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Void coalescence and fracture behavior of notched and un-notched tensile tested specimens in fine grain dual phase steel

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ABSTRACT

Due to growing global concern about the environmental issues, steel developers have been forced by automobile makers to produce more efficient steel grades with high strength to weight ratios along with high crashworthiness performance. In order to find deficiencies of the existing steels and develop superior steel products, detailed understanding of deformation and damage behavior in the existing steels is needed. In the present research, deformation and damage evolution during room temperature uniaxial tensile test of a modern high strength Dual Phase Steel, i.e. DP780, were studied. Detailed scanning electron microscopy (SEM) examination of the microstructures of notched and un-notched tensile fractured specimens revealed that in notched specimen, plastic deformation was concentrated more within the notched region. Therefore, much higher reduction in thickness with a high reduction gradient occurred in this region, In the un-notched specimen, however, plastic deformation was more uniformly distributed in larger parts of the gauge length, and therefore, thickness reduction happened with a lower gradient. Although geometric notch on the specimen did not change the void nucleation and growth mechanisms, the kinetics of these phenomena was influenced. On the other hand, voids linkage mechanism tended to change from void coalescence in the un-notched specimen to void sheeting in the notched specimen. Moreover, three different models developed by Brown & Embury (BM), Thomason and Pardoen were employed to predict the final fracture strain. It was revealed that, BM model showed much more accurate predictions for the studied DP steel in comparison with those of Thomason and Pardoens' models.

1. Introduction

Ductile fracture of metals mainly involves three processes of void nucleation [1–4], growth [5–8], and coalescence [9–13]. In order to control these phenomena and enhance fracture resistance of materials, a detailed understanding of fracture mechanism is needed.

Many parameters have been found to affect the fracture process; some of them are related to the geometry of the specimen such as size effect [14,15], while some others are related to the stress state [16–19] and the microstructure properties of the material such as work hardening [11–20], anisotropy [21–23] and the morphology of the microstructure [24–26]. For example, it has been reported [18] that increasing triaxiality leads to increasing void growth rate and consequently, lowering the fracture strain, in an exponential manner. Moreover, it has been shown that [14] void coalescence is decreased in small specimen sizes, leading to the higher ductility of the specimen.

Generally, in dual phase (DP) steels, the second hard phase particles act as void nucleation sites, mainly by ferrite–martensite interface decohesion mechanism [27,28]. However, nucleated cavities in DP steels, due to the constraint effect of martensite particles, cannot grow much in transverse direction [6]. On the other hand, the higher density of void nucleation sites, in the interfaces of ferrite–martensite grains, causes more void density and lower inter-void spacing in DP steels, in contrast to the single phase ferritic steels. Also, it has been shown that [29] the high interaction of closely spaced voids results in the acceleration of their growth rate. Therefore, higher void growth is expected in DP

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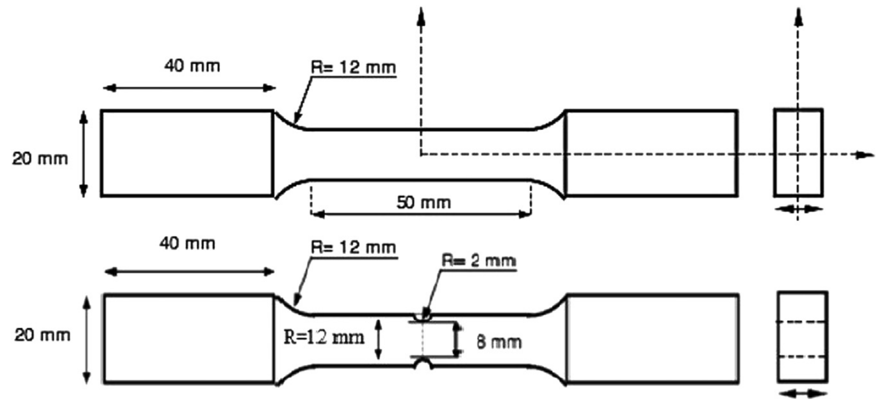

Fig. 1. Schematic representation of tensile specimens, un-notched specimen was named as R and notched specimen named as R2.

steels than ferritic steels. Void coalescence is the last step of ductile fracture. It can happen in three ways:

