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Isolating contribution of individual phases during deformation of high strength–high toughness multi-phase pipeline steel

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ABSTRACT

An innovative approach to fundamentally understand the contribution of individual phases in governing deformation and collapse behavior of high strength–high toughness combination microalloyed multi-phase steel is elucidated. The study indicates that slip and local crystal rotation of ferrite and the rotation of bainite are the primary mechanisms that contribute to the deformation of multi-phase steel. Stress concentration was observed at ferrite–bainite and ferrite–ferrite interface and also within the bainite phase, which contributed to the rotation of bainite and nucleation of voids. Different types of voids formed within different phases and phase boundary, which also lead to different fracture morphologies.

1. Introduction

In recent research of high strength pipeline steels for oil and gas transport, fracture process is a major concern for the safe design and operation at high internal pressure [1–3]. Generally, the increase in strength is accompanied with loss in ductility. In this case, multi-phase design approach is preferred to obtain good combination of strength, ductility, and toughness in high strength steels [4,5]. The multi-phase steels comprising of ferrite, bainite and martensite/austenite (M/A) constituents with high deformability and yield strength range of 500–700 MPa are being considered for structural applications including pipeline and long-span bridges [4,6]. From an engineering perspective, the arrest of ductile fracture of steel is determined by the plastic collapse behavior [1,2]. But from the metallurgical point of view, the collapse failure of steel is correlated with micromechanics and microstructure of the steel. Although, significant progress has been made in the development of multi-phase steel with an excellent uniform elongation and low yield/tensile strength (Y/T) ratio [4,5], the mechanism of deformation and collapse behavior of the multi-phase microstructure is still unclear.

The deformation and collapse behavior of multi-phase steels is relatively more complex than conventional bainitic steel. Recent studies indicated that ferrite–martensite dual phase steels experience stress concentration at interfaces such that void nucleation occurred in ferrite in conjunction with crack initiation in martensite [7–9]. Void nucleation was also observed at the F–B phase boundary besides interior of the ferrite grain in an automotive steel [10], but the mechanism of deformation of bainite in ferrite–bainite multi-phase steel was not discussed. Recently we proposed, cooperative deformation of ferrite and bainite in multi-phase pipeline steel as the primary mechanism for stress distribution [11]. But the mechanism of the cooperative deformation of ferrite and bainite is unclear; to find out the deformation behavior of ferrite and bainite in ferrite–bainite multi-phase steel is necessary.

In the study of deformation behavior, stress distribution can be studied by electron back scattered diffraction pattern (EBSD) [12–17], high-energy X-ray diffraction [18,19], and *in situ* neutron diffraction [20,21]. On the other hand, strain distribution can be measured *via in situ* tensile test in a scanning electron microscope (SEM) in combination with digital image correlation and digital image processing [9,22]. Irrespective of the above, experimental measurements of stress and strain distribution are not well developed unlike the finite element method (FEA) simulation [23–25]. Furthermore, polycrystalline material is isotropic in the context of macromechanics and is anisotropic in micromechanics.

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Also, FEA does not take into consideration the crystal orientation variation. Thus, the objective of the study described here is to isolate the contribution of individual phase during deformation and collapse in high strength–high toughness ferrite–bainite steel.

2. Experiment procedure

2.1. Material

The nominal chemical composition of multi-phase steel was Fe–0.06C–0.25Si–1.90Mn–0.09Nb–(Ni–Cr–Mo–Ti) < 1.0 (in wt%). The experimental steel was industrially processed on a trial basis *via* thermo-mechanical control processing (TMCP) and the details are presented elsewhere [5]. The final thickness of the steel plate was 18.4 mm. Specimens were cut longitudinally from the plate.

2.2. Experiment techniques

SEM (Zeiss Supra 55VP FEG) was used to observe the microstructure and fracture surface. *In situ* tensile testing in SEM equipped with EBSD was used to explore stress distribution, strain behavior, and crystal rotation in multi-phase steels. A non-standard thin plate tensile testing specimen (50 mm × 10 mm × 3 mm) was prepared by electropolishing in a solution containing ethanol, perchloric acid, and glycerin in the ratio of 8.5:1:0.5. Next, *in situ* observation was carried out at strains of 0%, 3% and 8%, respectively, using field-emission SEM equipped with EBSD. EBSD scanning was performed at an acceleration voltage of 20 kV; working distance of 16 mm; title angle of 70°, and step size of 0.15 μm. Channel 5 software was used to process the orientation data, and Matlab was used to calculate the misorientation of crystal.

