Effect of Bainite Volume Fraction on Deformability of Mesostructures for Ferrite/Bainite Dual-Phase Steel

Gui-ying Qiao,1,2 Zhong-tao Zhao,2 Xian-bo Shi,3 Jun-si Wang,2 and Fu-ren Xiao2

1Key Lab of Applied Chemistry of Hebei Province, School of Environment and Chemical Engineering, Yanshan University, Qinhuangdao 066004, China
2Key Lab of Metastable Materials Science & Technology, Hebei Key Lab for Optimizing Metal Product Technology and Performance, College of Materials Science & Engineering, Yanshan University, Qinhuangdao 066004, China
3Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110072, China

Correspondence should be addressed to Gui-ying Qiao; qiaoguiying@ysu.edu.cn

Received 27 July 2020; Revised 5 October 2020; Accepted 4 November 2020; Published 24 November 2020

Copyright © 2020 Gui-ying Qiao et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

To obtain high strength and excellent deformability for ferrite/bainite dual-phase (F/B DP) pipeline steel for gas pipelines based on strain-based design, the volume fractions of ferrite and bainite should be considered first. In this work, abstract representative volume elements (RVE) of finite element models (FEMs) of mesostructure for F/B DP pipeline steel with volume fractions of bainite between 30% and 58% were established, and the effects of volume fraction of bainite on the tensile properties and deformation compatibility were studied. Results show that the stress and strain in the mesostructure were primarily distributed in the bainite and ferrite, respectively, and strain concentration occurs at the ferrite/bainite interface. With increasing volume fractions of bainite, the strain localization factor (SLF) and strain ratio of ferrite with bainite ($\epsilon_F/\epsilon_B$) decrease, which can improve the deformation compatibility of the F/B DP pipeline steel. However, the stress ratio of bainite with ferrite ($\sigma_B/\sigma_F$) and the contributions of bainite to stress and strain sequentially increase, and, as a result, the strength increases and the ductility decreases. Therefore, a balance of strength and deformability can be obtained when the optimal volume fraction of bainite is in the range of 40% to 48%.

1. Introduction

Recently, the strain-based design has been adopted in the pipeline for passing through the geological hazardous areas, such as oceans, swamps, landslides, frozen soils, and earthquakes [1–6]. Hence, the deformation resistance of the pipeline pipe becomes an important parameter to prevent deformation collapse caused by geological and ocean current movement [7, 8]. The deformation resistance of the pipeline pipe is related to the pipe diameter, wall thickness, and longitudinal strain-hardening exponent of the pipeline steel [6, 8]. Therefore, it is necessary for the pipeline steel to exhibit high strain-hardening ability, i.e., excellent deformability. The strain-hardening ability and deformability of the pipeline steel are generally characterized by stress ratio, yield ratio (yield strength/tensile strength), strain hardening exponent, and uniform elongation [1, 9], which have been specified in some pipeline steel specifications such as DNV 2000 [6, 9] and Q/SYGJX 118-2012 [10]. The F/B DP steel consists of a mixed microstructure of ferrite and bainite, where the ferrite is a soft phase with high ductility and the bainite is a hard phase with high strength, and, thus, a balance of high strength and excellent deformability can be obtained [9–11]. Therefore, F/B DP steel with excellent deformability has become a type of special functional pipeline steel, which is one of the best options to replace traditional ferrite/pearlite and acicular ferrite pipeline steels [9].

For the F/B DP pipeline steel, the balance of strength and ductility strongly depends on the volume fraction, distribution, morphology, and mechanical properties of each phase in the ferrite and bainite steel [1, 9, 11, 12]. The
microstructure, mechanical properties, strain-hardening behavior, microscopic deformation, and failure mechanism of the F/B steel have been broadly studied [1, 9–13]. Research has been more focused on the effects of the volume fraction of bainite on strength, yield ratio, uniform elongation, and strain hardening exponent. Although differences were observed in the research, a suitable volume fraction of ferrite and bainite may exist for the F/B DP steel to obtain a balance of strength and ductility [1, 9]. Liu et al. [14] reported that ferrite deformation occurs relatively more easily during plastic deformation. At the same time, bainite must accommodate high deformation characteristics of ferrite because of the stress concentration at the F/B interface, where the crack first initiates. The deformation compatibility between the ferrite and bainite during deformation is an important factor affecting the strain and stress concentration and crack initiation at the F/B interface. Therefore, it is particularly important to consider the deformation compatibility between the ferrite and bainite, which can help to explain the deformation mechanism of the DP steel.

However, due to the strain and stress distribution within the ferrite and bainite in the microstructure, it is difficult to detect the distribution of stress and strain and characterize the localized strain area in the microstructure by conventional experimental methods. In view of this, a finite element method (FEM) has been proposed to analyze the distribution of the stress and strain within the mesostructure DP steel [15–18] and multi-phase steel [19]. These investigations have mainly focused on the ferrite/martensite (F/M) DP steel [15–17], and there is little research on F/B DP steel [20]. The tested and simulated results show that the volume fraction, size, distribution, and hardness of the hardening phase (martensite and/or bainite) have a significant effect on the mechanical properties, deformation and fracture mechanism, and stress and strain distribution between ferrite and the hardening phase of the DP steel [20–22]. Nevertheless, for these results, most of the DP structures were obtained by heat treatment, and the hardening phase is primarily equiaxial and homogeneous. The F/B DP pipeline steel is manufactured by a thermomechanical controlled process (TMCP) [23–25]. The distributed bainite in the ferrite matrix for the DP pipeline steel is usually in elongated form. Meanwhile, the amount, size, distribution, and hardness of the bainite strongly depend on the parameters of TMCP including rolling temperature, finishing rolling temperature, beginning cooling temperature, cooling rate, and finishing cooling temperature [26–28]. In this case, the volume fraction of bainite with elongated form will become an important influencing parameter of the deformation behavior and mechanical properties. Therefore, the effect of volume fraction of bainite with elongated in F/B DP steel on the deformation compatibility deserves more attention.

