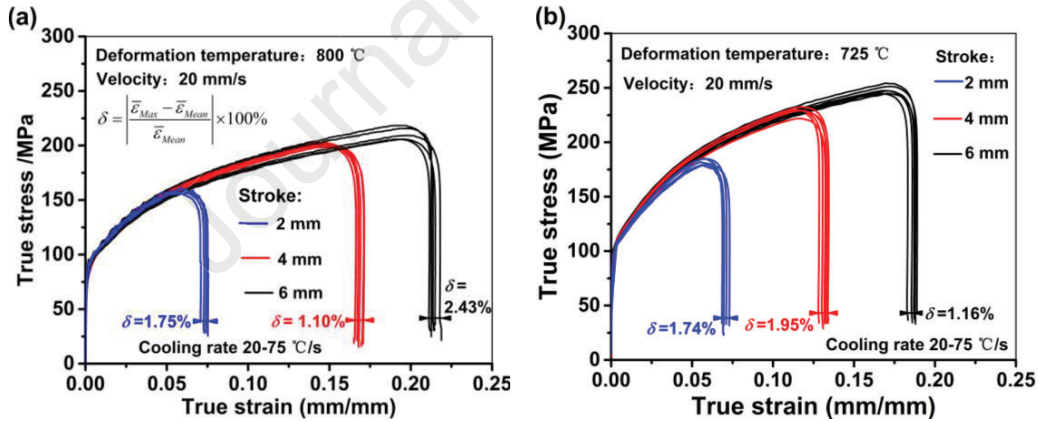


Fig. 5. The stress-strain curves based on dilatometer and Gleeble system.

There is indeed a data scatter in the maximum strain even for the same stroke. This data scatter can be attributed to the systematically errors of Gleeble induced by the deformation heterogeneity in gauge length, such as inconsistent clamping positions of dilatometers and welding points of thermocouples, uneven heat conduction of grip jaws, etc. To reduce the dispersion of the pre-strain, a large number of experimental tests are repeated to control the deformation within a small deviation range. The uniaxial tensile stress-strain curves obtained after the optimization

experiment are shown in Fig. 5. The deviation of the maximum strain at each tension stroke is less than 3%. The average maximum strain corresponding to each tension stroke is used to indicate the exact value of pre-deformation.

2.4 Phase transformation calculation based on dilatometric results

The applicability of dilatometry in quantitative evaluation on phase transformation is due to the change in the specific volume before and after the phase transformation. Austenite is face-centered cubic (FCC) in structure, which has a smaller specific volume as compared to the body-centered structure of product phase. Once the material undergoes an austenite decomposition, the nonlinear dilation appears on the dilation curves, which breaks the linear relation between dilation and temperature for pure cold contraction. The turning points on the dilation curve indicate the starting and finishing temperatures of the phase transformation. Fig. 6 shows the dilatometric curves of B1500HS specimens measured during continuous cooling from 900 °C to room temperature at rates of 0.5-30°C/s, which correspond to the different types and degrees of phase transformation, including diffusive and martensitic transformation.

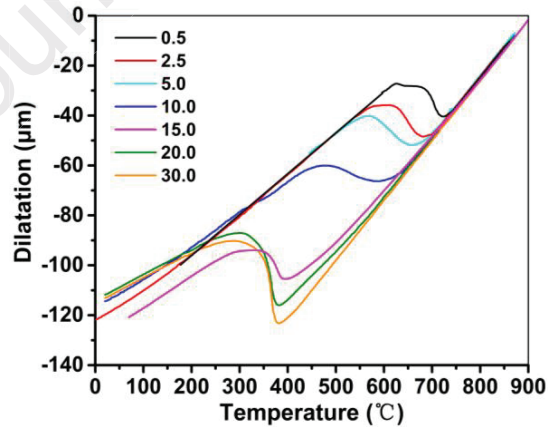


Fig. 6. Dilatation curves of CCT specimens at different cooling rates.

The dilation occurring at high temperatures over 600°C during slow cooling at rates of 0.5~5°C/s is attributed to ferritic and pearlitic transformations. The dilation at medium temperatures between 450°C and 600°C, at rates of 5~20°C/s is probably related to pearlitic and bainitic transformations. The dilation at low temperatures

below 400 °C and at rates of 25~50 °C/s may be attributed to a martensitic transformation.

To evaluate the volume fraction of constituent phases during austenite decomposition, the lever rule is used repeatedly under a specific cooling rate according to the dilation curves. However, the disadvantage of this method is that when the austenite is transformed into more than two product phases, the final volume fraction of each phase cannot be determined accurately. To solve this problem, the final volume fraction of each phase after transformation at a certain cooling rate is determined by the metallographic method. By combining the lever rule with the final volume fraction of each constituent phase, the phase transformation evolution law of the whole transformation process can be obtained. The determination method and process of the phase volume fraction evolution are shown in Fig. 7.

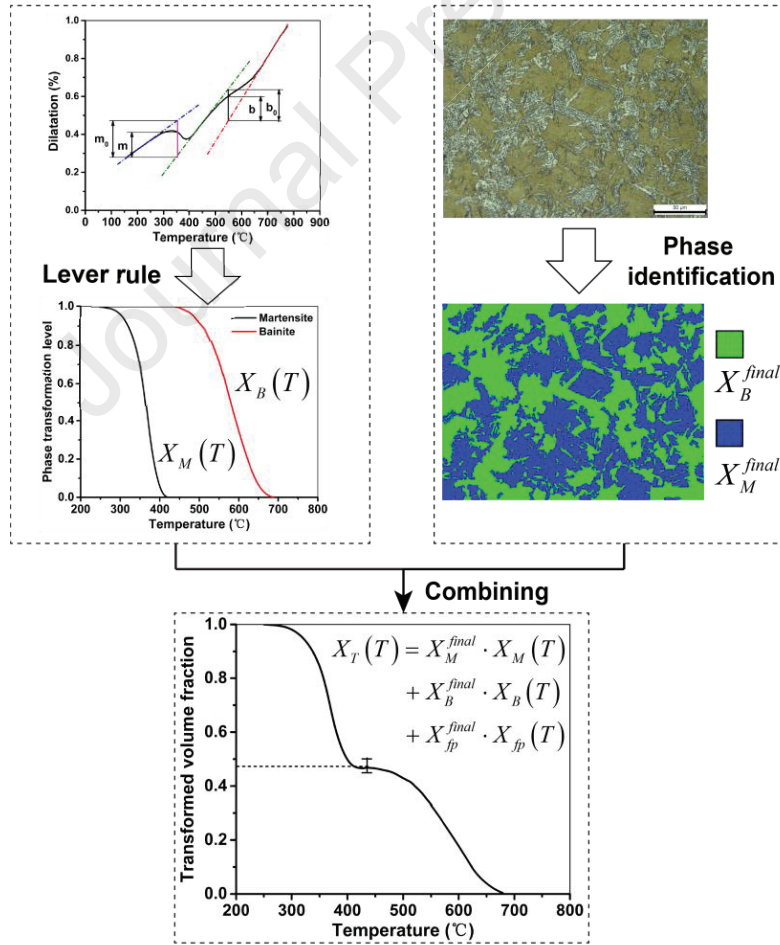


Fig. 7. Determination method of phase volume fraction evolution curve.

2.5 CCT test results

Accurate determination of the final phase volume fraction is important for establishing a kinetic model of phase transformation. The microstructures are measured by optical microscopes after cooling at different rates as shown on the left side of Fig. 8. An advanced algorithm of image processing is adopted to perform phase classification and labeling, and the identification results are shown on the right side of Fig. 8. The final phase volume fractions for the different cooling rates are determined by the proposed methods. The composition of the final phase fraction for each product phase are given in Table 2.

Table 2 Final phase fraction after cooling to room temperature with different cooling rates.

$CR(^{\circ}C/s)$ (cooling rate)	$t_{85}(s)$ (300/CR)	Final phase volume fraction X_i^{final}			
		Ferrite	Pearlite	Bainite	Martensite
0.5	600	0.79	0.21	0.0	0.0
1.0	300	0.75	0.25	0.0	0.0
1.5	200	0.74	0.26	0.0	0.0
2.5	120	0.73	0.27	0.0	0.0
3.0	100	0.70	0.30	0.0	0.0
4.0	75	0.32	0.08	0.6	0.0
5.0	60	0.186	0.01	0.804	0.0
7.5	40	0.078	0.0	0.90	0.022
10	30	0.039	0.0	0.903	0.058
15	20	0.01	0.0	0.49	0.50
20	15	0.0	0.0	0.25	0.75
25	12	0.0	0.0	0.06	0.94
30	10	0.0	0.0	0.0	1.0
40	7.5	0.0	0.0	0.0	1.0
50	6	0.0	0.0	0.0	1.0

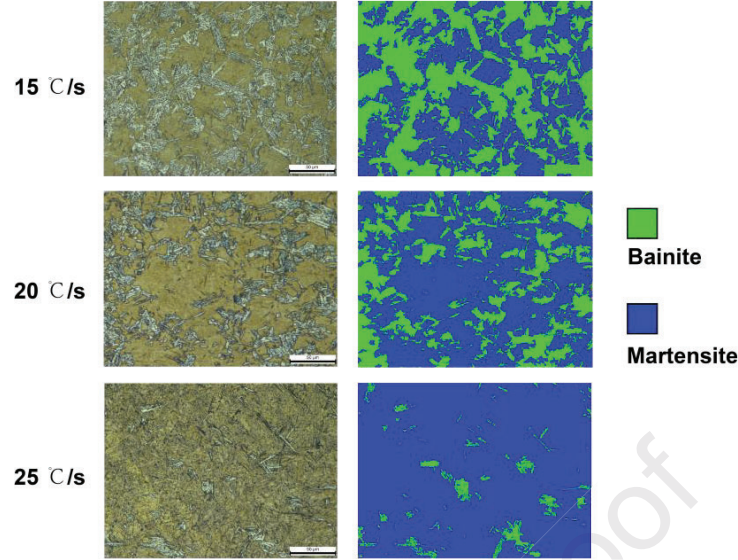


Fig. 8. Optical microscopic structures and phase identification according to cooling rates of 15-25 °C/s.

Fig. 9 shows the change of transformed volume fraction with temperature during continuous transformation under different cooling conditions using the lever rule and metallographic analysis. The parameters of the proposed kinetic model shows in Eq. (4) can be identified by using the evolution curves of phase volume fraction.

The starting and finishing temperatures (or time) of phase transformation for each product phase in CCT cooling conditions are identified based on the analysis of dilation curves. The CCT diagram for B1500HS steel is constructed by fitting of the transformation starting and finishing points, as shown in Fig. 10.

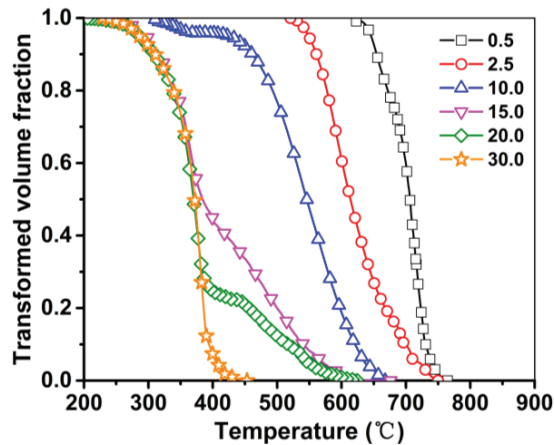


Fig. 9. Phase transformed volume fraction varies with temperature.

