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The effect of martensite volume and distribution on shear fracture propagation of 600–1000 MPa dual phase sheet steels in the process of deep drawing

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A B S T R A C T

Due to its excellent strength and formability combinations, dual phase (DP) steels offer the potential to improve the vehicle crashworthiness performance without increasing car body weight and have been increasingly used in new vehicles. However, a new type of crack mode termed as shear fracture is accompanied with the stamping application of these high strength DP steel sheets. This paper presents a study of DP shear fracture through macroscopic identification and micro-level metallographical observation. By the cup drawing experiment to identify the limit drawing ratio (LDR) of three DP AHSS with strength level from 600 MPa to 1000 MPa, the study compared and categorized the macroscopic failure mode of these three types of materials. The metallographical observation using scanning electron microscopy (SEM) along the direction of crack was conducted for the DP steels to discover the micro-level propagation mechanism of the fracture and its relation with the martensite volume and distribution. Plasticity analysis and finite element method (FEM) simulation were provided to explain the observed behavior, which was further confirmed by the comparison between DP fracture and high strength low alloy (HSLA) fracture.

1. Introduction

The application of advanced high-strength steel (AHSS) has been one of the major ways to reduce the vehicle weight and fuel consumption, while improving vehicle crashworthiness. Dual Phase (DP) steel sheets, as the most common type of AHSS, have been increasingly used in vehicles and serve as structural parts due to the combination of special mechanical properties such as high tensile strength, high work hardening rate at early stages of plastic deformation as well as very good ductility. One of the key issues associated with DP AHSS is the springback occurring in the process of stamping. To reduce springback, small radii were often recommended [1]. However, a new type of crack mode which was termed as "shear fracture" was periodically seen along small bending radii in the stamping with DP AHSS [2]. Besides the factor of bending radii, Wagoner et al. [3] discovered that the thickness of the sheet and deformation rate also affect the fracture initiation and shear failure occurs preferentially for smaller R/t and higher deformation rates. Shear fracture is termed because the fracture cracks with limited localized necking, and cracks on alternating 45° planes, through thickness. While for traditional low carbon steel or high strength low alloy (HSLA) steels, obvious necking can be observed when materials crack [4].

Due to the nature of limited necking in shear fracture of DP, the traditional theory based Forming Limit Diagram (FLD) seems insufficient to predict such fractures because the theory based FLD was mainly derived on the basis of concentrated necking [5]. A significant effort has been made to address this challenge. Microstructure changes were taken into account by Caballero et al. [6] to model stress and strain relationship for DP steel to analyze its strain hardening properties. Sun et al. [7] suggested considering plastic strain localization, resulting from the incompatible deformation between the harder martensite phase and the softer ferrite matrix, to predict ductile failure of dual phase steels. Luo and Wierzbicki [8] developed a Modified Mohr–Coulomb (MMC) ductile fracture criterion and applied it to analyze the failure behavior of a DP steel sheet during a simple quasi-static stretch-bending operation. In our previous study, different hardening formulas and yield functions were compared in the numerical prediction of onset crack for DP steel sheet forming. The investigation showed that a Swift and Hockett–Sherby combined formula was in good agreement with the flow curve of the tensile test and Batlat-89 yield model successfully predicted the onset shear crack of DP AHSS [9].

DP steels contain two major phases, ferrite and martensite. Such ferrite–martensite structure is called dual phase microstructure in

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which, soft ferritic network provides good ductility, while hard particles and martensitic phase play the load-bearing role [10]. Many researches compared the martensite morphology produced by some variations of two basic heat treatments, the quenching process from austenite region, or the intercritical annealing [11]. Martensite morphology and volume has a significant influence in the void nucleation and crack propagation. Avramovic-Cingara et al. [12] investigated the effect of martensite morphology and distribution in a ferrite matrix on the mechanical properties and the damage accumulation in uniaxial tension of two different automotive-grade dual phase DP600 steels. And they found that voids nucleation occurred by martensite cracking, separation of adjacent martensite regions, or by decohesion at the ferrite/martensite interface. In the SEM observation of DP780 fracture by 3-point bending, H.C.Shih and Shi [13] revealed that (i) ductile fracture initiates from void nucleation and grows in ferrite phases and (ii) zigzag crack path bypasses martensitic grains. However, according to Kim and Thomas [14], cleavage fracture occurred at ferrite in a coarse martensite structure, whereas voids initiated at ferrite–martensite interfaces in a fine martensite structure. Zeng et al. [15] suggested that the shear fracture is due to the failure of martensitic grains at micro-level when certain criteria are reached, and the macroscopic failure mode during forming operations was viewed as the competition between localized necking and the shear fracture, whichever criterion is satisfied first. The cause why different damage mechanisms of particular dual phase steels were reported may be due to their differences in chemical compositions, heat treatment history, and in their final microstructure. Nevertheless, an investigation of metallographical observation for understanding the effect of martensite volume and distribution on fracture propagation mechanism of DP AHSS of strength level from 600 MPa to 1000 MPa in the process of deep drawing is required.