In this work, representative volume elements (RVE) of FEMs based on the mesostructure of the F/B DP pipeline steel have been built. The effect of volume fraction of bainite with elongated form on tensile properties and the distribution of strain and stress in ferrite and bainite in the mesostructure of F/B steel were simulated. Furthermore, the effect of bainite volume fraction on deformation compatibility was discussed. The goal is to reveal the mechanism for the effect of volume fraction of bainite on the deformation compatibility in the mesostructure and help to optimize the microstructure for F/B DP steel to obtain a balance between strength and deformability.

2. Materials and Simulation

2.1. Materials. The steel employed in this work was cut from a commercial API X80 ferrite/bainite double-phase (F/B DP) pipeline steel plate produced by TMCP. The chemical composition and microstructure of the steel are presented in Table 1 and Figures 1(a) and 1(b). The microstructure of the steel consists of elongated bainite distributed in the ferrite matrix, and the volume fraction of bainite is about 43% (Figure 1(a)). The electron back-scattered diffraction (EBSD) image quality maps with grain boundary misorientation distribution show that the ferrite mainly consists of the high-angle boundaries, while the bainite mainly consists of low-angle boundaries (Figure 1(b)).

2.2. FEM Model Generation and Analysis. Previous works show that the RVE model based on mesostructure and/or abstract RVE model are effective methods to study the mechanism of plasticity deformation behavior of multi-phase steel [18, 19, 29]. According to our previous work [29], the RVE model based on mesostructure (Figures 1(a) and 1(b)) was first built as shown in Figure 1(c). However, the aim of this work is to study the effect of volume fraction of bainite on the mechanical properties of F/B DP pipeline steels with excellent deformability. It is difficult to obtain the microstructure with different volume fractions of bainite to build the RVE model based on real mesostructure. Therefore, abstract RVE models with different volume fractions of bainite were created, as shown in Figure 2. In the abstract RVE models, a volume fraction of bainite over a range from 30% to 58% was selected, and other factors, like morphology and distribution of bainite, were controlled based on the microstructural characteristic of bainite in F/B DP pipeline steel (Figure 1(a)).

According to our previous work [29], the mechanical properties of each individual phase were measured by means of micro-indentation tests according to [30] and [31]. Figure 1(d) shows the stress-strain curves obtained from the simulation and tensile test. The simulated curve is similar to the test curve, which indicates that the model can appropriately affect the overall behavior of F/B DP steel.

Finite element analysis can show the distribution of the stress and strain directly in the mesostructure. In this work, the microscopic stress and strain in the single phases were calculated by the method in [32]. After calculating the stress and strain in the single phase, the macroscopic stress and strain of the RVE can be calculated by the method in [33]. In this work, strains of 1%, 5%, and 10% were selected as the applied strains corresponding to the three stages of the deformation, i.e., elastic deformation, stable plastic deformation, and unstable plastic deformation.
3. Results

3.1. Mechanical Properties of Models with Different Fractions of Bainite. The stress-strain curves and mechanical properties of the models with different fractions of bainite were obtained by simulation as shown in Figure 3. Yield strength ($\sigma_y$), tensile strength ($\sigma_s$), and yield ratio ($\sigma_y/\sigma_s$) increase with increasing fractions of bainite. The increase in yield ratio implies that the uniform elongation (UE) decreases with increasing fractions of bainite.

For the DP steel, the strength can be expressed as follows:

$$\sigma_{DP} = \sigma_B V_B + \sigma_F (1 - V_B), \quad (1)$$

where $\sigma_{DP}$ is the strength of the F/B DP steel, $\sigma_B$ and $\sigma_F$ are the strengths of bainite and ferrite, and $V_B$ is the volume fraction of bainite.

According to equation (1), the strength of the F/B DP steel will linearly increase with an increasing volume fraction of bainite. However, the simulated results show that the yield strength linearly increases with an increasing volume fraction of bainite, while, for the tensile strength, the increment of tensile strength when the bainite fraction increases from 30% to 40% is higher than the increment when the bainite fraction increases from 40% to 58%. As a result, the yield ratio slightly increases when the bainite fraction increases from 30% to 40%, while, as the fraction of bainite increases over 40%, the yield ratio quickly increases (Figure 3(b)). Conversely, the uniform elongation rate slightly decreases when the bainite fraction increases from 30% to 40% and then quickly decreases when the bainite fraction increases from 40% to 58%. Sun et al. [34] reported that the uniform elongation of M/F DP steel decreases with increasing volume fractions of martensite, but the uniform elongation is not linearly related to martensite volume fraction. For DP steels, the size, distribution, and morphology of each phase in the microstructure will affect the distribution of stress and strain during the deformation process, which will directly affect the mechanical properties of the steel [35].

3.2. Distribution of Strain in the Deformed Mesostructure. The simulated distribution of the equivalent plastic strain within the mesostructure in the RVE models when applied strains are 1%, 5%, and 10% is presented in Figure 4. Strain localization can be observed from the mesostructure when the strain is applied, and the strain localization increases...
with increasing applied strain. When the applied strain is 1% (Figures 4(a)–4(d)), the plasticity strain primarily exists in the ferrite phase, and a small amount of plastic strain can be observed in bainite because of its high yield strength. Thus, the deformation first occurs in ferrite and the strain localization occurs in the ferrite at the grain boundary between ferrite and bainite. The strain localization presents an angle of 45° to the loading direction due to the maximum shear stress. The equivalent plastic strain is quite small, and its distribution is relatively homogeneous in the mesostructure. However, the fraction of bainite has a major impact on the distribution of the equivalent plastic strain in the mesostructure. With increasing bainite fractions, the number of bainite phases with plastic strain increases, and the plastic strain in ferrite appears to show a decreasing trend, which indicates that strain localization will be improved with increasing volume fraction of bainite.