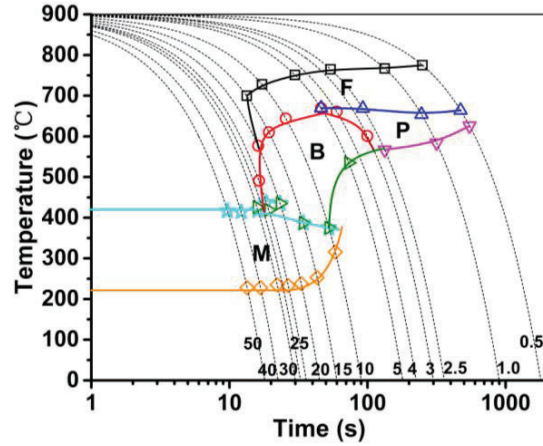


Fig. 10. CCT diagram of B1500HS steel.

Table 3 shows the measured value and standard deviation of Vickers hardness of CCT specimens. The deviation of the hardness test results is small, and the standard deviation of the hardness of the test is large **only** when the cooling rate is large. A possible explanation for this might be that the system error of the microhardness tester increases with the hardness. But the percentage error is still small. Fig. 11 shows the Vickers hardness of the CCT specimen as a function of the cooling rate. As the cooling rate increases, the hardness increases. When the cooling rate is greater than 30 °C/s, the hardness changes to saturation and the increase is not obvious. This is because austenite is almost completely transformed to martensite at a cooling rate of more than 30 °C/s.

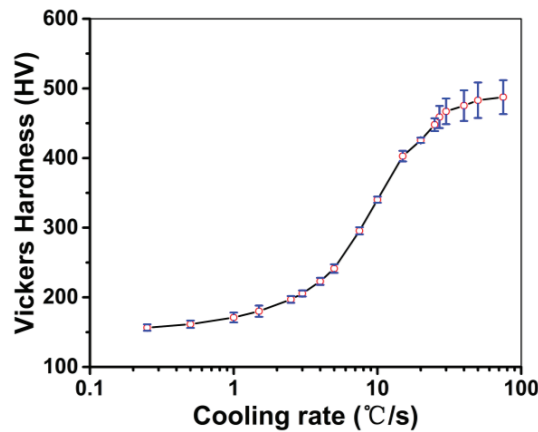


Fig. 11. Vickers hardness of CCT specimens with different cooling rates.

Table 3 Vickers hardness of CCT specimens

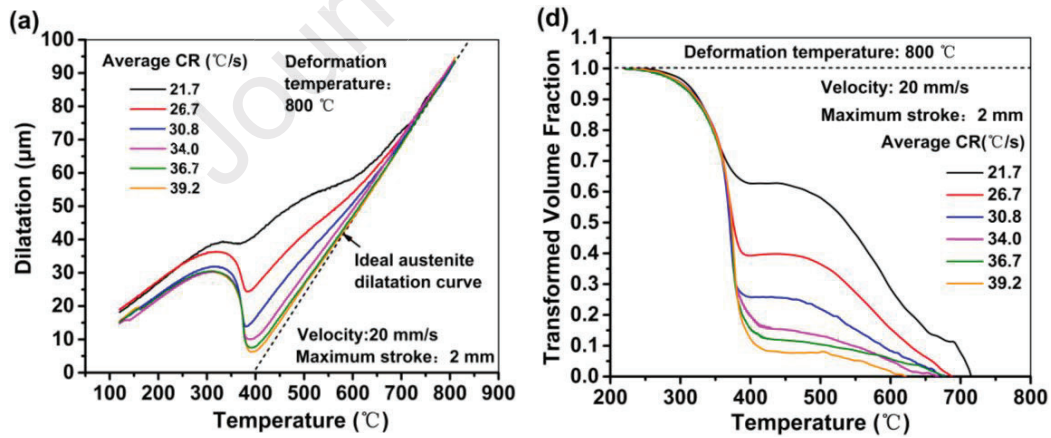
CR ($^{\circ}C/s$)	$t_{85}(300/CR)$ (s)	Average hardness (HV)	standard deviation (HV)
0.5	600	161.35	5.33
1.0	300	171.01	7.11
1.5	200	180.06	8.02
2.5	120	197.04	4.87
3.0	100	205.48	4.39
4.0	75	222.97	5.14
5.0	60	241.31	6.16
7.5	40	295.48	5.10
10	30	340.24	4.33
15	20	402.73	7.65
20	15	425.51	3.77
25	12	447.94	9.20
30	10	458.89	15.87
40	7.5	467.06	18.44
50	6	475.30	21.95
75	4	483.04	25.47

2.6 DCCT test results and analysis

Hot stamping is a non-isothermal deformation process. The deformation response of the blank varies at different areas due to the different loading conditions, i.e., the geometric constraint of parts, the constantly changing strain rates and temperatures. In this section, the effects of strain, deformation temperature, and strain rate on phase transformation are analyzed through measuring the dilation curves and calculating the phase fraction evolution by the proposed method in Section 2.3.

2.6.1 Effect of strain level on transformation

The holding time longer than 5 sec is necessary to ensure the stability of the temperature during the isothermal tensile testing process, as shown in Fig. 2. The isothermal holding time will affect the overall average cooling rate. The average cooling rate in this paper can be expressed as $CR=(800-500)/t_{85}$. Fig. 12 shows the effect of deformation on phase transformation at different average cooling rates. Fig. 12 (a), (b) and (c) show the change of the dilation curves when the stroke is 2, 4, and 6 mm. Fig. 12 (d), (e) and (f) show the evolution of the phase volume fraction of the DCCT specimen under different tensile strokes. The results show that the amount of deformation has a significant effect on the phase transformation. With the increase of deformation, the diffusive phase transformation is promoted at the same cooling rate, resulting in less martensitic transformation. This is mainly attributed to the fact that the accumulated dislocation density and storage energy rise with the increase of deformation, which provides more nucleation sites for the transformation of the diffusive phase, and also a greater driving force for the growth of the new phase. In addition, the larger the deformation, the finer the grain is [35], and the increase of grain boundary is conducive to the nucleation of the new phase at the grain boundary.



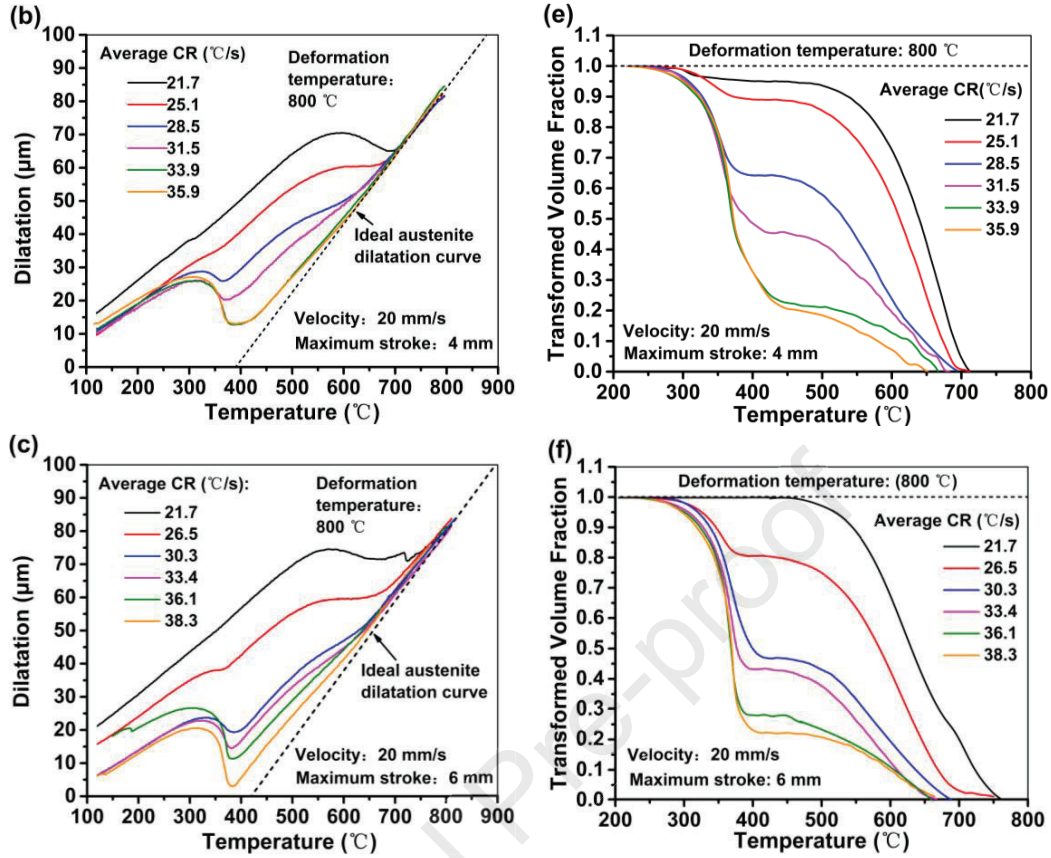


Fig. 12. The effect of the amount of strain on phase transformation. (a), (b) and (c) are the dilatation curves with the stroke of 2, 4 and 6 mm, respectively; (d), (e) and (f) are the phase fraction evolution curves with the stroke of 2, 4 and 6 mm, respectively.

2.6.2 Effect of deformation temperature on transformation

During the hot stamping process, the material undergoes non-isothermal deformation. Studying the influence of deformation temperature on the phase transformation is very significant for accurately establishing the kinetic model of phase transformation with the effect of deformation. Fig. 13 shows the effect of deformation temperature on phase transformation at different average cooling rates. Fig. 13 (a), (b) and (c) show the change of the dilatation curves at deformation temperatures of 800 , 725 , and 650°C , respectively. Combining the dilatation curves and the final phase volume fraction test results, the phase volume fraction evolution curves under the same pre-strain and strain rate are calculated as shown in Fig. 13(d), (e) and (f). The results show that the deformation temperature has a significant effect on the phase transformation. With the decrease of deformation temperature, more

diffusive transformation products than martensitic transformation are obtained from austenite. This is because that dislocation accumulation has become dominant other than the recovery and recrystallization at lower deformation temperatures. Therefore, the lower the deformation temperature, the more defects such as dislocations and vacancies, which is more conducive to nucleation and growth of diffusive products.

