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Examination and modeling of void growth kinetics in modern high strength dual phase steels during uniaxial tensile deformation

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HIGHLIGHTS

- Damage mechanism in two modern high strength dual phase steels was studied.
- Creation of cellular substructures can reduce the stored strain energy within the ferrite grains.
- The experimental values were examined by Agrawal as well as RT family models.
- A modified model was proposed for prediction of void growth behavior of DP steels.

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ABSTRACT

Ductile fracture mechanisms during uniaxial tensile testing of two different modern high strength dual phase steels, i.e. DP780 and DP980, were studied. Detailed microstructural characterization of the strained and sectioned samples was performed by scanning electron microscopy as well as EBSD examination. The results revealed that interface decohesion, especially at martensite particles located at ferrite grain boundaries, was the most probable mechanism for void nucleation. It was also revealed that the creation of cellular substructure can reduce stored strain energy and thereby, higher true fracture strain was obtained in DP980 than DP780 steel. Prediction of void growth behavior based on some previously proposed models showed unreliable results. Therefore, a modified model based on Rice-Tracey family models was proposed which showed a very lower prediction error compared with other models.

1. Introduction

Ductile fracture of metals mainly involves three processes of void nucleation, growth, and coalescence [1]. In order to control these phenomena and enhance the resistance of materials to fracture, a detailed understanding of fracture mechanism is required. Although the subject is well established for various ductile alloys, in the new important field of modern high strength dual phase (DP) steels, especially in giant automobile industry, few researches have been reported [2,3]. It has been shown that in DP steels, the second hard phase particles act as void nucleation sites [4,5] and decohesion of ferrite/martensite interface is the most probable mechanism of voids nucleation, growing mostly perpendicular to the tensile direction along ferrite grain boundaries; this process can be affected by the size, shape and distribution of the second phase particles as well as the presence of impurities or hydrostatic stress [6].

Landron et al. [2] have concluded that nucleated cavities in DP steels, due to the constraint effect of martensite particles, cannot grow in the transverse direction. Moreover, different mechanical behaviors of two constituent phases, ferrite and martensite, impose non-uniform strain distribution as well as specific strain hardening behavior [7], thereby affecting the void growth kinetics within the microstructure. Review of some major studies done on modeling and analyzing void growth kinetics is presented in Table 1. For more

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Table 1
Review of published literature on modeling of void growth kinetics.

Researcher	Noticeable findings
Rice-Tracey (1969) [1]	Void growth rate increases exponentially with the hydrostatic stress
Beremin (1981) [8]	Substitute equivalent stress for yield stress, in order to account for strain hardening
Marini (1985) [9]	Showed that in real materials, the constants of RT model could be larger
Fleck (1989) [10]	Showed that voids contracts for triaxiality (T) lower than 0.5
Huang (1992) [11]	Re-evaluated the RT model
Agarwal (2003) [12]	Proposed a new model that showed good prediction of experimental data, variation of voids diameter with strain
Chae (2004) [13]	Modified RT model by introducing corrective coefficients
Maire (2008) [3]	Modified RT model, considering progressive damage initiation
Taktak (2009) [14]	Modified RT model by introducing corrective coefficients
Kumar (2009) [15]	Showed that RT model presents good prediction, but it is not well applicable at high triaxiality ratios in the order of T = 2.25

than 40 years, researchers have been trying to find the influential factors on void growth behavior and present a reliable model to predict void growth behavior. As can be inferred from Table 1, most findings are mainly based on the Rice-Tracey (RT) model. In this context, Agrawal model, which is an empirical model, is considerably different from Rice-Tracey family models as its reliability has only been manifested for 6061 aluminum alloy.

