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# Microscopic deformation and strain hardening analysis of ferrite–bainite dual-phase steels using micro-grid method

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## ABSTRACT

The local strain measurement method using nanometer-scaled micro grids printed on the surface of a specimen by an electron lithography technique (the micro-grid method) has been established. Microscopic deformation behavior of the ferrite–bainite steels with different bainite volume fraction, 16% and 40% of bainite, was evaluated. Strain localization in the ferrite phase adjacent to the ferrite/bainite boundary was clearly observed and visualized. Highly strained regions expanded toward the inner region of the ferrite phase and connected each other with an increase of macroscopic strain. The existence of hard bainite phase plays an important role for inducing strain localization in the ferrite phase by plastic constraint in the boundary parallel to the tensile direction. In order to obtain further understanding of microscopic deformation behavior, finite element analysis using the representative volume element, which is expressed by the axisymmetric unit cell containing a hard phase surrounded by a soft phase matrix, was conducted. It was found that the macroscopic stress–strain behavior of ferrite–bainite steels was well simulated by the unit cell models. Strain concentration in the ferrite phase was highly enhanced for the ferrite-40% bainite steel, and this imposed higher internal stress in the bainite phase, resulting in higher strain hardening rate in the early stage of the deformation. However, smaller ferrite volume fraction of ferrite-40% bainite steel induced bainite plastic deformation in order to fulfill the macroscopic strain of the steel. Accordingly, strain hardening capacity of the ferrite-40% bainite steel was reduced to a significant degree, resulting in a smaller uniform elongation than the ferrite-16% bainite steel.

## 1. Introduction

Dual-phase (DP) steels are widely used in many applications which are subjected to large plastic deformation. One of the major applications of DP steel is high strength sheet steel for automobile parts. In order to improve both strength and formability, mixed microstructure that consists of hard martensite and soft ferrite matrix is adopted. The ferrite–martensite type DP steel exhibits higher strain hardening rate and longer uniform elongation than conventional steels with single phase microstructure [1,2].

Linepipes installed in the seismic or permafrost regions must have sufficient resistance against buckling caused by the large deformation of buried pipeline. High deformability linepipes have been developed by applying the dual-phase microstructure control. Higher strain hardenability and lower yield ratio, the ratio of yield strength to tensile strength, were achieved by ferrite–bainite microstructure [3,4]. Many experimental and analytical investigations were carried out to improve strain hardenability of steels. It has been reported that microstructural characteristics such as volume fraction and morphology of second phase and strength difference between soft and hard phases affect the tensile properties of dual-phase steels to a significant degree [5–9]. In the case of ferrite–bainite steel, it was reported that ferrite with 30–40% of bainite shows highest strain hardenability [7]. Ferrite–martensite DP steel with linked shape of martensite phase exhibits higher

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strain hardening rate [8]. Larger hardness difference in the ferrite and martensite phase also gives higher strain hardening rate [9].

An analytical model to estimate the stress–strain behavior of dual-phase material from the stress–strain curves of each constituent phase was developed by Tomota [10] and applied to many materials including dual-phase steels [6,11–13]. This model was based on the Eshelby's inclusion theory [14] and Mori and Tanaka's mean field theory [15]. It was pointed out that the internal stress produced by the misfit strain between two phases is the reason for the enhanced strain hardenability of dual-phase materials. The effect of internal stress on the strain hardening of dual-phase steel was investigated by the in-situ neutron diffraction measurement. Substantial strain partitioning between the ferrite and martensite phases was directly measured, which can be a strong evidence of increased internal stress [16]. However, these investigations can only provide the averaged stress/strain value for each constituent phase, while strain localization inside the soft phase around the phase boundary region is expected. In order to simulate microscopic deformation behavior of dual-phase material, the finite element unit cell model that can represent three dimensional distribution of hard phase was developed [17,18]. It was shown that significant strain concentration occurs in the soft phase connecting to the hard phase, and the ferrite–bainite steel with optimum volume fraction of bainite exhibited highest strain gradient in the boundary region [7,18]. Strain concentration is also enhanced by lager strength difference between soft and hard phases, resulting in higher strain hardenability [19]. The electron back scattering diffraction (EBSD) is another method to evaluate microscopic deformation behavior by measuring the misorientations in adjacent measurement points (KAM) [20,21]. However, local strain investigated by the EBSD technique is not a direct measurement of material deformation, and it is not clear that the EBSD strain measurement can be applicable to a large and localized plastic deformation.