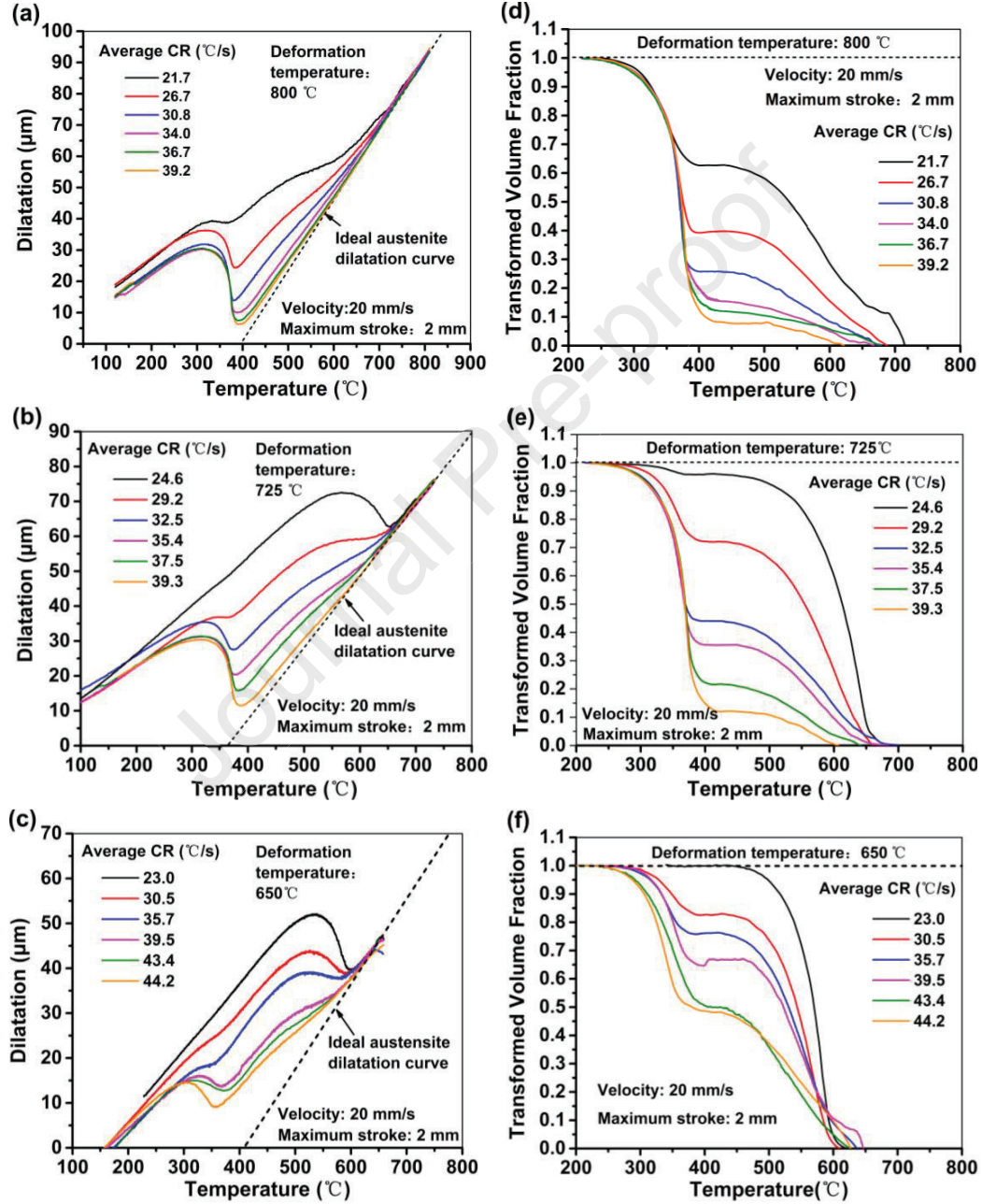
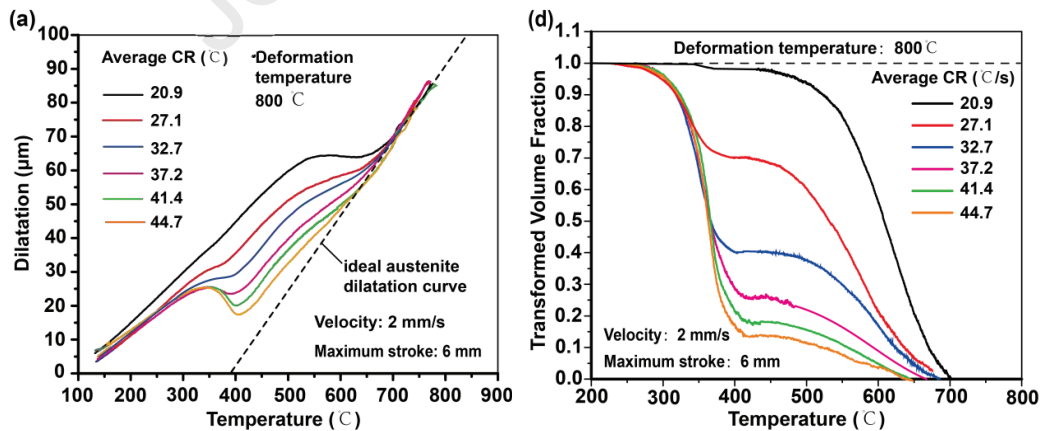


Fig. 13. The effect of the deformation temperature on phase transformation. (a), (b) and (c) are the dilatation curves with the deformation temperature of 800, 725 and 650 °C, respectively; (d), (e) and (f) are the phase fraction evolution curves with the deformation temperature of 800, 725 and 650 °C, respectively.

2.6.3 Effect of strain rate on transformation

During the hot stamping process, the strain rate at each region of the parts is different, and the strain rate is constantly changing during the deformation process. The high-temperature deformation of austenite is strain rate sensitive, so it is very important to study the effect of strain rate on phase transformation. Fig. 14 shows the effect of strain rate on phase transformation. Fig. 14(a), (b) and (c) show the variation of the dilation curves at tensile speeds of 2, 20, and 200 mm/s, respectively. Combining the dilation curves with the final phase volume fraction test results, the phase volume fraction evolution curves under the same pre-deformation amount and deformation temperature are calculated as shown in Fig. 14(d), (e) and (f). The results show that the diffusive transformation is promoted and the martensitic transformation is inhibited with the increase of strain rate. This is attributed to the fact that the recovery mechanism of dislocation is gradually suppressed with the increase of strain rate at the same pre-strain and deformation temperature, and the same deformation will accumulate more dislocation defects, which provides more nucleation sites for the diffusive transformation. In addition, as increasing the strain rate, the flow stress and stored energy increase, which provides more driving force for the growth of new phase.



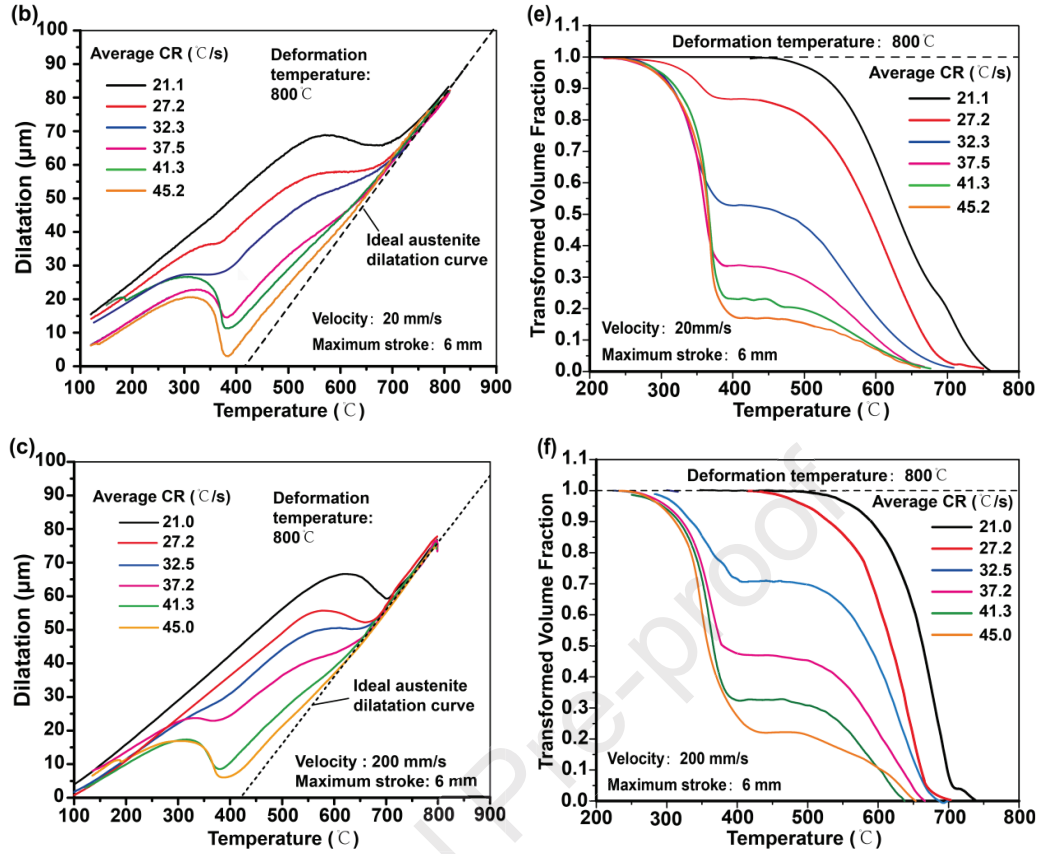
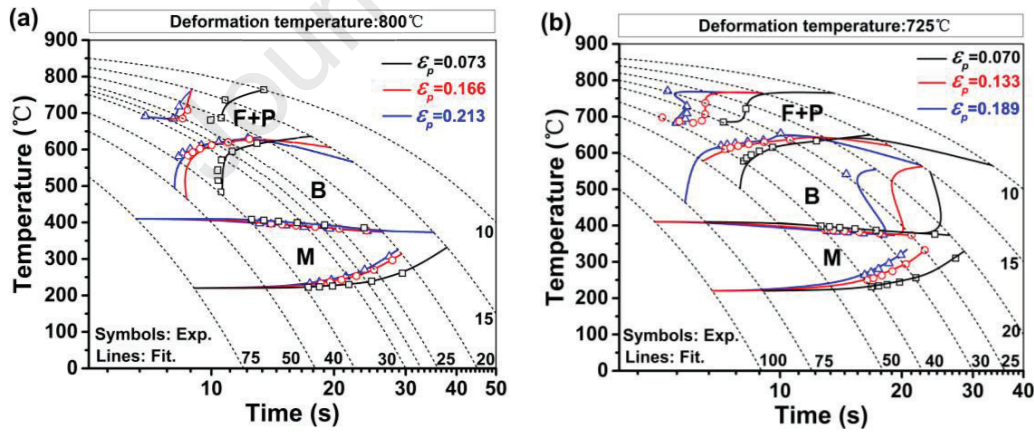


Fig. 14. The effect of the strain rate on phase transformation. (a), (b) and (c) are the dilation curves with the tensile velocity of 2, 20 and 200 mm/s, respectively; (d), (e) and (f) are the phase fraction evolution curves with the tensile velocity of 2, 20 and 200 mm/s, respectively.

2.6.4 Effect of deformation on CCT diagram

It is known from the Section 2.6.1 that deformation will promote the occurrence of diffusive transformation, and deformation has a significant influence on the phase transformation starting and finishing temperatures, that is, the deformation has a great impact on the CCT diagrams. It is very important to understand the influence of deformation on the CCT diagram to establish the kinetic model of phase transformation. Fig. 15 shows the effect of the deformation on the CCT diagram. Fig. 15 (a) and (b) show CCT diagrams with different deformation amounts at deformation temperatures of 800 °C and 725 °C, respectively. The plastic deformation affects the position and shape of the CCT curves. As the deformation increases, the increase of transformation starting temperature and translation of the *FP* and bainite phase

transformation to shorter time can be observed, indicating that the earlier the diffusive transformation occurs at the same cooling rate. As shown in Fig. 15(a), when the deformation temperature is 800 °C and the strain is 0.213, the critical cooling rate for transforming into complete martensite is about 50 °C/s, which is much larger than 27 °C/s without deformation[1]. Comparing Fig. 15 (a) and (b), as the deformation temperature decreases, the translation of diffusive transformation starting point (*FP* and bainite transformation) in a direction of shorter time is increased observably. The transformation starting temperature of diffusive transformation at the same cooling rate increases as the deformation temperature decreases. When deforming at a lower temperature, a larger cooling rate is required to avoid diffusive transformation. As shown in Fig. 15(b), when the deformation temperature is 725 °C and the strain is 0.189, the critical cooling rate for the complete occurrence of martensite transformation is about 75 °C/s, which is larger than the critical cooling rate when the deformation temperature is 800 °C. Fig. 15(c) and (d) show the DCCT diagram represented by t_{85} , which shows the same change law as the general CCT in Fig. 15(a) and (b), where t_{85} is the cooling time from 800 to 500°C.