When the applied strain was raised to 5%, the localized strain area expanded, and the plastic deformation spread to most of the ferrite and bainite in the model, while the equivalent plastic strain in ferrite and bainite significantly increased. In addition, some unusual local strain concentration can be found in some parts of ferrite between the bainite, which may be related to the strain concentration caused by the geometric shapes of bainite (Figures 4(e)–4(h)). As the applied strain increased to 10%, the localized strain band began to shrink, and the average strain in the localized band increased (Figures 4(i)–4(m)). Moreover, the difference in equivalent plastic strain between the ferrite and bainite also increased. It was also shown that the bainite volume fraction in the mesostructure did not affect the distribution of the equivalent plastic strain in ferrite and bainite, but even more importantly, it significantly affected the strain localization between ferrite and bainite. With increased bainite volume fraction, the difference in average equivalent plastic strain between the ferrite and bainite exhibits decreasing trends. The supposition can be confirmed by statistical results of the probability distribution function (PDF) of equivalent plastic strain calculated from Figure 4. Furthermore, strain localization factor (SLF) was calculated based on PDF, which can quantitatively reveal the strain localization and deformation compatibility between two phases in DF steel. The SLF is defined as follows [36]:

$$\text{SLF} = \sum_{i=1}^{n} \left( \varepsilon_{i,F} F_{i,F} - \varepsilon_{i,B} F_{i,B} \right), \quad (2)$$

where $\varepsilon_{i,F}$ and $\varepsilon_{i,B}$ are the equivalent plastic strains of $i$-th bins for ferrite and bainite, respectively, and $F_{i,F}$ and $F_{i,B}$ are the area frequencies of $\varepsilon_{i,F}$ and $\varepsilon_{i,B}$, respectively.

Figures 5–7 show the PDF of equivalent plastic strain when the applied strains are 1%, 5%, and 10%, respectively. Meanwhile, the SLFs are listed in each figure and clearly demonstrate the degree of strain localization between ferrite and bainite. As the applied strain is 1%, the PDFs of bainite and ferrite appear with the same distribution trait. The strain of ferrite is in the range from 0 to 0.06, and the strain of 80% ferrite is about 0.02, while the strain of bainite is also about 0.02. Therefore, the SLFs are small, which are only in the range of 0.0027 to 0.0038 (Figure 5), and the results coincide with the heterogeneous distribution of the equivalent plastic strain in the mesostructure (Figure 4).

When the applied strain is 5% (Figure 6), both curves reflecting the distribution of equivalent plastic strain in bainite and ferrite have become wider and lower, which means that more bainite and ferrite have taken part in plastic deformation, and plastic deformation in bainite and ferrite increases. Also, the bainite volume fraction strongly affects the PDF and SLF. When the bainite volume fraction is 30%, the plastic strain in bainite mainly distributes in the range from 0 to 0.1, and the plastic strain in ferrite mainly distributes on a scale of 0 to 0.2. Thus, the SLF reaches 0.0409 (Figure 6(a)). With increased bainite volume fraction to 40%, the distribution of plastic strain in ferrite changes slightly, but plastic strain in bainite increases to the range from 0 to 0.2. As a result, the SLF reduces to 0.0271 (Figure 6(b)). Inversely, with further increases of bainite volume fraction, the distribution of plastic strain in bainite shows little change, but the fraction of ferrite at lower plastic strain shows an increasing trend (Figures 6(c) and 6(d)). The SLFs increase to 0.0273 and 0.0293 for the model with 48% bainite and 58% bainite, respectively.

As the applied strain is 10%, the change rules of distribution of plastic strain in bainite and ferrite with increasing bainite volume fraction are similar to that when the applied strain is 5%, and, as a result, the SLF also shows similar change rules. The difference is that the distribution of strain in bainite and ferrite further extends to the high strain zone, and the SLFs further increase (Figure 7).

Figure 8 shows the SLFs of the mesostructures with different bainite volume fractions at different applied strains. The SLFs of all mesostructures increase with increasing applied strain, but the growth rates are different, as shown in Figure 8(a). As the applied strain is 1%, all mesostructures show lowered SLF, but the SLF shows an increasing trend. However, when the applied strain increases to 5%, the SLF of the mesostructure with 30% bainite volume fraction is higher than that of other mesostructures. Moreover, the increasing amplitude further increases when the applied strain reaches 10%. With increasing bainite volume fraction, the lower SLF appears when the bainite volume fraction is 40% (Figure 8). The SLF is regarded to reflect the degree of strain concentration and deformation compatibility between the bainite and ferrite in the mesostructure and, furthermore, affects the mechanical properties of the F/B DP steel. As stated above, the PDF and SLF results indicate that the deformation compatibility of the mesostructure can be affected by the volume fraction of the secondary phase [37]. From the viewpoint of deformation compatibility, an optimal volume fraction of bainite in the F/B DP steel may exist. In this work, as the volume fraction of bainite is in the range from 40% to 48%, a lower SLF can be obtained, and, therefore, the F/B DP steel will exhibit excellent deformation compatibility.

