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Micromechanical Behavior and Failure Mechanism of F/B Multi-phase High Performance Steel

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Abstract: The deformation and micro-voids formation mechanisms in ferrite/bainite (F/B) multi-phase steel with the volume fraction of bainite less than 50% were studied by numerical simulation and experimental observation. The results show that the micro-strain concentrates at the soft/hard phase (F/B) interface in the multi-phase steel, which should be correlated with the mechanism of incoordinate deformation. During the necking of the steel, the micro-voids initially form around the F/B interface, which also form in ferrite and bainite with the severe strain. The micro-voids in bainite are more dense and finer than those in ferrite. The failure mechanism of bainite is the coalescence of micro-voids, and the failure mechanism of ferrite is the growth and tearing of micro-voids. Due to the different failure mechanisms of ferrite and bainite, a suitable part of soft phase would be beneficial to the capability of anti-failure of F/B multi-phase steel during the ductile fracture.

Key words: ferrite/bainite multi-phase steel; numerical simulation; ferrite/bainite interface; micro-strain; micro-void; failure mechanism; soft phase

In order to increase the transportation efficiency and reduce the construction cost, the pipeline project is heading to the development of higher grade, higher pressure level and larger diameter. The Second West-East Gas Pipeline Project has been constructed in China. The grade of X80 pipeline steel was used in the main line with the diameter of 1219 mm and the pressure of 12 MPa[1,2]. However, with the increasing demands of natural gas in China, pipeline projects with more efficiency and much higher transportation capacity are under planning and designing. Conventional X80, X90, X100 and X120 pipeline steels are mostly composed of low carbon bainitic microstructure[3-6]. The low carbon bainitic microstructure is beneficial to high strength and good toughness of the steel[3,4], but has adverse effects on uniform elongation, yield ratio, strain aging sensitivity and so on[3,7]. The conventional pipeline steel cannot meet higher safety requirement. In order to improve the safety of higher grade pipeline, a kind of third generation pipeline steel has been developed by the concept of control multi-phase (soft and hard phase) by TMCP (thermo-mechanical controlled processing)[6,8]. The microstructure of the third generation pipeline steel is composed of ferrite (soft) phase and bainite/martensite (hard) phase, which can ensure the low yield ratio and high uniform elongation[8,9]. Ferrite acts as a soft phase, which can deform firstly in the deformation process and contribute to a high uniform elongation and a low strain aging sensibility[3,10]. Bainite/martensite acts as a hard phase, which contributes to a high tensile strength.

Currently, multi-phase X70, X80, even X100 grade pipeline steels have been developed in China for new pipeline projects[11]. Generally, deformation behavior and collapse/failure phenomenon of multi-phase steels are much more correlated with the safety criteria of the pipeline. Therefore, the deformation behavior and failure mechanism of multi-phase steels should be studied intensively. In the present work, the deformation behavior and failure mechanism of F/B (ferrite/bainite) multi-phase steel with the volume fraction of bainite less than 50% (X80 grade) were investigated by micromechanical analysis and

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experimental observation.

1 Experimental and Simulation Method

1.1 Chemical compositions and microstructure of experimental steel

A low carbon micro-alloyed steel was employed to investigate the deformation behavior and failure mechanism. The chemical compositions (mass%) of the experimental steel were as follows: C 0.04, Mn 1.75, Si 0.22, Nb 0.10, (Cu+Cr+Ni) 0.5 and Fe for balance. The experimental steel was obtained by TMCP. Cylindrical tensile specimens for mechanical properties testing were cut in the longitudinal direction of the steel plate. Metallographic specimens were ground and polished firstly, then etched by a 5 vol.% nitric acid alcohol solution for a few seconds. The mechanical properties of the steel are listed in Table 1. The steel reaches the grade of X80, and the main components of the steel are acicular ferrite, bainite and a few quasi-polygonal ferrite, as shown in Fig. 1. The volume fraction of bainite was obtained by measuring the area fraction of bainite in optical microstructure (OM) of the steel.