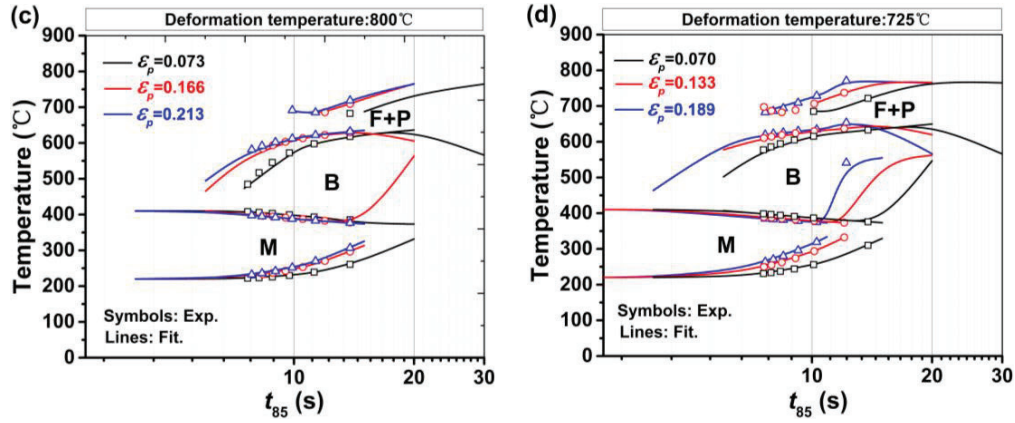


Fig. 15. Effect of deformation on CCT diagrams.

3. Kinetic modeling of phase transformation

3.1 Non-isothermal kinetic model of phase transformation

Based on the transformation kinetics under continuous cooling conditions proposed by Kamamoto et al. [38], the evolution of volume fraction of each phase can be uniformly expressed by exponential function as

$$\varphi_i(T, CR) = 1 - \exp\left(-k_i(CR)(\tau)^{n_i(CR)}\right), \quad i = FP, B, M \quad (4)$$

$$\tau = \frac{T_i^s - T}{T_i^s - T_i^f} = \frac{t - t_i^s}{t_i^f - t_i^s} \quad (5)$$

where T is the current temperature, CR is the cooling rate; φ_i is the transformation level of the i -th product phase; τ is the normalized temperature or time; T_i^s and T_i^f are the starting and finishing temperatures for the i -th product phase of phase transformation respectively; Similarly, t_i^s and t_i^f are the starting and finishing time of phase transformation.

The starting and finishing temperatures of the phase transformation vary with the cooling rate. Fig. 16 shows the determination method of the starting and finishing temperatures of phase transformation. For a certain type of transformation, the starting and finishing temperatures can be expressed as a polynomial function of the cooling rate:

$$T^{s,f}(CR) = \sum_{i=1}^m a_i^{s,f} CR^{i-1} \quad (6)$$

where $a_i^{s,f}$ is the polynomial coefficient for calculating the starting and finishing temperatures of phase transformation.

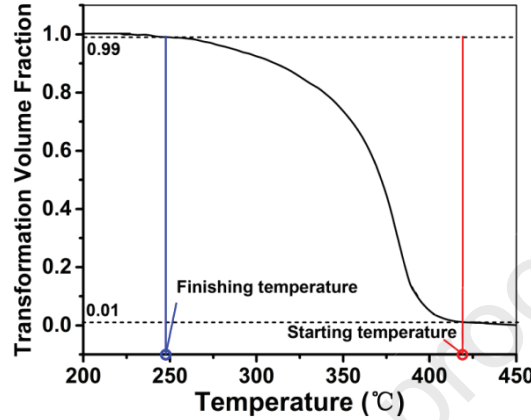


Fig. 16. Calculation method for starting and finishing temperature of phase transformation

The k_i and n_i in Eq. (4) are the model parameters, which are dependent on CR , and can be expressed as

$$k_i = \gamma_i(CR), \quad n_i = \lambda_i(CR) \quad (7)$$

where γ_i and λ_i are the function of the cooling rate, which will be determined in Section 3.3.3.

Combined with the final phase volume fraction identified by the metallographic analysis, the total transformed volume fraction can be expressed as

$$X_i(T) = X_i^{final} \cdot \varphi_i(T, CR), \quad i = M, B, FP \quad (8)$$

where X_M^{final} , X_B^{final} and X_{F+P}^{final} are the final phase volume fraction for martensite, bainite and ferrite+pearlite respectively.

The properties of ferrite and pearlite are relatively close. The product phase is assumed as an aggregation of ferrite and pearlite, which is referred to as the FP mixed-phase. The final volume fraction of the product phase can be expressed as a function of the cooling rate, and the final fraction of the martensite and FP mixed phase can be expressed as

$$X_M^{final}(t_{85}) = \frac{1}{2} \left(1 + \operatorname{erf} \left(\frac{\ln(t_{85}) - \psi_m(t_{85})}{\sqrt{2a_m}} \right) \right) \quad (9)$$

$$X_{FP}^{final}(t_{85}) = \frac{1}{2} \left(1 + \operatorname{erf} \left(\frac{\ln(t_{85}) - \psi_f(t_{85})}{\sqrt{2a_f}} \right) \right) \quad (10)$$

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-\eta^2} d\eta \quad (11)$$

where t_{85} is the cooling time from 800 to 500 °C according to the applied cooling rate ($t_{85} = (800-300)/CR$); a_m and a_f are model parameters for the final phase fraction of the martensite and the *FP* mixed-phase, respectively. $\operatorname{erf}(x)$ is the standard error function; $\psi_m(t_{85})$ and $\psi_f(t_{85})$ are nested functions in the calculation model of the final volume fraction of martensite phase and *FP* mixed-phase, which can be expressed as the polynomial function of t_{85}

$$\psi_m(t_{85}) = \sum_{i=1}^n m_i t_{85}^{i-1} \quad (12)$$

$$\psi_f(t_{85}) = \sum_{j=1}^n f_j t_{85}^{j-1} \quad (13)$$

where m_i and f_j are the coefficients of the polynomial function, which can be obtained by fitting the final volume fraction of various product phases at different cooling rates.

The final phase volume fraction of bainite can be obtained directly from the total austenite volume fraction (total austenite volume fraction, generally equal to 1) minus the final volume fraction of the martensite and *FP* mixed-phase, ie

$$X_B^{final}(t_{85}) = 1 - X_M^{final}(t_{85}) - X_{FP}^{final}(t_{85}) \quad (14)$$

3.2 Modeling of phase transformation considering the effect of deformation

It can be seen from Fig. 15 that the deformation will promote the transformation of diffusion phase, that is, the CCT curve will shift to the left with different deformation conditions, but it is very cumbersome to describe the DCCT curve under various deformation conditions. Therefore, a concept of virtual cooling rate is

proposed to transform the actual cooling rate of pre-deformed austenite into the non-deformed condition. The virtual cooling rate can be directly substituted into the phase transformation model established in the Section 3.1 to predict the phase volume fraction of pre-deformed austenite. The concept of virtual cooling rate is shown in Fig. 17.

According to the similarity principle, the normalized temperature τ in Eq. (4) is the same for the actual and virtual cooling paths, which varies between 0 and 1.

$$\tau = \frac{T_i^s - T}{T_i^s - T_i^f} = \frac{T_i^{s'} - T}{T_i^{s'} - T_i^{f'}} \quad (15)$$

where T_i^s and T_i^f are the starting and finishing temperatures of phase transformation in the virtual cooling path.

The relationship between the virtual and the actual cooling rate CR_v can be expressed as

$$\frac{CR}{CR_v} = 1 + \frac{\Delta t_\varepsilon}{\Delta t_0} = \omega(\varepsilon, \dot{\varepsilon}, T) \quad (16)$$

where Δt_ε is the shortened incubation time caused by deformation-induced nucleation; Δt_0 is the actual incubation time of pre-deformed austenite; ε , $\dot{\varepsilon}$, and T are strain, strain rate, and deformation temperature respectively.

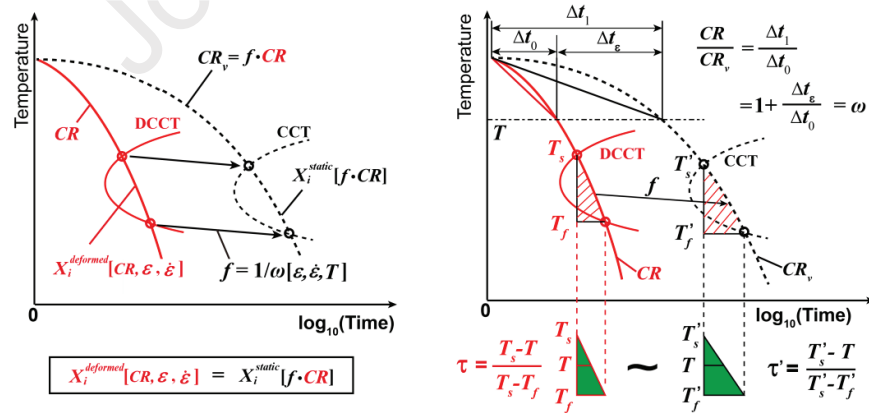


Fig. 17. The principle of introducing the effect of deformation on phase transformation.

A final volume fraction calculation model for various product phases at different cooling rates without pre-deformation is established in Section 3.1. The model represents the final phase volume fraction as a function of cooling rate with high

prediction accuracy under undeformed conditions. To consider the influence of deformation on the final phase volume fraction, the virtual cooling rate are introduced to correct the original model. The conversion factors ω of the virtual cooling rate are different for different product phases, the virtual cooling rate can be expressed as

$$CR_{v,i} = \frac{CR}{\omega_i(\varepsilon, \dot{\varepsilon}, T)}, \quad i = FP, M \quad (17)$$

$$t_{85}^i(\varepsilon, \dot{\varepsilon}, T) = \frac{300}{CR_{v,i}} = \omega_i(\varepsilon, \dot{\varepsilon}, T) \frac{300}{CR} = \omega_i(\varepsilon, \dot{\varepsilon}, T) t_{85} \quad (18)$$

where, ω_i is the coefficient that converts the actual cooling path to the virtual one, as shown in Fig. 18. According to Eq. (16), $\omega_i \in [1, +\infty]$.

Substituting Eq.(18) into Eq.(9) and (10), the final phase volume fraction calculation model of the martensite and *FP* mixed phases considering the influence of deformation can be written as

$$X_M^{final}(t_{85}) = \frac{1}{2} \frac{\dot{\varepsilon}}{\dot{\varepsilon}_1} + \operatorname{erf} \left[\frac{\ln(\omega_M t_{85}) - \psi_m(\omega_M t_{85})}{\sqrt{2} a_m} \right] \quad (19)$$

$$X_{FP}^{final}(t_{85}) = \frac{1}{2} \frac{\dot{\varepsilon}}{\dot{\varepsilon}_1} + \operatorname{erf} \left[\frac{\ln(\omega_{FP} t_{85}) - \psi_f(\omega_{FP} t_{85})}{\sqrt{2} a_f} \right] \quad (20)$$

where ω_M and ω_{FP} are the virtual cooling rate conversion coefficients of martensite and *FP* transformations respectively. The definition of the inline function and the model parameter values are consistent with Eq.(11) to Eq. (13).

After the virtual cooling rate is calculated, the evolution of phase volume fraction under any virtual cooling path can be calculated by using Eq.(4) to (6) and Eq. (8). However, the conversion factor ω , which converts the actual cooling path to the virtual one, is still unknown. Because the current deformation does not reach the critical strain of dynamic recrystallization (The minimum critical strain is 0.367 [35] when deformation temperature is 800 °C and strain rate is 0.1 s⁻¹), the static recrystallization can be ignored in the process of die-quenching within 10 s of hot stamping. Therefore, the effect of deformation on phase transformation is mainly attributed to the increase of nucleation sites due to the increase of accumulated dislocation density.