3.3. Distribution of Stress in the Deformed Mesostructure.

Figure 9 shows the distribution of equivalent stress within the mesostructure with different bainite volume fractions
when the applied strain is 1%, 5%, and 10%. Overall, the distribution of equivalent stress is opposite to the distribution of equivalent strain (Figure 4). The level of equivalent stress in bainite is higher than that in ferrite because the bainite as a strengthening phase bears the main stress. Meanwhile, the equivalent stresses in bainite and ferrite increase with increasing applied strain. On the other hand, the bainite volume fraction affects the stress in bainite and ferrite. The stress in bainite and ferrite increases with increasing bainite volume fraction.

Figures 10–12 show statistical stress distributions of the mesostructures when the applied strain is 1%, 5%, and 10%, respectively. When the applied strain is 1%, the equivalent stress distribution in ferrite for all mesostructures shows similar features. The bainite volume fraction does not influence the stress distribution in ferrite. The stress peak is maximized at about 600 MPa, and the frequency is higher than 0.7 (Figure 10). However, the stress distribution in bainite is obviously influenced by bainite volume fraction. As the bainite volume fraction is 30%, the distribution peak of stress in bainite is broad. The stress peak is at about 1000 MPa, and the frequency is only 0.2 (Figure 10(a)). As the bainite volume fraction increases to 40%, the distribution peak concentrates on high stress, and the frequency of high stress obviously increases (Figure 10(b)). However, further increases in bainite volume fraction have little effect on the distribution of stress in bainite (Figures 10(c) and 10(d)). As the applied strain reaches 5%, the distribution peaks of stress in ferrite and bainite broaden and move to high stress, while the distribution of stress changes a little with increasing bainite volume fraction (Figure 11). Further increasing the applied strain has little effect on the distribution of stress in ferrite and bainite for all mesostructures (Figure 12).

To discuss the variations of equivalent stress in ferrite and bainite with the applied stress, the cumulative distribution function (CDF) of the equivalent stress was statistically calculated, and the CDFs in ferrite and bainite for all mesostructures are illustrated in Figure 13. The results demonstrate that the frequency distribution of equivalent stress in ferrite is focused mainly at low stress, and the equivalent stress in ferrite nearly exceeds yield strengths under all applied strain conditions. Additionally, the frequency distribution of equivalent stress in bainite mainly distributes at high stress and in a wider range. However, owing to the differences in mechanical properties between the ferrite and bainite, some different effects of the applied strain and volume fraction of bainite on the CDF of equivalent stress in ferrite and bainite can be found.

For the ferrite, with increasing applied strain, the CDF curves move in the direction of high stress. However, when the applied stress exceeds 5%, the moving degree significantly decreases. Moreover, the effect of volume fraction of bainite on the CDF of ferrite appears similar to that of the applied strain. The bainite volume fraction has little effect on the CDFs of ferrite when the bainite volume fraction is over 40%. This result suggests that the stress mainly distributes in bainite because bainite as the strengthening phase restrains the deformation of ferrite with increasing bainite volume fraction, which can be clearly reflected by analyzing the results of the CDF of bainite. Meanwhile, the cumulative fraction of bainite with stress over yield strength was calculated for quantitative analysis of the deformed bainite and is listed in Table 2.

When the applied strain is 1%, the equivalent stress in bainite distributes over a larger range when the bainite volume fraction is 30%, and only a portion of the bainite increases beyond the yield strength (Figure 13(a)), and the fraction of deformed bainite is only 41% (Table 2). When increasing the bainite volume fraction to 40%, the cumulative fraction of bainite with higher equivalent stress over yield strength obviously increases (Figure 13(b)), and the fraction of deformed bainite reaches 71% (Table 2); however, the CDF curves show little change with further increases in bainite volume fraction (Figures 13(c) and 13(d)), where the fraction of deformed bainite is 73% and 75% for the mesostructures with 48% and 58% bainite, respectively. When the applied strain is 5%, the CDF curves for all mesostructures move to higher equivalent stresses, and the

![Figure 3: Simulated results of the effects of bainite volume fraction on (a) stress-strain curves and (b) mechanical properties.](image-url)
cumulative fraction of bainite with equivalent stress over yield strength obviously increases. Nevertheless, the cumulative fraction of deformed bainite for the microstructure with 30% bainite is even lower (Figure 13(a)), which is only 81% (Table 2). When the fraction of bainite is over 40%, the cumulative fraction of deformed bainite increases to above 93% (Table 2). With further increases in applied strain to 10%, the CDF curves of bainite do not markedly change (Figure 13), and the cumulative fraction of deformed bainite is at the same level as that of applied strain of 5% (Table 2). With further increases in applied strain to 10%, the CDF curves of bainite do not markedly change (Figure 13), and the cumulative fraction of deformed bainite is at the same level as that of applied strain of 5% (Table 2). However, from Figures 13(c) and 13(d), the CDF curves of bainite for mesostructure with 48% and 58% bainite show that the equivalent stress distributes in the larger range. The results imply that the inhomogeneity of equivalent stress allocated in bainite increases. In addition, in Table 2, it can be found that the cumulative fraction of deformed bainite tends to decrease when the applied strain increases to 10%, which may be attributed to stress relief because the allied strain is greater than the uniform elongation.