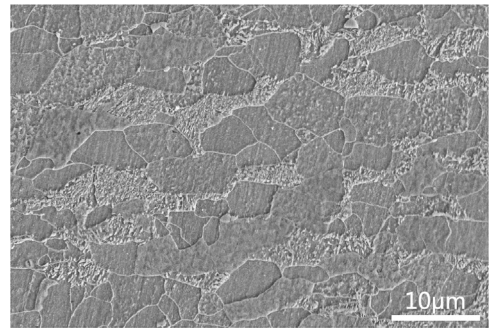

Fig. 1. Microstructure of hot rolled multi-phase steel.

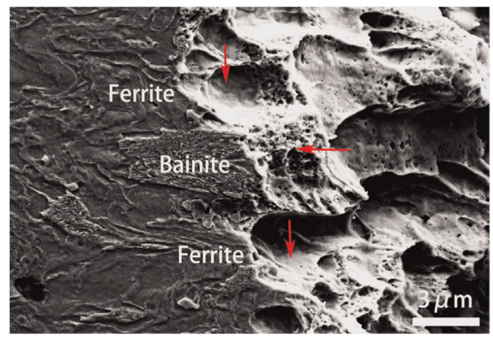

Fig. 2. SEM micrograph of the fracture surface of the standard tensile specimen. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

3. Results and discussion

3.1. Mechanical properties, microstructure, and fracture surface

The mechanical properties of the steel are presented in Table 1. The steel was characterized by lower *Y*/*T* ratio and high uniform elongation. The yield ratio was less than 0.85 and the uniform elongation was higher than 8%, and were superior than conventional 550 MPa grade (X80) pipeline steel [4]. These properties can achieve high level safety design criteria of high strength pipeline steel. The microstructure of the steel consisted of ~40% by volume of bainite and ~60% ferrite, and the ferrite grain size was in the range of 3–10 μm (Fig. 1). In the previous study, we correlated the outstanding mechanical properties with multi-phase volume fraction and distribution [11].

The morphology of the fracture surface and the microstructure beneath the fracture surface as observed by SEM are shown in Fig. 2. The left side in Fig. 2 is the highly deformed microstructure, while on the right side there were two kinds of dimples on the fracture surface, *viz.*, the large-sized dimples in ferrite (indicated by red arrow pointing down) and the small-sized dimples in bainite with high density (red arrow pointing left). The difference in the size of dimples may be related to different operating mechanisms and to the different degrees of deformability of ferrite and bainite.

Table 1
Mechanical properties of multi-phase steel.

Yield strength (YS) (MPa)	Tensile strength (TS) (MPa)	YS/TS ratio	Uniform elongation (UEL) (%)	Impact toughness/J (−20 °C)	DWTT (−15 °C) SA%
629	778	0.8	8.55	425	100

3.2. Mechanism of nucleation of micro-voids

To fundamentally study the mechanism of formation of two types of dimples: the microstructure in neck region (region 1 marked by red frame 1 in Fig. 3a) and region 2 which is closed to neck region (marked by red frame 2 in Fig. 3a) of the non-standard tensile specimen was observed in SEM. The undeformed microstructure is shown in Fig. 3b. Two types of voids were observed in the neck region (Fig. 3(e) and (f)). The large-sized voids located within the ferrite grains were referred as type I and the small-sized voids of high density located within the bainite were referred as type II.

A void with diameter less than 100 nm was observed to nucleate at the phase boundary in region 2, as shown in Fig. 3(c) and (d). The micro-strain around the void extended into ferrite, and the strain in bainite was relatively much slighter by observation. Type I voids in the interior of the ferrite grain were found in the neck region (red arrow pointing down in Fig. 3e). Since SEM micrograph is the cross-sectional view and voids of type I could be as large as ~2 μm in diameter (Fig. 3e), this did not confirm that type I voids were nucleated in ferrite interior. Since, they may nucleate at the grain boundary below the observed surface.

Type II voids in bainite are shown in Fig. 3e (red arrow pointing left), and it is found that some of this kind of voids coalesced as seen in Fig. 3f (red arrow pointing left). Thus, it is believable that type II voids nucleated separately, and the fracture of bainite was caused by coalescence of voids. According to the size and location, it is reasonable to infer that type I voids developed into large-sized dimples in ferrite and type II developed into small-sized dimples in bainite, as shown in Fig. 2.