In the present work, three commercial DP steel sheets of strength level from 600 MPa to 1000 MPa were studied. Firstly, their chemical compositions were analyzed. Martensite distribution and volume were also identified. Then cup drawing experiments were conducted for these three types of materials to identify their limit drawing ratios (LDR). Macroscopic failure modes were determined for the LDR failure parts. Later, with the help of scanning electron microscope (SEM), the fracture propagation mechanisms were observed and compared with each other. The relationship between their propagation mechanism and corresponding martensite distribution was also discussed. Finally, through plasticity analysis and FEM simulation, the explanation for the observed behavior was provided. The comparison between DP fracture and HSLA fracture further confirmed the discussion.

2. Materials and experimental procedure

The steel sheets selected in this study are cold reduced dual phase steels. The steels are subjected to special heat treatment in the continuous annealing line, which involves quenching from a suitable temperature in intercritical range between AC1 and AC3. Then the austenite phase in low carbon alloys (carbon content less than 0.2%) transforms to martensite, which will produce a ferrite–martensite structure instead of the conventional ferrite–pearlite microstructure. In this two phase structure, the ferrite imparts unique forming properties, and the martensite accounts for the strength. The strength increases with increasing proportion of the hard martensite phase. DP is named by its minimum ultimate tensile strength. For example, DP600 means such steels provide at least 600 MPa of the ultimate tensile strength. Three commercial DP AHSS sheets, 1.7 mm thick DP600, 1.2 mm thick DP800 and 1.0 mm thick DP1000, were studied in the as-received condition. The chemical compositions of the three steels are shown in Table 1. With increasing strength level, steels contain more C, Si and P.

To observe the martensite distribution and volume of three DP steels, three samples were cut from the original sheets by electrical discharge machining (EDM). Then the samples were mechanically polished and etched in a 4% Nital solution for 10–15 s. The revealed microstructure in JSM-6700 F SEM shows a dark ferrite phase with embedded white martensite. From Fig. 1, one can see that the martensite phase in DP600 and DP800 is in island shape, while in DP1000, the martensite phase shows a continuous mesh shape. For the particular DP600, DP800 and DP1000 sheets in this study, the martensite volume is approximately 18%, 32% and 50%, respectively. As mentioned in the introduction, the martensite distribution and volume will play a dominant role in load bearing and will have a significant effect on the fracture propagation.

LDR is an indicator of material formability, defined as the ratio of the maximum blank diameter that can be safely drawn into a cup without flange to the punch diameter. A punch of ϕ32 mm diameter recommended by the International Deep-Drawing Research Group (IDDRG) was selected in this study. Fig. 2 shows

Table 1
The chemical compositions of steels in wt%.

Steel	C	Si	Mn	P	Cr	Ni	Al	Co	Fe
DP600	0.110	0.193	1.400	0.005	0.170	0.017	0.0457	0.0066	balanced
DP800	0.134	0.202	1.490	0.034	0.016	0.037	0.0461	0.0186	balanced
DP1000	0.161	0.501	1.480	0.037	0.021	0.036	0.060	0.0189	balanced

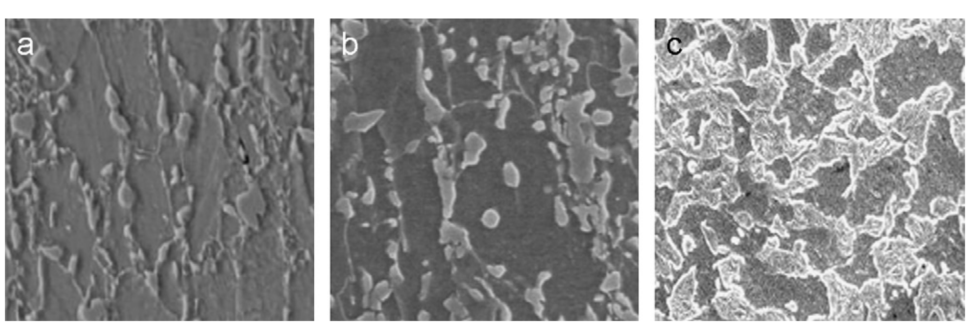

Fig. 1. Microstructure of three DP steels: (a) DP600, (b) DP800, and (c) DP1000.