1. Coalescence of the neighboring initial voids by cross-linkage. In this case, the ligament between the neighboring voids suffers from necking and contraction until these voids are linked to each other. In this case, the coalesced voids are mostly oriented normal to the loading direction [30].
2. Nucleation of secondary voids due to the local plastic shear deformation within the ligament of the neighboring initial voids that accelerates the linkage between the initial voids. This process is called void sheeting. In this case, the coalesced voids are mostly oriented at 45° to the loading direction. It is mostly observed in high strength materials with rather low work hardening capacity [30].
3. Necklace coalescence, in this process elongated voids are coalesced with each other in a columnar way, parallel to the loading direction. This mechanism has smaller effects on the macroscopic failure and ductility than the previous two mechanisms [31].

The most common void coalescence mechanisms are mechanism numbers 1 and 2. In order to study the coalescence behavior of voids during deformation, Weck et al. [30] embedded array of voids in Aluminum tensile sheet specimens drilled by laser. The voids at first had the orientation of 15° and 45° with the loading direction. In this examination, through in-situ SEM analysis during tensile testing, it became clear that the voids with the orientation of 45° tended to be coalesced by void sheet coalescence mechanism, while voids with 15° tended to be coalesced mostly by necking of the inter void ligament. It was shown [32] that Thomason's model could give excellent predictions for copper samples containing holes coalescing normal to the tensile axis. Moreover, they showed that for other configurations in which holes were oriented at an arbitrary angle with respect to the tensile axis, Thomason's model resulted in poor predictions.

Using X-ray computed tomography coupled with in-situ uniaxial tensile testing, Hosokawa et al. [33] studied the void growth and coalescence in materials constituting a pre-existing three-dimensional void array during deformation. By using a picosecond laser machining system, different void geometries were prepared. Moreover, they performed Finite element simulations to study the influence of void shape on the void growth behavior. Finally, it was shown [33] that coalescence models developed by Thomason [34] and Pardoen [11] could provide accurate predictions of coalescence strain when the voids were aligned perpendicular to the tensile axis. However, offsets could induce shear effects that lowered the coalescence strain in a manner not predicted by the models.

As reviewed in this section, most of the studies on void coalescence mechanisms were done on single phase materials suffering from uniform plastic deformation, but it is expected that non-uniform plastic deformation and constraint effects of the second hard phase in the microstructure can affect the void growth and coalescence behavior in DP steels. So, in the present investigation, it was tried to study void evolution and coalescence in a ferrite–martensite dual phase (DP) steel, in two geometries of notched and un-notched tensile specimens, during room temperature uniaxial tensile test. The studied steel was a fine grained modern DP steel, i.e. DP780. To the best of our knowledge, there is little published work on damage behavior of this material. Damage analysis was done by sectioning, metallographic preparation and Scanning Electron Microscopy (SEM) qualitative and quantitative analysis of deformed tensile specimens.

2. Materials and methods

Material used for this research was DP780, with the sheet thickness of 1 mm. Steel was provided by POSCO Company, South Korea. Tensile specimens were machined according to ASTM E8 standard [35], in rolling direction, using Electrical Discharge Machining (EDM) method (Fig. 1). Moreover, in order to study the effect of notch on void evolution and coalescence in the mentioned steel, notches 2 mm in radius were embedded in the standard tensile specimens as shown in Fig. 1. The notched specimen was labeled as R2 and the un-notched specimen was referred to as R specimen. The gauge length was 50 mm and the tensile tests were done at a constant cross head speed of 0.03 mm/s with a

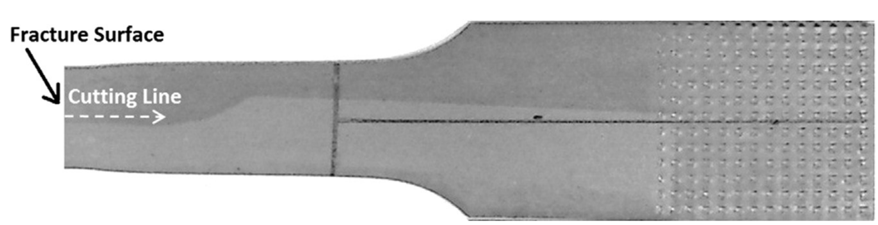

Fig. 2. Specimens was sectioned along the line shown in this image.