Triaxiality (T) in Table 1 stands for the ratio of hydrostatic stress to equivalent stress. Considering mechanical properties and strain hardening behavior in DP steels, which are so different from most single phase materials studied, shows that it seems necessary to study the void growth behavior in these materials. So, in the present work, ductile damage evolution of two different commercial high strength sheet steels, i.e. DP780 and DP980, was studied. These two types of steel, which have different martensite particles morphology and volume fraction, are rather new and their damage behavior has not been studied. The main objective of this study was to evaluate and compare void growth behavior in DP780 and DP980 steel sheets during room temperature uniaxial tensile test. Moreover, the reliability and applicability of different developed models, Rice-Tracey family models and empirical Agrawal model, were examined in order to well present the void growth behavior in both steels studied. Damage analysis was performed by the examination of metallographic sections and quantitative fractography of tensile specimens using scanning electron microscopy (SEM). It should be taken in mind that void growth is an important step in damage evolution during plastic deformation. So, finding a well predictive model for this step would be vey beneficial in damage analysis and prediction of failure strain.

2. Materials and methods

Materials used for this research were DP780 and DP980 sheet steels provided by POSCO Company, South Korea. The sheets thicknesses of DP780 and DP980 steel were 1.00 ± 0.02 mm and 1.18 ± 0.02 mm, respectively. Tensile specimens were machined according to ASTM E8 standard [16], in rolling direction, using electro discharge machining (EDM) method. Three specimens were tested for each steel. The gauge length was 50 mm and tensile tests were carried out at room temperature and at a constant cross head speed of 0.03 mm/s with a servo-hydraulic MTS machine.

Fracture surface of the specimens was analyzed by SEM equipped with an electron backscattered diffraction (EBSD) detector. The specimens were then sectioned through thickness along the mid-width in the longitudinal direction (Fig. 1) using Struers cutting machine. In order to measure local strains during deformation, these sectioned specimens were mounted, ground and polished till 4000 grit finish. This was followed by polishing with 1 μm diamond suspension and etching in 2% Nital solution. Then variation of void features, in terms of void area fraction, voids average diameter and void areal density across the length of the specimen, was studied by

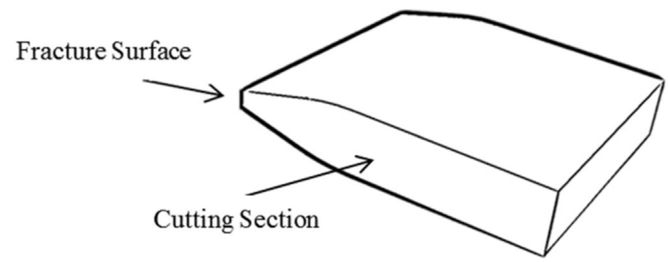

Fig. 1. Schematic illustration of longitudinal sectioned specimens.

image analysis of SEM micrographs using Image J software [17]. Moreover, in order to measure martensite grain size, linear intercept method [18] was employed. According to Martin et al. [19], the equivalent strains across the length of the specimens were estimated as:

$$\varepsilon_i = \left(2\Big/\sqrt{3}\right)Ln(t_i/t_0) \tag{1}$$

where t_i is the thickness of the sample at a position i from the fracture surface, in the middle of the specimen. Void average diameters were then modeled using the three equations of Rice-Tracey (Eq. (2)) [2], Huang (Eq. (3)) [11] and Agarwal (Eq. (4)) [12], as presented in the following equations:

$$D = D_0 \exp(0.283\varepsilon \exp(1.5T)) \tag{2}$$

$$D = D_0 \exp\left(0.427T^{0.25}\varepsilon \exp(1.5T)\right) \tag{3}$$

$$D = D_0 + \alpha\, Ln(\varepsilon) + \beta T \tag{4}$$

where D is the average void Diameter, D_0 is the initial void diameter, ε is the equivalent strain, α and β are constants and T is triaxiality measured by the following equation, as proposed by Maire et al. [3] for sheet DP steel:

$$T = 0.33 + 0.27\left[1 - \exp\left(-4(\varepsilon - 0.17)^2\right)\right] \tag{5}$$

In order to evaluate the accuracy of the prediction by the mentioned models, prediction error was measured by mean square method (MSE) as shown in Eq. (6).

$$MSE = \frac{1}{L}\sum_{n=1}^{L}(Y(n) - P(n))^2 \tag{6}$$

where L is the number of data points analyzed, Y is the experimental value and P is the predicted value.

EBSD analysis was also employed to reveal the substructures