By summarizing the previous studies, the evolution of dislocation density in the high-temperature deformation of boron steel can be expressed as

$$\rho_d = \lambda d_0^m \dot{\varepsilon}^{n_0} \exp\left\{\frac{Q_b - Q_c}{T} \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right\} - \exp\left\{\frac{Q_c}{T} \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right\} \beta \dot{\varepsilon}^{n_1} \bar{\varepsilon} \exp\left\{\frac{Q_c}{T} \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right\} + \rho_0 \quad (21)$$

where λ , m , n_0 , and n_1 are material coefficients; d_0 is the initial austenite grain size; Q_b and Q_c are activation energy related parameters for dislocation density accumulation and dynamic recovery respectively; ρ_0 is the initial dislocation density; $\bar{\varepsilon}$, $\dot{\varepsilon}$, and T are strain, strain rate, and deformation temperature, respectively.

The dislocation accumulation rate of plastic deformation is the ratio of the current dislocation to the initial dislocation, which is given by:

$$v = \frac{\rho_d}{\rho_0} = \frac{\lambda d_0^m \dot{\varepsilon}^{n_0}}{\rho_0} \exp\left\{\frac{Q_b - Q_c}{T} \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right\} - \exp\left\{\frac{Q_c}{T} \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right\} \beta \dot{\varepsilon}^{n_1} \bar{\varepsilon} \exp\left\{\frac{Q_c}{T} \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right\} + 1 \quad (22)$$

The relationship between the ω , plastic stain, and deformation temperature can be expressed as

$$\omega(\bar{\varepsilon}, \dot{\varepsilon}, T) = \alpha v \quad \eta = \alpha \frac{\lambda d_0^m \dot{\varepsilon}^{n_0}}{\rho_0} \quad (23)$$

$$\omega_k(\bar{\varepsilon}, \dot{\varepsilon}, T) = \eta_k \exp\left\{\frac{Q_{b,k} - Q_{c,k}}{T} \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right\} - \exp\left\{\frac{Q_{c,k}}{T} \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right\} \beta_k \dot{\varepsilon}^{n_k} \bar{\varepsilon} \exp\left\{\frac{Q_{c,k}}{T} \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right\} + 1, \quad k = FP, M \quad (24)$$

where α is scaled factor; η is material constant related to initial grain size and dislocation density; The other parameters are consistent with Eq. (21). When the strain is zero, the conversion coefficient of virtual cooling rate is equal to 1, the final phase volume fraction calculation model degenerates into the continuous cooling transformation without pre-deformation.

3.3 Identification of kinetic parameters for B1500HS boron steel

3.3.1 The starting and finishing temperatures of phase transformation

Accurate description of CCT curves is very important for predicting the evolution of phase transformation. The test results shown in Fig. 10 are piecewise fitted by using Eq. (6) to calculate the starting and finish temperature of transformation at any

cooling path. The calculation coefficients of phase transformation starting and finishing temperatures are shown in Table 4 and Table 5, respectively.

Table 4 Coefficient for calculating transformation starting temperature.

Coefficient	a_1	a_2	a_3	a_4	a_5	CR
F+P	783.00	-21.36	7.70	-0.949	0.0337	0.5-15°C/s
	748.56	-220.52	109.60	-13.65	0	0.5-5°C/s
Bainite	564.50	54.97	-8.51	0.47	-0.00889	5-27°C/s
	173.2	204.55	-20.65	0	0	3-5°C/s
Martensite	787.0	-86.67	5.64	-0.1093	0	$\leq 25^\circ\text{C/s}$
	844.0	-30.68	0.7225	-0.00628	1.69×10^{-5}	$> 25^\circ\text{C/s}$

Table 5 Coefficient for calculating transformation finishing temperature.

Coefficient	a_1	a_2	a_3	a_4	a_5	CR
F+P	748.56	-220.52	109.60	-13.65	0	0.5-15°C/s
	708.58	-212.05	100.067	-12.60	0	0.5-5°C/s
Bainite	593.67	14.4	-3.6267	0	0	2.5-10°C/s
	787.0	-86.67	5.64	-0.1093	0	$> 10^\circ\text{C/s}$
Martensite	549.63	-35.19	1.3466	-0.0206	1.033×10^{-4}	$> 25^\circ\text{C/s}$

3.3.2 Parameter identification of final phase volume fraction

Table 6 shows the model parameters for the final phase volume fraction obtained by fitting the experimental data in Table 2. Fig. 18 shows the comparison of the final phase fractions between the model calculations and the experimental results. It can be seen from the figure that the final phase fraction calculation model proposed in this paper can accurately predict the final volume fractions of different product phases under various cooling rates. This model is very convenient for calculating the final phase volume fraction under any cooling conditions.

Table 6 Parameters for calculating of the final phase volume fraction

Phase	a_f/a_m	f_1/m_1	f_2/m_2	f_3/m_3
Ferrite+Pearlite(<i>FP</i>)	0.0948	2.6030	0.0386	-2.06E-4
Martensite(<i>M</i>)	0.3180	2.9676	0	0

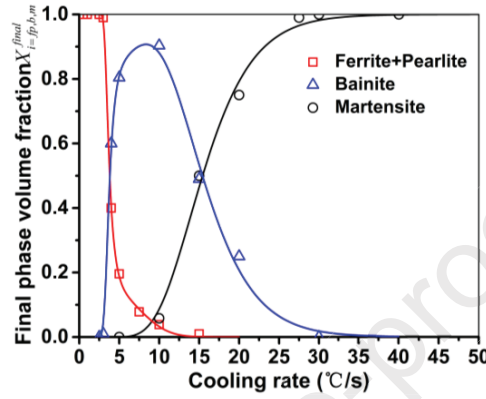


Fig. 18. Comparison of fitting final phase fraction with the experimental results.

3.3.3 Phase transformation evolution parameters

The phase transformation evolution parameters k and n in Eq.(4) are used to describe the evolution in the whole process of phase transformation. Each cooling rate corresponds to a set of parameter values. The objective of optimization is to obtain a set of optimal parameters k and n to minimize the deviation between the volume fraction evolution curve of austenite calculated by the model and the experimental test value, i.e

$$\begin{cases} \int_{T_f}^{T_i} (X_{f,tot}^{exp}(T) - X_{f,tot}^{cal}(T)) dT = \min \\ \int_{T_b}^{T_{fp}} (X_{b,tot}^{exp}(T) - X_{b,tot}^{cal}(T)) dT = \min \end{cases} \quad (25)$$

where $X_{f,tot}^{exp}$ and $X_{f,tot}^{cal}$ are the experimental test and calculated volume fraction of F+P phase; $X_{b,tot}^{exp}$ and $X_{b,tot}^{cal}$ are the experimental test and calculated volume fraction of bainite respectively.

When two or more product phase are formed at a certain cooling rate, the transformed volume fraction of austenite, as shown in Fig. 12 to Fig. 14, can be

expressed as

$$X_{tot}^{cal}(T) = X_{fp}^{max} \left(1 - \exp(-k_{fp} \tau_{fp}^{n_{fp}}) \right) + (1 - X_{fp}^{max}) \left(1 - \exp(-k_b \tau_b^{n_b}) \right) \quad (26)$$

$$\tau_{fp} = h \left(\frac{T_{fp}^s - T}{T_{fp}^s - T_{fp}^f} \right), \tau_b = h \left(\frac{T_b^s - T}{T_b^s - T_b^f} \right) \quad (27)$$

$$h(x) = \frac{|x| - |x-1| + 1}{2} \quad (28)$$

where $h(x)$ is a switching function that determines the current transformation type and calculates the normalized temperature. When the temperature is not cooled to a certain phase transformation starting point, the value of h function is zero, and its graph is shown in Fig. 19.

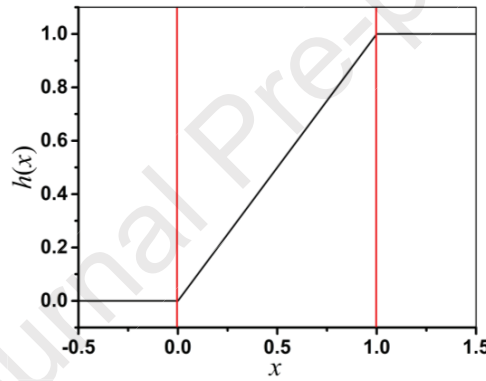


Fig. 19. The graph of switch function

The deviation between the phase transformation evolution curve calculated by the Eq.(26) and the experimental test curve is used as the objective function, and the kinetic parameters k and n are obtained for different transformation type at various cooling rates. The identification results are shown in Table 7.

Table 7 Parameters of phase transformation with continuous cooling.

Product phase	Parameters	0.5	2.5	5.0	10.0	15.0	20.0
F+P	k	5.69	5.75	3.26	8.93	8.60	—
	n	2.88	3.18	6.72	18.10	22.14	—
Bainite	k	—	—	3.61	6.31	2.28	1.93
	n	—	—	1.37	2.08	2.13	1.81

Fig. 20(a) shows the variation of the identification parameters with the cooling rate. For a certain product phase of transformation, there is a corresponding relationship between the cooling rate and the final phase volume fraction, as shown in Fig. 18. Using this relationship, the model parameters can be expressed as a function of the final phase volume fraction, as shown in Fig. 20(b) and (c). Fig. 20(d) shows the comparison of the transformed volume fraction predicted by the identification parameters and the experimental test results. The results show that the identified parameters can accurately predict the evolution of phase volume fraction during the whole transformation process.

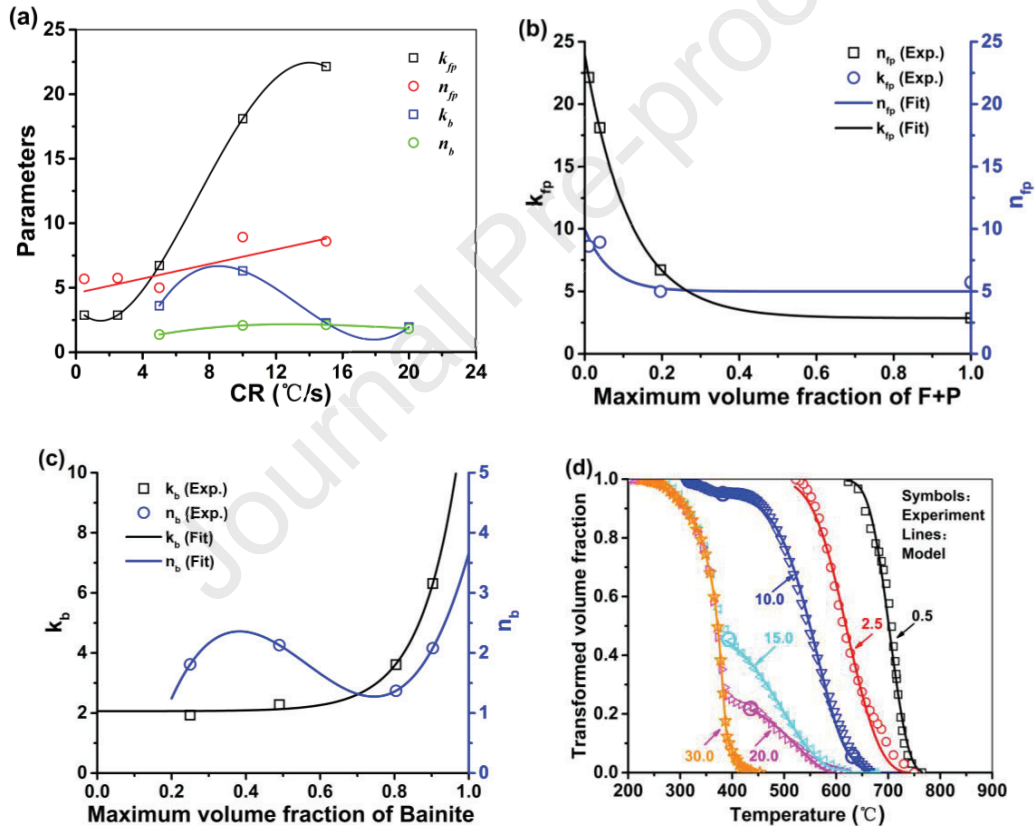


Fig. 20. Identification results. (a) variation of the identification parameters with the cooling rate; (b) and (c) variation of the identification parameters with phase fraction; (d) comparison of simulated and measured phase fraction.

