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3D-Simulation of ductile failure in two-phase structural steel with heterogeneous microstructure

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ABSTRACT

The effort of this study is to develop a simulation method to predict the effect of micro-structural morphology in two-phase steel, Ferrite–Pearlite steel, on structural performance in terms of ductile failure resistance. This is based on a clarification of a *damage mechanism* to control the ductile cracking with focusing on the heterogeneity in strength of micro-structure. The large number of micro-voids nucleation at lower strength side near two-phase boundary associated with the localization of stress/strain is found to control ductile cracking. According to this experimental result, we develop meso-scale 3D-model to reproduce micro-structural morphology of practical two-phase steel of interest for analyzing stress/strain localization behaviors associated with heterogeneity of microstructure. Moreover, damage evolution model including plastic potential to nucleate micro-void is proposed, so that ductile crack nucleation and subsequent growth and linking could be simulated.

The ductile cracking behavior for two-phase structural steel is simulated by means of the developed meso-scale 3D micro-structural FE-model together with the damage evolution model. The effect of applied triaxial stress state on critical macro-strain for ductile cracking as well as damage evolution behavior, in which the critical strain could be decreased with increasing stress triaxiality, is numerically predicted.

1. Introduction

Ductile cracking sometimes precedes unstable fracture in brittle manner in steel structure and ductile failure under manufacturing process associated with large plastic straining. Generally, such fracture process is prone to occur under complicated history of straining with various triaxial stress states that influences critical load for ductile cracking. There have been several damage models to simulate and evaluate critical load for ductile cracking followed by ductile failure of steel structures [1–5]. Most of these simulation methods are based on the homogeneous and continuous mechanics that can only be taken into account a basic and common understanding of the process of ductile cracking; nucleation, growth and coalescence of voids associated with large inclusions or second phase particles, especially the growth process, can control ductile cracking.

On the other hands, recent and future-focused structural steels have micro-structural heterogeneity in strength with few large inclusions, which are dual- or multi-phase steels. One of the authors revealed that the ductile cracking controlling damage for the two-phase Ferrite–Pearlite steel could not be nucleation and growth of voids originated from large inclusions, but formation of particular number of micro-voids near the Ferrite–Pearlite boundary just before final failure [6,7]. It was found

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that the strength heterogeneity between crystal grains with different phases could affect ductile cracking behavior through difference in stress/strain localization behaviors.

This study proposes a simulation method for predicting the effect of micro-structural morphology on ductile failure limit for two-phase structural steel on the basis of micro-mechanism for ductile failure through the following developments: one is a 3D meso-scale FE-model that enables the analysis of stress/strain localization behaviors dependent on the morphology of two phases with strength heterogeneity in real steel, another is a damage evolution and subsequent micro-void nucleation model. The simulated ductile properties as well as the damage evolution in terms of micro-voids formation for micro-tensile specimen are compared with the experimental results.

2. Experiment of ductile cracking behaviors

2.1. Experiment

The structural steel JIS SM490YB with Ferrite–Pearlite two phases with different strength in Vickers hardness (F–P steel) was used, as shown the microstructures in Fig. 1 [6,7]. Table 1 shows the chemical composition of the steel, and Table 2 lists the mechanical properties. The strength expressed by Vickers hardness of the Pearlite phase is averagely 1.4 times larger than that of the Ferrite phase. Area fraction of the hard Pearlite phase is roughly 30%.

The ductile cracking tests were conducted under uniaxial tensile loading for flat micro-tensile specimens with/without side notches in order to compare the ductile cracking behaviors under different triaxial stress state during loading. In addition, the damage behaviors in terms of voids nucleation and growth in the specimens up to ductile cracking were examined taking notice of the heterogeneous microstructures. Fig. 2 shows the configuration of the employed micro-tensile specimens. The flat smooth specimens with different net-section (0.4 mm $\times$ 0.3 mm and 0.2 mm $\times$ 0.2 mm) were prepared. The side notched specimen has a notch with radius of notch-root curvature R of 0.1 mm (R0.1 specimens), which would provide higher stress triaxiality in the middle of net-section than smooth specimens. The gage-length for measuring tensile displacement of all the specimens is 1 mm.

2.2. Ductile cracking process

The damage evolution, that is voids nucleation and growth behavior, up to ductile crack nucleation was observed in detail by conducting tension tests for round-bar specimens with/without circumferential notch [6,7]. Until applying a large scale strain just before ductile cracking, no remarkable micro-voids were detected. After that, a particular number of micro-voids, whose size is about 1 μm, and in some parts micro-voids induced micro-cracks were observed mostly at the softer Ferrite side near the Ferrite–Pearlite boundary. Finally, the ductile cracking was found to form by unstable shear fracture between these micro-voids or micro-cracks in Ferrite, in Pearlite or along Pearlite phase. These behaviors were observed irrespective of the triaxial stress states during loading. Consequently, the main controlling factor for ductile cracking in the employed two-phase steel was found to be not growth of voids induced by larger inclusions, but formation of a particular number of micro-voids just before cracking mainly at Ferrite side near the Ferrite–Pearlite boundary followed by shear fracture between them. These micro-voids formation and subsequent cracking would be caused by stress/strain localization due to heterogeneous microstructure and further localization behaviors between micro-voids.

The similar ductile cracking behaviors were confirmed in the middle of minimum cross-section even for micro-tensile specimens used in this study. As presented for the case of Smooth-2 specimen in Fig. 3, the micro-voids and micro-cracks that mainly nucleated at Ferrite side near the Ferrite–Pearlite boundary are observed only after a large amount of plastic straining.

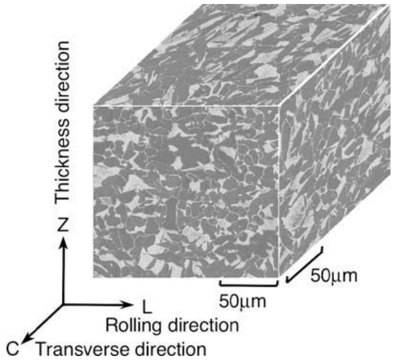

Fig. 1. Microstructures of SM490YB steel used (F–P steel).