3.4. Strain Ratio and Stress Ratio of Two Phases. The simulated results of strain and stress distributed in the mesostructure of P/B DP steel show the strain mainly distributes in ferrite because the ferrite has low strength, and the deformation first occurs in this region. Then, the deformation concentrates in the interface between the ferrite and bainite, and, as a result, the stress mainly distributes in bainite as the bainite has high strength. The strain

Figure 4: Distribution of equivalent plastic strain within the mesostructure in RVE models of applied different strain.
and stress behaviors in the mesostructure may relate to the applied macroscopic strain. Figure 14 shows the relationship of the strain ratio and stress ratio of two phases in DP steel with applied strain. At the initial stage of deformation, the two phases of ferrite and bainite are mostly in elastic deformation, and the elasticity moduli of the two phases are similar, so the distributions of strain and stress are approximately equal [38]. As a result, the strain ratio and stress ratio of the two phases are about 1 (Figure 14). With increasing applied strain, the deformation is mainly concentrated in ferrite with lower strength, and the strain ratio of ferrite with bainite \( \frac{\varepsilon_F}{\varepsilon_B} \) quickly increases. Meanwhile, the stress is mainly concentrated in bainite, and the stress ratio of bainite with ferrite \( \frac{\sigma_B}{\sigma_F} \) is also rapidly increasing. Furthermore, further increases in applied strain will lead to deformation beginning to occur in bainite, and, thus, increases of strain ratio and stress ratio of the two phases are retarded and they are stable when the applied strain is over 2%. However, when the applied strain is over 6%, the strain ratio appears to increase.

3.5. Effect of Bainite Volume Fraction on Contribution Rate to Stress and Strain. For the F/B DP steel, due to the differences in mechanical properties between ferrite and bainite, the stress and strain responses of ferrite and bainite during deformation are different. Therefore, the contribution of ferrite and bainite to stress and strain is used to analyze the effects of bainite and/or ferrite volume fraction on deformation behaviors, which can be presented as follows:

Figure 5: PDF curves of equivalent plastic strain for models with bainite concentrations of (a) 30%, (b) 40%, (c) 48%, and (d) 58% and applied strain of 1%.
where $\sigma_t$ and $\varepsilon_t$ are the overall strength and strain at any moment.

The contribution of ferrite and bainite to stress and strain for mesostructures is illustrated in Figure 15. With either bainite or ferrite, the contribution to stress and strain quickly changes with increasing applied strain and then stabilizes at a certain value when the applied strain reaches 1%. However, due to the differences in mechanical properties between ferrite and bainite, the change rules of the contribution of bainite and/or ferrite to stress and strain show a contrary variational tendency. For the bainite, with the increasing applied strain, the contribution rate to strain quickly decreases (Figure 15(b)) and the contribution rate to stress quickly increases (Figure 15(a)), and the contribution rate to stress quickly decreases (Figure 15(d)). When the applied strain is greater than 1%, the contribution rates to strain and stress of both bainite and ferrite stabilize.

Moreover, the bainite volume fraction has a strong effect on the contribution rates to strain and stress of both bainite and ferrite. The contribution of bainite to strain and stress increases with increasing bainite volume fraction (Figures 15(a) and 15(b)). Ferrite displays an opposite trend, and the contribution of ferrite to strain and stress decreases with increasing bainite volume fraction (Figures 15(c) and 15(d)).

4. Discussion

As stated above, for F/B DP pipeline steel, with increasing volume fractions of bainite in the range of 30% to 58%, yield strength, tensile strength, and yield ratio increase, while the contribution rate to stress quickly decreases (Figure 15(d)). When the applied strain is greater than 1%, the contribution rates to strain and stress of both bainite and ferrite stabilize.

Moreover, the bainite volume fraction has a strong effect on the contribution rates to strain and stress of both bainite and ferrite. The contribution of bainite to strain and stress increases with increasing bainite volume fraction (Figures 15(a) and 15(b)). Ferrite displays an opposite trend, and the contribution of ferrite to strain and stress decreases with increasing bainite volume fraction (Figures 15(c) and 15(d)). With increases of bainite volume fraction from 30% to 58%, the contribution rate to strain of bainite increases from about 0.15 to 0.47 (Figure 15(a)), and the contribution rate to stress of bainite increases from about 0.38 to 0.69 (Figure 15(b)). These results indicate that the bainite volume fraction has a greater effect on strength.
Figure 7: The PDF curves of equivalent plastic strain for models with bainite concentrations of (a) 30%, (b) 40%, (c) 48%, and (d) 58% and applied strain of 10%.

Figure 8: Effect of bainite volume fraction on strain localization factor (SLF).
uniform elongation decreases (Figure 3). The increasing of yield ratio and the decreasing of uniform elongation are nonlinearly related to bainite volume fraction (Figure 3(b)). As the volume fraction of bainite increases from 30% to 40%, the increment of the yield ratio and the decrement of the uniform elongation are very small. However, with further increases in volume fraction of bainite to 40% to 58%, the yield ratio markedly increases and the uniform elongation significantly decreases. This result is slightly different from the tested results reported by Zhang et al. [1] and Tang et al. [9]. Zhang et al. [1] reported that strength increases while ductility nonlinearly decreases. In addition, Tang et al. [9] reported that tensile strength linearly increases with increasing volume fraction of bainite, while the yield strength shows little increase when the volume fraction of bainite is lower than 47%, and, hence, a lower yield ratio is obtained. Comparing the microstructures in [1] and [9] with the mesostructure in this work, fine equiaxed bainite uniformly distributes in the ferrite matrix [1], and the non-equiaxed bainite uniformly distributes in the acicular ferrite matrix [9]. In this work, the microstructure primarily consists of the elongated shape of the bainite distributed in the ferrite matrix. The difference in mechanical properties among those works may be attributed to the distribution, morphology, and mechanical properties of each phase in the DP steel [11, 12]. However, from the results stated above, the difference in steels among those works mainly occurs when the volume fraction of bainite is lower than 50%. The results

Figure 9: Distribution of equivalent stress within mesostructures in RVE models with different applied strains.
indicate that the volume fraction, size, distribution, and morphology of bainite show greater effects on yield strength, yield ratio, and ductility.