3.3.4 Parameter identification of the model considering deformation effect

The transformation model considering the effect of deformation is based on the conversion coefficient to transform the actual cooling rate into the virtual one. The

value of the conversion coefficient can be obtained by using Eq.(19) and (20) to fit the relationship between the final phase volume fraction under different deformation conditions tested by DCCT and the cooling rate as shown in Fig. 12-14. Fig. 21 shows the comparison of the final phase volume fraction of the martensite and the model fitting results (fitting with Eq. 20) under different deformation conditions and cooling rates. Fig. 22 shows the comparison of the final phase volume fraction of *FP* mixed phase and the fitting results of the Eq.(19) under different deformation conditions and cooling rates. The comparison results show that the proposed model can describe the relationship between the final phase volume fraction and the cooling rate under various deformation conditions.

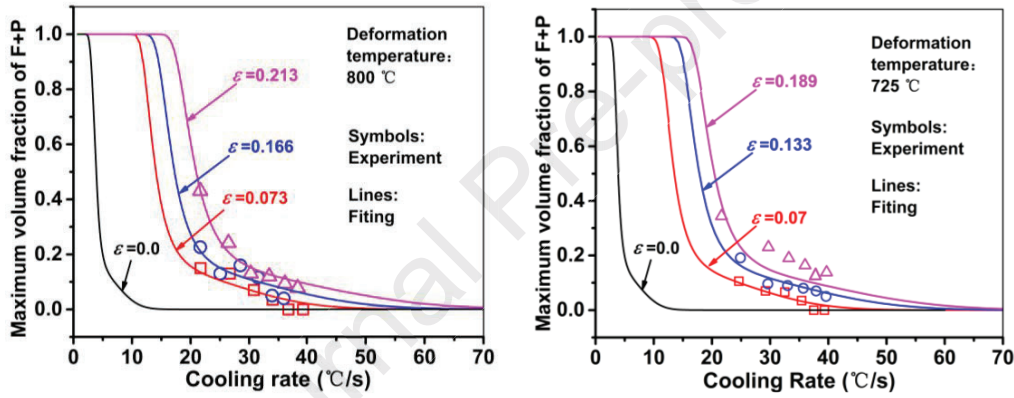


Fig. 21. The fitting results of the relationship between the final volume fraction of *F+P* and the cooling rate under different deformation conditions.

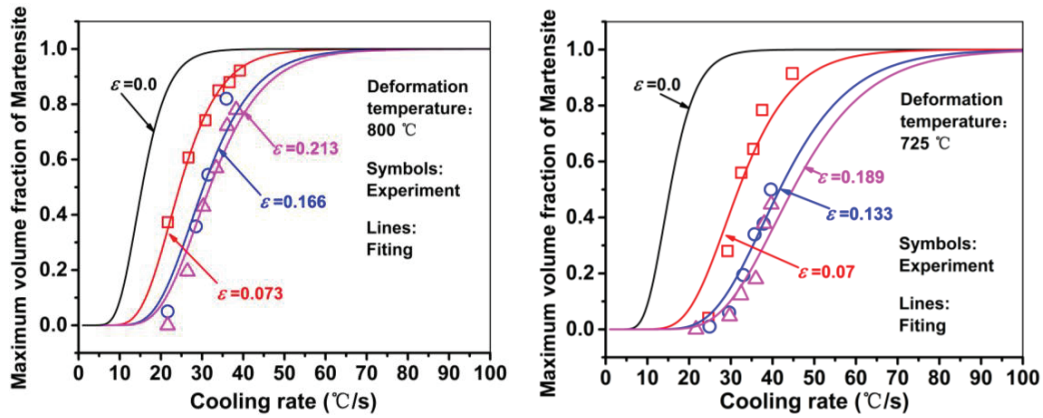


Fig. 22. The fitting results of the relationship between the final volume fraction of martensite and the cooling rate under different deformation conditions.

Table 8 shows the conversion coefficient ω of the actual cooling path to the virtual one under different deformation conditions obtained by fitting the experimental data in Fig. 21 and Fig. 22. The coefficient ω increases with the increase of the deformation amount and decreases with the increase of the deformation temperature. The data in Table 8 can be used to identify the model parameters of conversion coefficient shown in Eq. (24). The calculation parameters of the conversion factor ω are shown in Table 9. Fig. 23 shows the comparison of the experimental test ω and the model fitting results. The results show that the proposed model can predict the conversion coefficient ω under various deformation conditions accurately.

Table 8 Conversion factor under different deformation conditions (strain rate is 1s^{-1})

Deformation temperature ($^{\circ}\text{C}$)	Strain	ω_{FP}	ω_M
650	0	1.000	1.000
650	0.053	3.420	2.790
650	0.130	4.770	4.380
650	0.183	5.630	4.920
725	0	1.000	1.000
725	0.07	3.534	2.064
725	0.133	4.680	2.703
725	0.189	5.356	2.908
800	0	1.000	1.000
800	0.073	3.694	1.591
800	0.166	4.524	1.966
800	0.213	5.497	2.067

Table 9 Parameters for deformation correction factor of final phase volume fraction model

Phase	η_k	β_k	$Q_{b,k}$	$Q_{c,k}$
Ferrite+Pearlite(FP)	1.79	34.62	-949.86	-172.43
Martensite(M)	2.91E-3	6.47	223.60	5087.25

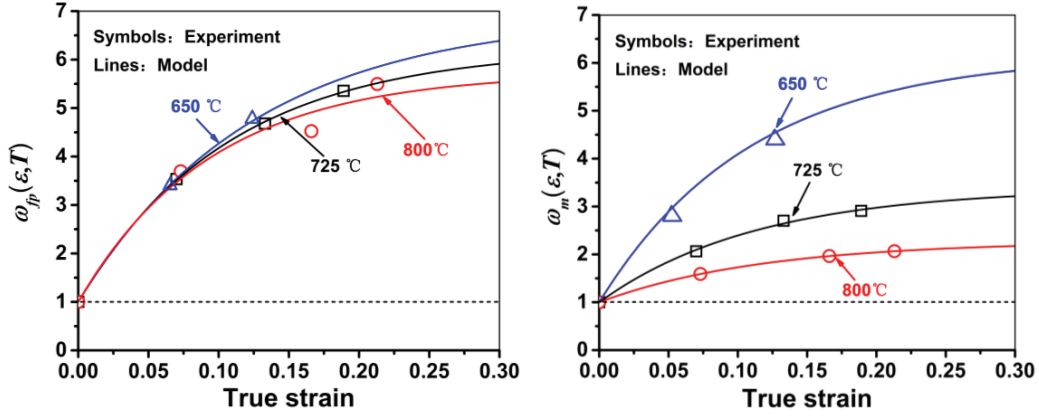


Fig. 23. Comparison of model and experimental results for the calculation coefficient of equivalent cooling rate.

4. Model verification and application

4.1 Experimental verification

To study the effect of deformation on the final mechanical properties of boron steel, the hardness of all DCCT specimens is measured and analyzed using the microhardness tester. Fig. 24 shows the variation of the Vickers hardness of the central section of the DCCT specimens with cooling rate under different deformation conditions. The greater the deformation amount, the lower the hardness at the same cooling rate. This is because the deformation promotes the transformation of austenite into a more diffusion phase, resulting in a decrease in the martensite phase volume fraction. Therefore, a greater cooling rate is required to obtain greater hardness. Besides, the deformation temperature also has a significant effect on the hardness. The lower the deformation temperature, the lower the hardness at the same cooling rate. It shows that with lower the deformation temperature under the same deformation amount, smaller the volume fraction of austenite transforms into martensite, and more diffuse phase microstructure with lower hardness is formed.

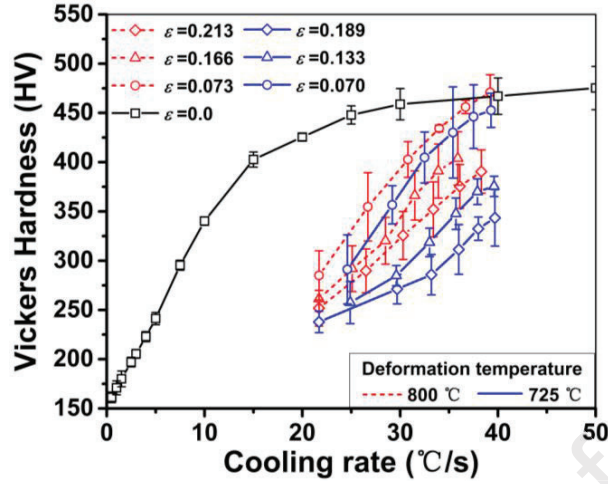


Fig. 24. Comparison of hardness of CCT specimen under different deformation conditions.

The final mechanical properties are related to the final microstructure. The hardness of each single phase can be easily obtained by single phase hardness test and literature search. Combined with the calculation results of the final phase volume fraction presented in Section 3, the final hardness under different deformation and cooling conditions can be expressed as

$$HV = X_M^{final} HV_M + X_{FP}^{final} HV_{FP} + (1 - X_M^{final} - X_{FP}^{final}) HV_B \quad (29)$$

where HV_M , HV_B and HV_{FP} are Vickers hardness for martensitic, bainite, and FP mixed-phase respectively. The specific values are shown in Table 10.

Table 10 Vickers hardness for each phase

Vickers hardness	HV_{FP}	HV_B	HV_M
Values	168.5	283.8	475.0

The hardness of all DCCT specimens is predicted to verify the reliability of the proposed kinetic model of phase transformation. Fig. 25 shows the comparison of the calculated hardness and the experimental test results of the DCCT specimens under different deformation conditions. The results show that the variation trend of hardness with cooling rate can be reliably captured by the proposed model under various deformation conditions. At the same deformation temperature, the larger the deformation amount, the smaller the hardness of the specimen is obtained under the

same cooling rate. Conversely, at the same deformation amount, the deformation temperature is higher, and the hardness is higher under the same cooling rate.

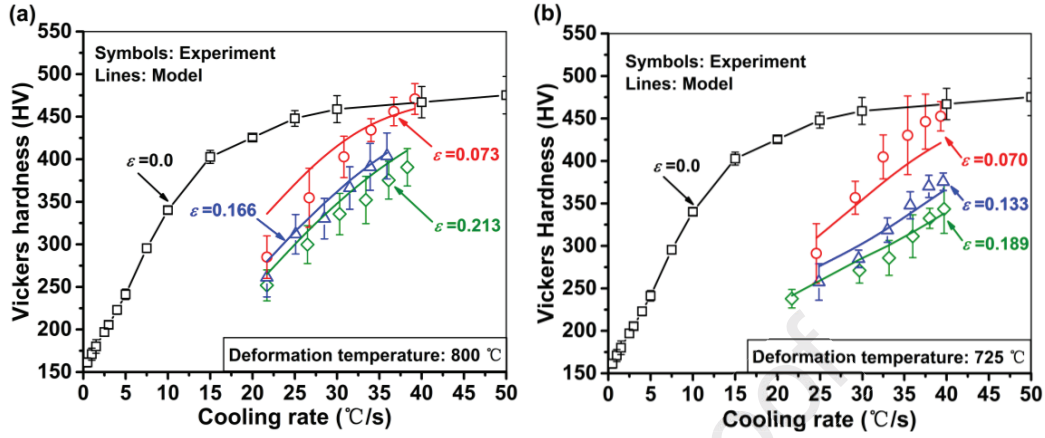


Fig. 25. Comparison of model prediction and experimental results of Vickers hardness for DCCT specimen under different predeformation.