In order to investigate microscopic deformation behavior inside the each constituent phase, a microscopic strain measurement technique has been developed using the submicron-sized fine grids drawn by an electron beam lithograph technique [22]. By using this technique, it was made possible to measure the nanometer-sized local strain in the ferrite–martensite steel, and strain localization in the boundary region was directly observed. However, the relation between microscopic deformation behavior and strain hardening property has not been cleared yet. Therefore, more precise investigation of microscopic deformation behavior of dual-phase steel was conducted using above mentioned technique in this paper. Numerical analysis using the finite element unit cell model was also carried out to evaluate local and averaged stress and strain conditions in order to get further understanding on the strain hardening mechanisms.

## 2. Experimental procedure

### 2.1. Materials

Ferrite–bainite steels with different bainite volume fractions of 16% and 40% were prepared by the laboratory heat and hot rolling. In order to investigate the stress–strain relation of each constituent phase, 100% ferrite and 100% bainite steels were also made. Table 1 shows chemical compositions of the steels used. Only carbon content was changed to obtain the same material properties of each constituent phase of ferrite and bainite, but different bainite volume fraction. Fig. 1 shows schematic illustration of Fe-C phase diagram showing the carbon contents of the steels used. The laboratory ingots were heated at 1200 °C and hot rolled to the plate with the thickness of 16 mm at the austenite temperature above 900 °C, then cooled in the air down to 720 °C. At this temperature, the point (a) in Fig. 1 is ferrite (α) single phase, (b) and (c) are ferrite and austenite phases and (d) is austenite (γ) single phase. By applying rapid cooling from this temperature, the austenite transforms into the bainite and the dual-phase microstructure consisting ferrite and bainite phases was obtained. Fig. 2 shows microstructure of the steels. Table 2 shows tensile properties of the steels with different bainite volume fraction. Tensile test specimen was round bar specimen with the parallel portion of 6 mm diameter and 30 mm gauge length. Tensile loading was applied with the crosshead speed of 2.5 mm/min at ambient temperature. Two samples were tested and the averaged values were listed in Table 2. Yield and tensile strength increases with increasing bainite volume fraction, but the F-16%B and F-40%B steels showed lower yield ratio, and higher $n$-values. It is obvious that strain hardenability increased to a significant degree by the dual-phase microstructure. Fig. 3 shows true stress-true strain curves and strain hardening rate of the F-16%B and F-40%B steels. The F-40%B steel shows higher strain hardening rate in the lower strain level lower than 0.03, while the F-16%B steel kept higher strain hardening rate in the higher strain level resulting in higher uniform elongation.

**Table 1**
Chemical composition of the steels.

| Microstructure | Chemical compositions (mass%) | | | | |
|---|---|---|---|---|---|
| | C | Si | Mn | Nb | V |
| 100%F | 0.01 | 0.28 | 1.46 | 0.041 | 0.051 |
| F-16%B | 0.036 | 0.29 | 1.52 | 0.046 | 0.051 |
| F-40%B | 0.08 | 0.29 | 1.51 | 0.044 | 0.051 |
| 100%B | 0.203 | 0.28 | 1.52 | 0.044 | 0.051 |

F: ferrite, B: bainite.

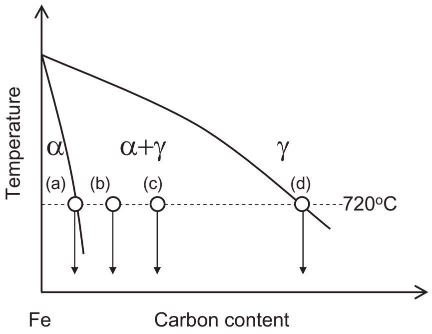

**Fig. 1.** Schematic illustration of ferrite–austenite equilibrium in the Fe-C phase diagram.

### 2.2. Local strain measurement by the micro-grid method

Small tensile specimen that enables SEM/EBSD measurement, as shown in Fig. 4, was used. Nanometer-sized small grids were drawn on the parallel portion of the tensile specimen by using the electron lithograph technique, which is commonly used in the semiconductor industry. The procedures of drawing small grid pattern on the specimen are shown in Fig. 5. Tensile specimen was first polished to have good flatness. Buffing with colloidal silica was applied in the final stage of the polishing. Then, surfactant and photoresist were put on the specimen by spin coating. Small grid pattern was transferred on the specimen by electron beam, which was removed by development and the trace of the grid pattern was remained. And then, gold deposition was applied on the specimen surface. Finally, the grid pattern of the gold deposition was obtained after removing all the remaining photoresist from