For DP steels, deformation first occurs in the soft phase of ferrite during tensile deformation, where the strain and stress accumulate at the F/B grain boundaries. As the accumulated stress is higher than the yield strength of bainite, the bainite begins to deform, and then the DP steels will show an overall yield phenomenon [31]. From this viewpoint, as the bainite volume fraction is lower than 50%, increasing the F/B grain boundaries can effectively restrain ferrite deformation and promote strain and stress accumulation at the F/B grain boundaries and in bainite (Figures 4 and 9). Therefore, the fine and elongated bainite can effectively decrease the accumulated strain of bainite deformation; as a result, a lower yield strength of the DP steel is obtained [1, 9]. On the other hand, Liu et al. [14] reported that slip and local crystal rotation of ferrite and the rotation of bainite are the primary mechanisms contributing to the deformation of multi-phase steel. When the stress concentration satisfied the fracture strength criteria, the local strain and local crystal rotation were responsible for initiation and growth of voids in ferrite, while the high stress concentration in bainite led to high density of small-sized voids and coalescence of voids leading to bainite fracture. The strain and stress accumulation will affect not only yield strength but also tensile strength; furthermore, they will affect the yield ratio and uniform elongation. Therefore, fine bainite that uniformly distributes in the ferrite matrix is helpful to improve the deformation compatibility between the ferrite and bainite phases. Consequently, the initiation and growth of voids can be restrained, and the tensile strength increases [1]. In addition, in our previous work [29], the DP steel with elongated bainite possesses better deformation compatibility than the steel with equiaxed bainite. This agrees with the simulated results of the effects of volume fraction of bainite on the distributions of strain (Figure 4) and stress (Figure 8). The distributions of strain and stress in bainite significantly increase as the bainite volume fraction increases from 30% to 48% (Figures 5 to 7 and Figures 10 to 12), and the fraction of deformed bainite increases (Table 2). Meanwhile, the strain ratio of ferrite with bainite \( \epsilon_f/\epsilon_B \)
Figure 11: Curves of the equivalent stress distribution of bainite and ferrite in models with bainite volume fractions of (a) 30%, (b) 40%, (c) 48%, and (d) 58% and applied strain of 5%.

Figure 12: Continued.
Figure 12: Curves of the equivalent stress distribution of bainite and ferrite in models with bainite volume fractions of (a) 30%, (b) 40%, (c) 48%, and (d) 58% and applied strain of 10%.

Figure 13: Curves of the cumulative distribution function (CDF) of equivalent stress in models with bainite volume fractions of (a) 30%, (b) 40%, (c) 48%, and (d) 58% when the applied strains are (I) 1%, (II) 5%, and (III) 10%.
Table 2: Fraction of deformed bainite in the mesostructure with different bainite volume fractions at different applied strains.

| Volume fraction of bainite (%) | Applied strain (%) | Volume fraction of deformed bainite (%) |
|-------------------------------|-------------------|----------------------------------------|
| 30                            | 1                 | 41                                     |
|                               | 5                 | 81                                     |
|                               | 10                | 80                                     |
|                               | 1                 | 71                                     |
| 40                            | 5                 | 93                                     |
|                               | 10                | 92                                     |
|                               | 1                 | 73                                     |
| 48                            | 5                 | 94                                     |
|                               | 10                | 92                                     |
|                               | 1                 | 75                                     |
| 58                            | 5                 | 93                                     |
|                               | 10                | 90                                     |

Figure 14: Strain ratio (a) and stress ratio (b) between ferrite and bainite.

Figure 15: Continued.
decreases (Figure 14(a)), and the stress ratio of bainite with ferrite \(\sigma_B/\sigma_F\) increases (Figure 14(b)). Thus, the F/B DP steel strength increases, which is inverse to the ductility; i.e., uniform elongation will decrease. However, Figure 8 shows that strain localization factor (SLF) decreases with increasing volume fraction of bainite from 30% to 48%, which indicates that deformation compatibility is improved. Zhang et al. [36] reported that microscopic plastic strain localization is a main factor affecting ductility. From the viewpoint of the SLF, the lowest SLF will little affect deformation (Figure 3(b)). Therefore, a balance of strength and plasticity of the F/B DP steel is obtained when the volume fraction of bainite is in a range of 40% to 48%.

As the volume fraction of bainite further increases beyond 50%, the microstructure is dominated by bainite. The deformation of ferrite is restricted to the space within elongated bainite. More bainite will participate in the deformation and the distribution of strain and stress in bainite obviously increases (Figure 13). The SLFs increase (Figure 8), and the contribution of ferrite to strain and stress further decreases (Figure 15). As a result, the yield ratio increases and uniform elongation decreases (Figure 3(b)). All simulated results, as stated above, suggest that an excellent balance of strength and deformability of the F/B DP steel can be obtained when the volume fraction of bainite is in the range of 40% to 48%. The volume fraction of bainite in the F/B DP steel agrees with the results reported in [9] and [10] and the current commercial pipeline steels with excellent deformability [4]. These results can be used to develop high pipeline steel with excellent deformability.

5. Conclusions
The effects of bainite volume fraction in the mesostructure of F/B DP steel on deformation compatibility have been studied by FEM with RVE models based on abstract models. The main conclusions from this work are as follows:

1. The mesostructure of F/B DP steel with volume fractions of bainite from 40% to 48% has a good balance of higher strength and excellent deformability.

2. Ferrite in the mesostructure of F/B DP pipeline steel has lower strength and superior deformability than bainite, the deformation in ferrite occurs relatively more easily during plastic deformation, and deformation can be impeded by high strength bainite. Strain concentration occurs at the ferrite/bainite interface. Thus, the deformation compatibility of the mesostructure between ferrite and bainite strongly affects the tensile properties. Increasing volume fraction of bainite from 30% to 40% can limit the deformation of ferrite in elongated bainite and facilitate bainite deformation, which decreases the strain localization factor (SLF) and improves the deformation compatibility of the F/B DP pipeline steel.

3. With further increases in volume fraction of bainite from 40% to 58%, SLFs begin to increase and the contribution of bainite to strain and stress increases significantly, which results in increased strength and decreased ductility.

Data Availability
The data used to support the findings of this study are included within the article.

Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.
Authors’ Contributions

Gui-ying Qiao, Zhong-tao Zhao, and Jun-si Wang designed the research and conducted the experiments; Gui-ying Qiao prepared the draft manuscript; Gui-ying Qiao, Xian-bo Shi, and Fu-ren Xiao supervised the project and participated in the discussions; Fu-ren Xiao revised the manuscript. All authors reviewed the manuscript.

Acknowledgments

This work was supported by the National Key R&D Program of China (Grant no. 2016YFC0303000), the National Natural Science Foundation of China (Grant no. 51671164), and the 13th Five-Year Key R&D Program of the Ministry of Science and Technology (Grant no. 2017YFB0304901).

References

[1] X. Zhang, H. Gao, X. Zhang, and Y. Yang, "Effect of volume fraction of bainite on microstructure and mechanical properties of X80 pipeline steel with excellent deformability," *Materials Science and Engineering: A*, vol. 531, pp. 84-90, 2012.

[2] L. K. Ji, H. L. Li, H. T. Wang et al., "Influence of dual-phase microstructures on the properties of high strength grade line pipes," *Journal of Materials Engineering and Performance*, vol. 23, no. 11, pp. 3867–3874, 2014.

[3] L. G. Liu, H. Xiao, Q. Li et al., "Evaluation of the fracture toughness of X70 pipeline steel with ferrite-bainite microstructure," *Materials Science and Engineering: A*, vol. 688, pp. 388–395, 2017.

[4] Z.-p. Zhao, G.-y. Qiao, L. Tang, H.-w. Zhu, B. Liao, and F.-r. Xiao, "Fatigue properties of X80 pipeline steels with ferrite/bainite dual-phase microstructure," *Materials Science and Engineering: A*, vol. 657, pp. 96-103, 2016.

[5] M. Guagnelli, J. Ferino, E. Anelli, and G. Mannucci, "High-strength line pipes with enhanced deformability," *International Journal of Offshore and Polar Engineering*, vol. 20, no. 4, pp. 298–305, 2010.

[6] H.-l. Li, X. Li, L.-k. Ji, and H.-d. Chen, "Strain-based design for pipeline and development of pipe steels with high deformation resistance," *Welded Pipe and Tube*, vol. 30, no. 5, pp. 5–11, 2007, in Chinese.

[7] P. Vazouras, S. A. Karamanos, and P. Dakoulas, "Mechanical behavior of buried steel pipes crossing active strike-slip faults," *Soil Dynamics and Earthquake Engineering*, vol. 41, pp. 164–180, 2012.

[8] L. K. Ji, H. L. Li, H. Y. Chen, and W. Z. Zhao, "Analysis of local buckling strain of line pipe," *Chinese Journal of Applied Mechanics*, vol. 29, no. 6, pp. 758–762, 2012, in Chinese.

[9] C. J. Tang, C. J. Shang, S. L. Liu, H. L. Guan, R. D. K. Misra, and Y. B. Chen, "Effect of volume fraction of bainite on strain hardening behavior and deformation mechanism of F/B multi-phase steel," *Materials Science and Engineering: A*, vol. 731, pp. 173–183, 2018.

[10] CNPC Pipeline Construction Project Department, *Q/SY GJX 118-2012 Technical Specification of High Strength SAWL Line Pipe for X80 Gas Pipeline Project*, CNPC Pipeline Construction Project Department, Beijing, China, 2012.

[11] A Saha Podder and R. K. Ray, "Deformation behavior of hot rolled ferrite-bainite dual phase steels," in *Proceedings of the Materials Processing Fundamentals 2007—Proceedings of Symposium Held during the 2007 TMS Annual Meeting*, pp. 11–19, TMS Annual Meeting, Orlando, FL, USA, 2007.

[12] L. K. Ji, H. Feng, J. M. Zhang, and H. Y. Chen, "Strain-hardening properties of high grade line pipes," *Materials Science Forum*, vol. 913, pp. 331–339, 2018.

[13] L. Ji, H. Chen, C. Huo et al., "Key issues in the specification of high strain line pipe used in strain-based designed districts of the 2nd west to east pipeline," in *Proceedings of IPC2008 7th International Pipeline Conference*, pp. 695–703, Calgary, Alberta, Canada, 2008.

[14] S. Liu, X. Li, H. Guo, C. Shang, and R. D. K. Misra, "Isolating contribution of individual phases during deformation of high strength-high toughness multi-phase pipeline steel," *Materials Science and Engineering: A*, vol. 639, pp. 131–135, 2015.

[15] M. R. Ayatollahi, A. C. Darabi, H. R. Chamani, and J. Kadkhodapour, "3D micromechanical modeling of failure and damage evolution in dual phase steel based on a real 2D microstructure," *Acta Mechanica Solida Sinica*, vol. 29, no. 1, pp. 95–110, 2016.

[16] J. Kadkhodapour, S. Schmauder, D. Raabe, S. Ziaei-Rad, U. Weber, and M. Calcagnotto, "Experimental and numerical study on geometrically necessary dislocations and non-homogeneous mechanical properties of the ferrite phase in dual phase steels," *Acta Materialia*, vol. 59, no. 11, pp. 4387–4394, 2011.

[17] M. Marvi-Mashhadi, M. Mazinani, and A. Rezaee-Bazaz, "FEM modeling of the flow curves and failure modes of dual phase steels with different martensite volume fractions using actual microstructure as the representative volume," *Computational Materials Science*, vol. 65, pp. 197–202, 2012.

[18] S. Basanta, V. Singh, A. Bhattacharya, N. Khitia, and D. Das, "Prediction of tensile behaviour of ferrite-martensite dual phase steel using real microstructure-based RVE simulations," *Materials Today: Proceedings*, vol. 5, no. 9, pp. 18275–18280, 2018.

[19] V. Uthaisangsuk, U. Prahl, and W. Bleck, "Characterisation of formability behaviour of multiphase steels by micro-mechanical modelling," *International Journal of Fracture*, vol. 157, no. 1–2, pp. 55–69, 2009.

[20] N. Ishikawa, K. Yasuda, H. Sueyoshi et al., "Microscopic deformation and strain hardening analysis of ferrite-bainite dual-phase steels using micro-grid method," *Acta Materialia*, vol. 97, pp. 257–268, 2015.

[21] S. Zarei, R. J. Nedoushan, and M. Atapour, "The sources of the micro stress and strain inhomogeneity in dual phase steels," *Materials Science and Engineering: A*, vol. 674, pp. 384–396, 2016.

[22] M. Basiruddin, I. Alam, and D. Chakraborti, "The role of fibrous morphology on the Charpy impact properties of low carbon ferrite-bainite dual phase steel," *Materials Science & Engineering A*, vol. 716, pp. 208–219, 2018.

[23] N. Ishikawa, M. Okatsu, S. Endo, and J. Kondo, "Design concept and production of high deformability linepipe," in *Proceedings of the Biennial International Pipeline Conference*, pp. 215–222, Calgary, Canada, September 2007.

[24] Y. K. Wang, Y. Ke, Y. Y. Shan, and M. C. Zhao, *Development of Acicular Ferrite/bainite TMCP Steel for the Natural Gas Pipeline Projects in China*, Microalloyed Steels, China, 2002.

[25] X. Zuo and Z. Zhou, "Study of pipeline steels with acicular ferrite microstructure and ferrite-bainite dual-phase microstructure," *Materials Research*, vol. 18, no. 1, pp. 36–41, 2015.
properties of ferrite-bainite dual-phase pipeline steels,” *Advanced Materials Research*, vol. 197-198, pp. 724–729, 2011.

[27] L. I. Zhuang and L. Wei, “Study of microstructure and mechanical properties of hot-rolled ultra-high strength ferrite-bainite dual phase steel,” *Materials Science Forum*, vol. 921, pp. 208–213, 2018.

[28] T. Waterschoot, B. C. De Cooman, and D. Vanderschueren, “Influence of run-out table cooling patterns on transformation and mechanical properties of high strength dual phase and ferrite-bainite steels,” *Ironmaking & Steelmaking*, vol. 28, no. 2, pp. 185–190, 2001.

[29] Z.-t. Zhao, X.-s. Wang, G.-y. Qiao, S.-y. Zhang, B. Liao, and F.-r. Xiao, “Effect of bainite morphology on deformation compatibility of mesostructure in ferrite/bainite dual-phase steel: mesostructure-based finite element analysis,” *Materials & Design*, vol. 180, p. 107870, 2019.

[30] W. C. Oliver and G. M. Pharr, “An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments,” *Journal of Materials Research*, vol. 7, no. 6, pp. 1564–1583, 2011.

[31] A. Gouldstone, N. Chollacoop, M. Dao, J. Li, A. Minor, and Y. Shen, “Indentation across size scales and disciplines: recent developments in experimentation and modeling,” *Acta Materialia*, vol. 55, no. 12, pp. 4015–4039, 2007.

[32] A. Fillafer, C. Krempaszky, and E. Werner, “On strain partitioning and micro-damage behavior of dual-phase steels,” *Materials Science and Engineering: A*, vol. 614, pp. 180–192, 2014.

[33] S. Kuang, Y.-l. Kang, H. Yu, and R.-d. Liu, “Stress-strain partitioning analysis of constituent phases in dual phase steel based on the modified law of mixture,” *International Journal of Minerals, Metallurgy and Materials*, vol. 16, no. 4, pp. 393–398, 2009.

[34] J. Sun, T. Jiang, Y. Wang, S. Guo, and Y. Liu, “Ultrafine grained dual-phase martensite/ferrite steel strengthened and toughened by lamella structure,” *Materials Science and Engineering: A*, vol. 734, pp. 311–317, 2018.

[35] S. K. Paul, “Real microstructure based micromechanical model to simulate microstructural level deformation behavior and failure initiation in DP 590 steel,” *Materials & Design*, vol. 44, pp. 397–406, 2013.

[36] C. Zhang, S. Yang, B. Gong, C. Deng, and D. Wang, “Effects of post weld heat treatment (PWHT) on mechanical properties of C-Mn weld metal: experimental observation and microstructure-based simulation,” *Materials Science and Engineering: A*, vol. 712, pp. 430–439, 2018.

[37] J. Zhang, H. Di, Y. Deng, and R. D. K. Misra, “Effect of martensite morphology and volume fraction on strain hardening and fracture behavior of martensite-ferrite dual phase steel,” *Materials Science and Engineering: A*, vol. 627, pp. 230–240, 2015.

[38] M. Amirmaleki, J. Samei, D. E. Green, I. Van Riemsdijk, and L. Stewart, “3D micromechanical modeling of dual phase steels using the representative volume element method,” *Mechanics of Materials*, vol. 101, pp. 27–39, 2016.