4.2 Application to hot stamping of W-channel part

As a practical application, hot stamping of a W-channel part is simulated using the developed kinetic model of phase transformation. The kinetic model is implemented in ABAQUS/Explicit using a developed subroutine VUMAT. The B1500HS boron steel with a thickness of 1.5 mm is used in experiments and simulation. Fig. 26(a) shows the FEM model, the clearance between the punch and die is set as 1.6 mm. In the current simulation, the upper tool (punch) moves up and down, and the lower tool (die) is stationary. The workpiece is formed at 810 °C at a stamping velocity of 200 mm/s and then held in die for 20 s. The interfacial heat transfer coefficient (IHTC) between tool and blank is shown in Fig. 26(b). The other conditions for the simulation are all kept identical, as shown in Table 11.

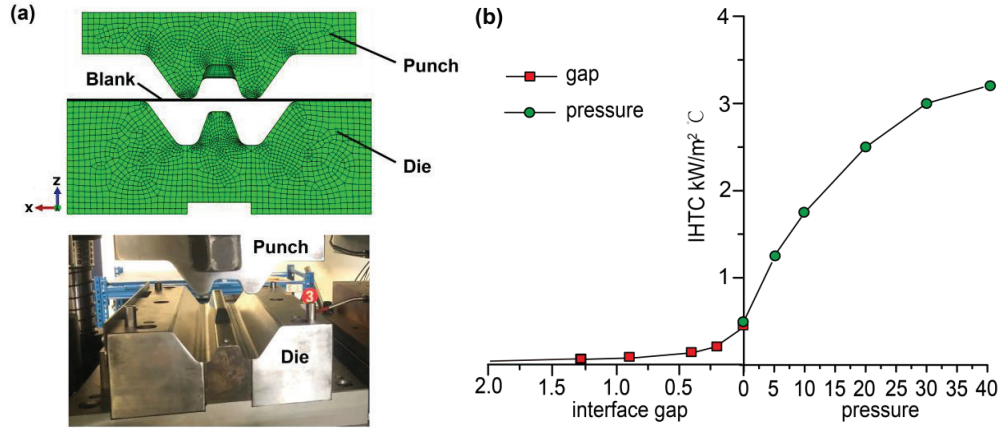


Fig. 26. (a) FEM model and (b) the IHTC for the hot stamping simulation of W-channel.

Table 11 Process conditions for the hot stamping of W-channel part

t_{forming} (s)	$t_{\text{quenching}}$ (s)	$T_{\text{blank_initial}}$ ($^{\circ}\text{C}$)	T_{tool} ($^{\circ}\text{C}$)	T_{air} ($^{\circ}\text{C}$)	Holding pressure(MPa)	Friction coefficient
2	20	810	60	25	10	0.3

Fig. 27 shows the comparison of the final martensite volume fraction predicted by the transformation model with and without deformation effect. The results show that the whole part is almost completely transformed into martensite without considering the effect of deformation, and the volume fraction of martensite is even more than 95%. However, the model considering the deformation effect predicted that the volume fraction of martensite at the large deformation region, such as the corner and side wall, was only about 40%, and more austenite is transformed to other product phases of diffusive transformation.

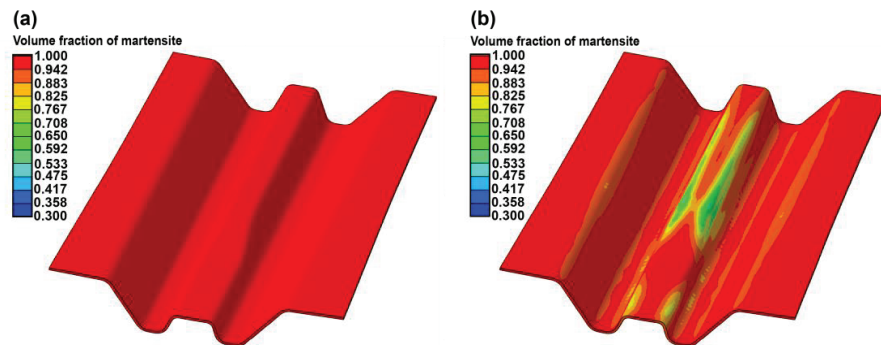


Fig. 27. Comparison of the martensite volume fraction predicted by the phase transformation model (a) without and (b) with the effect of pre-deformation.

Fig. 28 shows the comparison of the martensite volume fraction predicted by the model without and with the deformation effect. The results show that the hardness distribution predicted by the transformation model without considering the influence of deformation is very uniform, and the hardness varies between 455-475HV, which is similar to the distribution of martensite volume fraction. However, the hardness distribution predicted by the model considering the deformation effect is not uniform. The hardness of the corner and sidewall with large deformation is much lower than that of the flange and the minimum hardness is about 355 HV, which indicates that the proposed transformation model can successfully predict the influence of deformation on diffusive transformation.

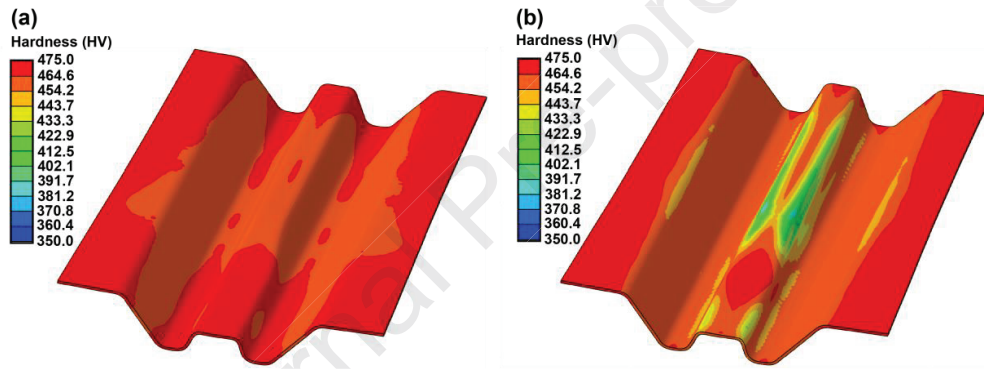


Fig. 28. Comparison of the hardness predicted by the model (a) without and (b) with the effect of pre-deformation.

To evaluate the accuracy and reliability of the simulation results of a different kinetic model of phase transformation, a separate forming experiment is carried out. A hot stamping testing platform for a W-channel part is developed. The clearance between punch and die is 1.6 mm, which is identical with the FEM simulation. Before the forming begins, the blank is heated in an electric furnace to approximately 900 °C and kept at this temperature for 240 s. The forming test is carried out on a Komatsu servo Press (H2W300S). The formed part and microstructure are shown in Fig. 29. The material points are selected for inspection of the mechanical properties and microstructure. These inspection points are positioned at the middle of the top face(P1), corner(P2), sidewall(P3 and P4) at the end of the forming. The results show that the microstructures of different regions of the parts are quite different, and more

bainite is formed in the corner and sidewall.

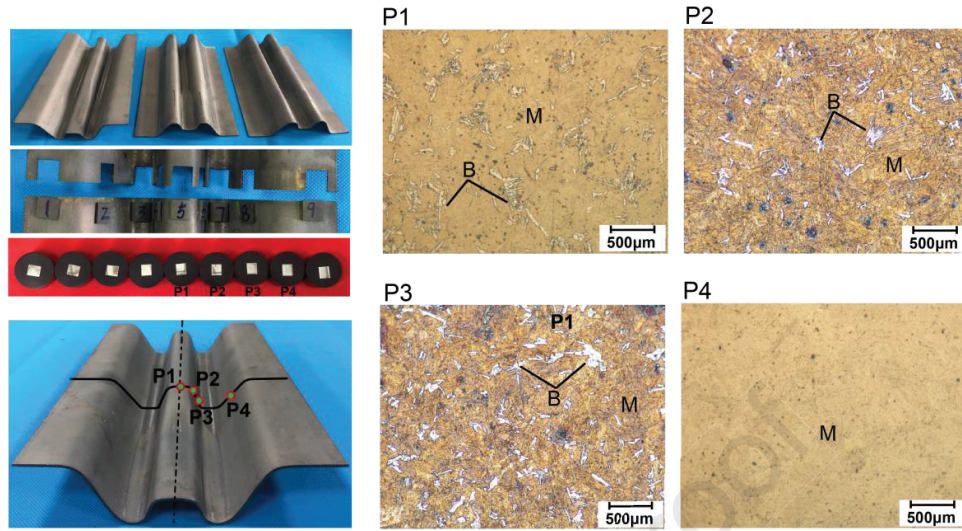


Fig. 29. The hot stamping W-channel part and optical microscopic structures at different area.

Fig. 30 shows the comparison of experiment and simulation results of hardness in the inspection section (AB). It shows that the simulation results of hardness based on the kinetic model of phase transformation considering the impact of deformation are in good agreement with the experimental values. The hardness of the inspection section reached a low point in the corner and sidewall, which is attributed to the greater deformation that occurs in that region. Larger deformation induces much more phase fraction of diffusive transformation. The hardness in the wall region predicted by the model without the effect of deformation is also slightly decreased due to imperfect thermal contact by the clearance in that region, but the predicted hardness is much higher than the measured value. Consequently, only the model considering the deformation effect can accurately predict the distribution of mechanical properties of hot stamping parts, and the reliability of the proposed model is verified.

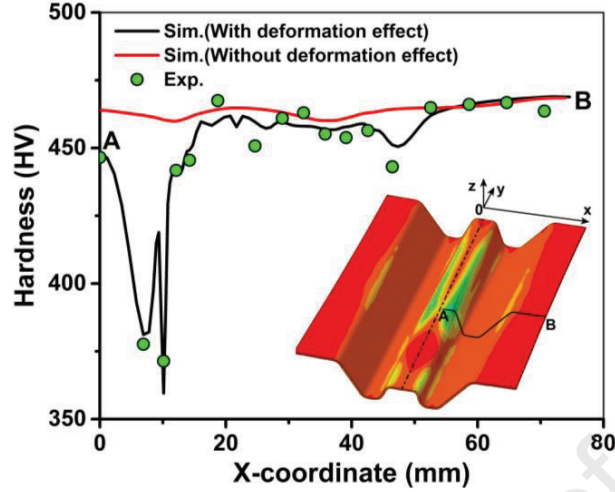


Fig. 30. Comparison of Vickers hardness between experiment and simulation with different phase transformation model.

5. Conclusion

In the present study, the phase transformation from austenite to diffusive and non-diffusive transformation in the B1500HS boron steel during continuous cooling with and without pre-deformation is investigated using dilatometry and ex-situ microstructure analysis. The influence of deformation on dilatation curves, CCT diagrams, and phase volume fraction is studied systematically. The kinetic model of phase transformation considering the deformation effect is established. The final mechanical properties of the specimens and W-channel parts are predicted using the proposed model. The obtained conclusions can be summarized as follows:

- 1) The deformation has a significant influence on the phase transformation. The increase of strain and strain rate or decrease of deformation temperature will promote the diffusive transformation and reduce the transformation of martensite microstructure.
- 2) The plastic deformation affects the position of the CCT diagrams. The deformation will cause an increase of translation of the *FP* and bainite phase transformation to shorter time. The larger the deformation, the larger the translation of the CCT diagrams. As the deformation increases, the translation of CCT diagrams will

gradually become saturated.

3) A non-isothermal kinetic model of phase transformation considering the influence of deformation is proposed based on the concept of virtual cooling rate. The parameters of the proposed model are identified by CCT and DCCT test experiments. The proposed model is simpler and more reliable than the traditional model because the effect of pre-deformation is taken into account.