Table 1 Volume fraction of bainite and mechanical properties of experimental steel (engineering value)

Volume fraction of bainite/%	Yield strength ($R_{t0.5}$)/MPa	Tensile strength (R_m)/MPa	Yield ratio ($R_{t0.5}/R_m$)	Uniform elongation (UEL)/%	Total elongation (TEL)/%
47.0	560	848	0.66	9.0	28.9

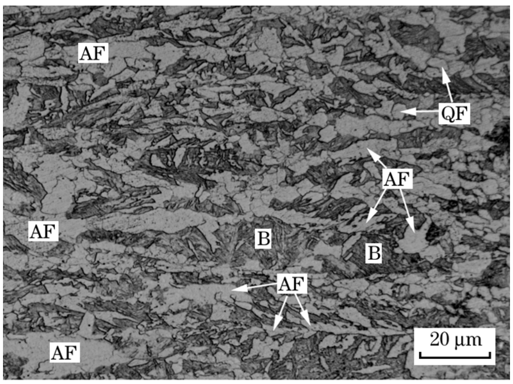
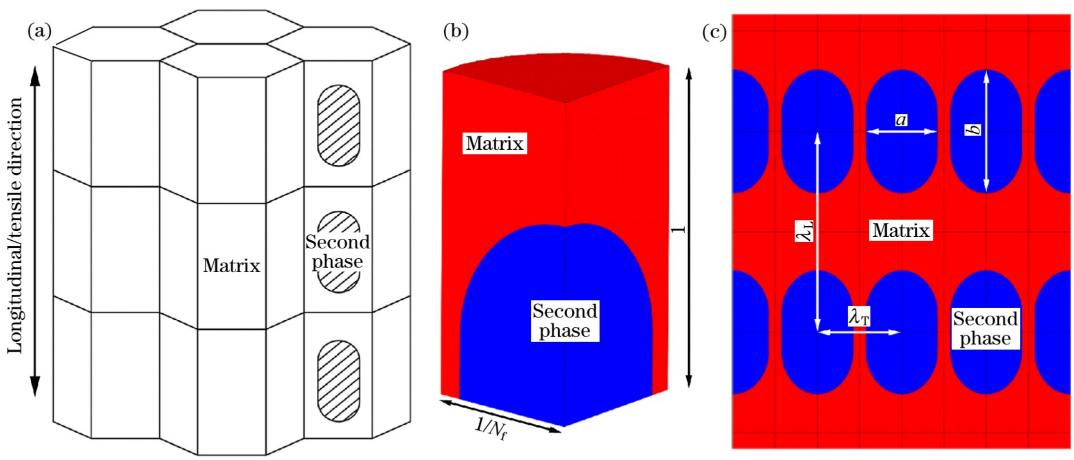


Fig. 1 Optical microstructure of experimental steel

1.2 FEM simulation method by SHA model

Micro-strain distribution in the experimental steel has been studied by SHA (stacked hexagonal array) model[12,13]. SHA model is one kind of RVE (representative volume element) model. The macro-scopic structure of the steel can be established by finite numbers of periodically arranged unit cells in RVE model, and the micromechanical behavior of the steel is characterized by the unit cell. Meanwhile, the stress-strain curve of the steel was obtained by homogeneous method[14,15], which can be used to compare with the experimental stress-strain curve. The structure of SHA model is approximately periodic honeycomb, as can be seen in Fig. 2(a). The unit cell of SHA model is shown in Fig. 2(b), which is approximated to a cylinder with the core of second phase. Meanwhile, the cross section of SHA model can be seen in Fig. 2(c). There are three basic parameters in SHA model known as the aspect ratio (R_a), the neighboring factor (N_f) and the volume fraction of second phase (V_S). The meanings of R_a



(a) Periodic honeycomb structure of SHA model; (b) An eighth of unit cell in SHA model; (c) Cross section of SHA model.

Fig. 2 Schematic of SHA model