4) The final hardness of boron steel specimens with pre-deformation under various cooling rates can be predicted accurately by the proposed kinetic model of phase transformation. The model has been successfully applied to predict the mechanical properties of hot stamping of the W-channel part. Compared with traditional model, the result indicated that the proposed model considering the effect of deformation has better accuracy for predicting the properties in the zone of plastic deformation, such as the corner and sidewall of the part.

Although the current testing and modeling method can quantify the effect of the prior austenite deformation on continuous cooling transformation, the model proposed in this paper only allows the determination of the transformation when the cooling path does not include an isothermal process. In the future, the phase-field method can be used to predict the phase transformation process to obtain a phase fraction evolution database under complex deformation and cooling conditions, and then deep learning methods can be used to establish a phase transformation prediction model under the arbitrary deformation and cooling conditions.

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Reference

- [1] H. Karbasian, A. E. Tekkaya, A review on hot stamping, *J. Mater. Process. Technol.* 210 (2010), 2103-2118. <https://doi.org/10.1016/j.jmatprotec.2010.07.019>.
- [2] M. Bambach, J. Buhl, T. Hart-Rawung, M. Lechner, M. Merklein, Towards virtual deformation dilatometry for the design of hot stamping process, *Procedia Eng.* 207(2017), 1821-1826. <https://doi.org/10.1016/j.proeng.2017.10.945>.
- [3] M. Merklein, M. Wieland, M. Lechner, S. Bruschi, A. Ghiotti, Hot stamping of boron steel sheets with tailored properties: A review. *J. Mater. Process. Technol.* 228(2016), 11-24. <https://doi.org/10.1016/j.jmatprotec.2015.09.023>.
- [4] K. I. Mori, P. F. Bariani, B. A. Behrens, A. Brosius, S. Bruschi, T. Maeno, J. Yanagimoto, Hot stamping of ultra-high strength steel parts. *CIRP Ann.-Manuf. Technol.* 66 (2017), 755-777. <https://doi.org/10.1016/j.cirp.2017.05.007>.
- [5] R. Neumann, S. Schuster, J. Gibmeier, T. Böhlke, Two-scale simulation of the hot stamping process based on a Hashin–Shtrikman type mean field model. *J. Mater. Process. Technol.* 267(2019), 124-140. <https://doi.org/10.1016/j.jmatprotec.2018.11.013>.
- [6] Y. Li, S. Li, J. He, Y. Chen, L. Yue, Identification methods on blank-die interfacial heat transfer coefficient in press hardening. *Appl. Therm. Eng.* 152(2019), 865-877. <https://doi.org/10.1016/j.applthermaleng.2019.02.079>.
- [7] Y. Chang, X. Tang, K. Zhao, P. Hu, Y. Wu, Investigation of the factors influencing the interfacial heat transfer coefficient in hot stamping. *J. Mater. Process. Technol.* 228(2016), 25-33. <https://doi.org/10.1016/j.jmatprotec.2014.10.008>.
- [8] P. Hu, L. Ying, Y. Li, Z. Liao, Effect of oxide scale on temperature-dependent interfacial heat transfer in hot stamping process. *J. Mater. Process. Technol.* 213(2013), 1475-1483. <https://doi.org/10.1016/j.jmatprotec.2013.03.010>.
- [9] M. Naderi, A. Saeed-Akbari, W. Bleck, The effects of non-isothermal deformation on martensitic transformation in 22MnB5 steel. *Mater. Sci. Eng. A* 487 (2008) 445-455. <https://doi.org/10.1016/j.msea.2007.10.057>.
- [10] Scheil, E. Anlaufzeit der austenitumwandlung. *Arch. Eisenhuettenwes* 12(1935)

565–567.

- [11] Jung, M., Kang, M., Lee, Y. K. Finite-element simulation of quenching incorporating improved transformation kinetics in a plain medium-carbon steel. *Acta Mater.* 60(2012) 525-536. <https://doi.org/10.1016/j.actamat.2011.10.007>.
- [12] M. Abbasi, A. Saeed-Akbari, M. Naderi, The effect of strain rate and deformation temperature on the characteristics of isothermally hot compressed boron-alloyed steel. *Mater. Sci. Eng. A* 538 (2012) 356-363. <https://doi.org/10.1016/j.msea.2012.01.060>.
- [13] Z. Shi, K. Liu, M. Wang, J. Shi, H. Dong, J. Pu, L. Jian, Effect of non-isothermal deformation of austenite on phase transformation and microstructure of 22SiMn2TiB steel. *Mater. Sci. Eng. A* 535 (2012) 290-296. <https://doi.org/10.1016/j.msea.2011.12.088>.
- [14] J. Min, J. Lin, Y. A. Min, F. Li, On the ferrite and bainite transformation in isothermally deformed 22MnB5 steels. *Mater. Sci. Eng. A* 550 (2012) 375-387. <https://doi.org/10.1016/j.msea.2012.04.091>
- [15] Lutz, S., Weninger, J., Helldörfer, B., Merklein, M., Numerical investigation of temperature and phase development of (deformation-) dilatometer specimens. *Key Eng. Mater.* 611(2014) 1539-1544. <https://doi.org/10.4028/www.scientific.net/KEM.611-612.1539>.
- [16] A. Barcellona, D. Palmeri, Effect of plastic hot deformation on the hardness and continuous cooling transformations of 22MnB5 microalloyed boron steel. *Metall. Mater. Trans. A* 40 (2009) 1160-1174. <https://doi.org/10.1007/s11661-009-9790-8>.
- [17] M. Abbasi, M. Naderi, A. Saeed-Akbari, Isothermal versus non-isothermal hot compression process: a comparative study on phase transformations and structure–property relationships. *Mater. Des.* 45 (2013) 1-5. <https://doi.org/10.1016/j.matdes.2012.08.062>.
- [18] M. Nikraves, M. Naderi, G. H. Akbari, W. Bleck, Phase transformations in a simulated hot stamping process of the boron bearing steel. *Mater. Des.* 84(2015) 18-24. <https://doi.org/10.1016/j.matdes.2015.06.108>.

- [19] T. Matsumoto, N. Li, X. Shi, J. Lin, An investigation of deformation effects on phase transformation in hot stamping processes. *SAE Int. J. Mater. Manuf.* 9 (2016) 501-505. <http://www.jstor.org/stable/26267466>.
- [20] H. H. Bok, S. N. Kim, D. W. Suh, F. Barlat, M. G. Lee, Non-isothermal kinetics model to predict accurate phase transformation and hardness of 22MnB5 boron steel. *Mater. Sci. Eng. A* 626 (2015) 67-73. <https://doi.org/10.1016/j.msea.2014.12.008>.
- [21] William J, Mehl R. Reaction kinetics in processes of nucleation and growth. *Trans. Metall. Soc. AIME* 135(1939) 416-442.
- [22] Avrami, M. Kinetics of phase change. I General theory. *The Journal of chemical physics* 7(1939) 1103-1112. <https://doi.org/10.1063/1.1750380>.
- [23] Avrami, M. Kinetics of phase change. II transformation-time relations for random distribution of nuclei. *The Journal of chemical physics* 8(1940) 212-224. <https://doi.org/10.1063/1.1750631>.
- [24] Kolmogorov, A. N. A study of the equation of diffusion with increase in the quantity of matter, and its application to a biological problem. *Moscow University Bulletin of Mathematics* 1(1937) 1-25.
- [25] Kirkaldy, J.S., Venugopalan D. Prediction of microstructure and hardenability in low alloy steels. In *Proceedings of the International Conference on Phase Transformation in Ferrous Alloys*, Philadelphia, USA, 1983 125-48.
- [26] Li, M. V., Niebuhr, D. V., Meekisho, L. L., Atteridge, D. G. A computational model for the prediction of steel hardenability. *Metall Mater Trans B* 29(1998) 661-672. <https://doi.org/10.1007/s11663-998-0101-3>.
- [27] Åkerström P., Oldenburg M. Austenite decomposition during press hardening of a boron steel-Computer simulation and test. *J. Mater. Process. Technol.* 174(2006) 399-406. <https://doi.org/10.1016/j.jmatprotec.2006.02.013>.
- [28] Behrens, B. A., Olle, P., Consideration of phase transformations in numerical simulation of press hardening. *Steel Res. Int.* 78(2007) 784-790.
- [29] Bok, H. H., Lee, M. G., Pavlina, E. J., Barlat, F., Kim, H. D., Comparative study of the prediction of microstructure and mechanical properties for a hot-stamped

- B-pillar reinforcing part. *Int. J. Mech. Sci.* 53 (2011) 744-752.
<https://doi.org/10.1016/j.ijmecsci.2011.06.006>.
- [30] Hippchen, P., Lipp, A., Grass, H., Craighero, P., Fleischer, M., Merklein, M. Modelling kinetics of phase transformation for the indirect hot stamping process to focus on car body parts with tailored properties. *J. Mater. Process. Technol.* 228(2016) 59-67.
- [31] Lee S J, Pavlina E J, Van Tyne C J., Kinetics modeling of austenite decomposition for an end-quenched 1045 steel. *Mater. Sci. Eng. A* 527(2010) 3186-3194.
- [32] Neumann, R., Schuster, S., Gibmeier, J., Böhlke, T. Two-scale simulation of the hot stamping process based on a Hashin–Shtrikman type mean field model. *J. Mater. Process. Technol.* 267(2019), 124-140.
- [33] S. Serajzadeh, Modelling of temperature history and phase transformations during cooling of steel. *J. Mater. Process. Technol.* 146 (2004), 311-317.
<https://doi.org/10.1016/j.jmatprotec.2003.11.010>.
- [34] P. Åkerström, G. Bergman, M. Oldenburg, Numerical implementation of a constitutive model for simulation of hot stamping. *Modelling Simul. Mater. Sci. Eng.* 15 (2007) 105. <https://doi.org/10.1088/0965-0393/15/2/007>.
- [35] H. H. Bok, J. Choi, F. Barlat, D. W. Suh, M. G. Lee, Thermo-mechanical-metallurgical modeling for hot-press forming in consideration of the prior austenite deformation effect. *Int. J. Plasticity* 58 (2014) 154-183. <https://doi.org/10.1016/j.ijplas.2013.12.002>.
- [36] T. Hart-Rawung, J. Buhl, M. Bambach, Extension of a phase transformation model for partial hardening in hot stamping. *J. Mach. Eng.* 18 (2018) 87-97.
<https://doi.org/10.5604/01.3001.0012.4619>.
- [37] K. Omer, R. George, A. Bardelcik, M. Worswick, S. Malcolm, D. Detwiler, Development of a hot stamped channel section with axially tailored properties—experiments and models. *Int. J. Mater. Form.* 11 (2018) 149-164.
<https://doi.org/10.1007/s12289-017-1338-7>
- [38] S. Kamamoto, T. Nishimori, S. Kinoshita, Analysis of residual stress and

distortion resulting from quenching in large low-alloy steel shafts. Mater. Sci. Tech-lond. 1(1985), 798-804. <https://doi.org/10.1179/mst.1985.1.10.798>.

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Highlights

- The influence of austenite deformation on phase transformation during continuous cooling is investigated by DCCT testing.
- A non-isothermal kinetic model of phase transformation considering the pre-deformation of austenite is proposed to predict the mechanical properties of deformation microstructure.
- The influence of austenite deformation on the CCT diagram under various process conditions is obtained.
- The proposed kinetic model of phase transformation for boron steel is verified by the DCCT specimens and hot stamping of W-channel parts.

Credit Author Statement

Yongfeng Li: Conceptualization, Methodology, Software, Investigation, Data curation, Writing- Original draft preparation. **Yuan Chen:** Visualization, Resources, Validation. **Shuhui Li:** Supervision, Project administration, Writing - Review & Editing.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: