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Effect of martensite distribution on damage behaviour in DP600 dual phase steels

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ABSTRACT

The effect of martensite morphology and distribution in a ferrite matrix on the mechanical properties and the damage accumulation in uniaxial tension was investigated in two different automotive-grade dual phase DP600 steels. The two sheet steels had roughly 20% volume fraction of martensite but dissimilar chemical composition. A detailed analysis of microstructure and damage accumulation has been conducted as a function of strain. SEM analysis revealed that voids nucleation occurs by martensite cracking, separation of adjacent martensite regions, or by decohesion at the ferrite/martensite interface. Martensite morphology and distribution had a significant influence in the accumulation of damage. The steel with a more uniform distribution of martensite showed a slower rate of damage growth and a continuous void nucleation during the deformation process, which resulted in a higher void density before fracture. On the other hand, the steel with a centre-line of martensite through the sheet thickness exhibited accelerated void growth and catastrophic coalescence in the transverse orientation to the applied load.

1. Introduction

The need to reduce the fuel consumption and emissions, while maintaining vehicle safety, is the main driving force for the lower vehicle weight in the next new generation of automobile design. Application of high-strength dual phase (DP) steels combined with new production technologies is being considered as one of the most efficient ways to achieve the above goal. Dual phase steels exhibit low yield strength and a high workhardening rate, thus providing a high-strength steel of superior formability [1–3].

Despite the generic name "dual phase", such steel may contain three or more phases. The matrix is typically soft ductile ferrite. The strengthening phase is martensite but may contain small amounts of bainite and retained austenite. It is now established that the martensite volume fraction is dominant in controlling tensile properties and increasing the amount of martensite decreases ductility. Studies have shown that morphology of martensite particles plays an important role in the strength and ductility of the dual phase steels [2–6]. However, most of the research work has been focused on comparison of martensite morphology produced by some variations of two basic heat treatments, the quenching (or step quenching) process from austenite region, or the intercritical annealing [3,5–12]. Martensite particles in the first treatment tend to have the same crystallographic orientation as the surrounding ferrite matrix [5,6]. As expected, there are remarkable differences in the resulting morphologies and most of the studies have compared the fine (uniform dispersion) and coarse (banded, or fibrous) martensite morphologies [3,6,8,10]. For a constant volume fraction of martensite, a microstructure of finely dispersed martensite has a better combination of strength and ductility. According to Kim and Thomas [3], cleavage fracture occurs at ferrite in a coarse martensite structure, whereas voids initiate at ferrite–martensite interfaces in a fine martensite structure. It has been demonstrated that optimum properties of DP steels are obtained at approximately 20% volume fraction of martensite [1,4].

In order to predict deformation behaviour of DP steels, one needs to have an understanding of constituent phases and also the partitioning of stress and strain between the two phases during deformation [13–16]. Different damage mechanisms of particular dual phase steels are related also to their chemical compositions, heat treatment history, and differences in their final microstructure [3–24]. Stevenson [12] reported that cracks initiate first in martensite under low strain and then propagate into ferrite. The fracture mechanism in a fine and coarse martensite morphology dual phase steels having 0.09% carbon and 17% martensite was studied by He et al. [11]. It was reported that in the coarse structures the initial void formation occurs due to cracking of the martensite at very low strain levels. At a higher strain this is followed by the formation of a second type of void by interfacial decohesion at ferrite/martensite interfaces. However, in the structures with fine martensite morphology, the majority of voids are formed by decohesion at the ferrite/martensite interface. This has been attributed to the widely different stress–strain characteristics of the two phases resulting in significant strain incompatibility [14,21]. The martensite under-

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Table 1
The chemical compositions of steels in wt.%.

Steel	C	Mn	Mo	Si	Cr	Ni	Ti
A	0.070	1.840	0.150	0.090	0.030	0.010	0.010
B	0.106	1.530	0.220	0.201	0.190	0.030	0.018

goes significantly less deformation than the ferrite and the voids form at the ferrite/martensite interface. On the other hand, significant plastic deformation of martensite occurs when its strength is reduced either by carbon content or by tempering. Szewczyk and Gurland [25] reported that extensive plastic deformation of martensite occurs mainly in the neck region of the tensile specimen. Localized deformation of martensite particles as a special distinctive void nucleation mechanism was studied by Erdogan [18] and Steinbrunner et al. [19]. Steinbrunner et al. [19] observed that the nucleation of voids due to localized deformation within the martensite or by martensite particle separation may be more complex than previously thought. A mechanism for separation of deformed martensite particles was proposed.

In the present work, two different versions of commercially produced DP600 sheet steels are studied. Both steels have banded martensite morphology with different distribution of bands. The steels are produced by intercritical annealing, have similar mechanical properties, and slightly different chemical compositions. The main objective of this work is to compare deformation and damage behaviour of these two dual phase steel sheets during uniaxial tensile straining. In addition, an effort has been made to clarify the effect of banded martensite morphology on the damage nucleation and development, as well as fracture behaviour in the two steels, designated here as “DP600-A” and “DP600-B”. The damage accumulation was investigated by quantitative metallographic analysis of deformed uniaxial tensile specimens. Further, the formation of damage was evaluated using post-test scanning electron microscopy (SEM), as well as by in situ SEM.

2. Experimental procedure

The two commercial high-strength dual phase DP600 steels, DP600-A and DP600-B, were studied in the as-received condition. The galvannealed steels were received in the form of 1.8 mm thick sheets. The galvannealing procedure has been widely used in the steel industry to promote inter-diffusion of zinc and iron, leading to an alloyed coating of better quality [26]. The chemical compositions of the two steels are shown in Table 1. The DP600-B steel contained higher levels of C, Mo, Si, and Cr compared to the DP600-A.

Tensile testing was performed at a crosshead speed of 1 mm/min on a servo-hydraulic MTS frame with 100 kN load-cell capacity. The tensile specimens were machined according to ASTM E8 standard with a gauge length of 25.4 mm in such a way that the applied tensile loading axis corresponded to either the rolling direction (RD) or transverse direction (TD) of the sheet [27].

As-received steel samples were etched in various etching solutions in order to clearly delineate the information about the dual phase steel constituents using light microscopy. Method 1 represents of a two-stage etching procedure consisting of 4% picral, followed by 10% aqueous sodium metabisulfite (SMB) solution [28,29]. It should be mentioned here that picral attacks interfaces between ferrite and carbide, therefore, carbides were better revealed by picral [29]. The distinct colour contrast between the martensite, bainite, and the ferrite matrix enabled measurement of the volume fraction of martensite through image analysis. Various samples were analyzed in all three-dimensional planes. Throughout the method 2 the samples were also separately etched with 2% nital to reveal ferrite grains and grain boundaries, as well as the martensite. The examination of steel microstructure and void spatial distribution was performed using a Zeiss Axioplan 2 light optical microscope. The area fractions of microstructural constituents were determined from optical micrographs using Northern Eclipse image analysis software [30]. The mean ferrite grain size was determined by the linear intercept method. SEM examination was conducted using a SEM Philips 515 and a JSM-7000F FESEM. X-ray diffraction analysis was applied to measure the retained austenite according to the ASTM E-975 standard.

Metallographic analysis of damage accumulated along the gauge length after uniaxial tensile testing was carried out on failed samples, on cross-sections along the tensile axis. Fractured specimens were sectioned through-thickness along the mid-width in longitudinal direction. Both sides of failed tensile samples were characterized. To preserve any damage during specimen preparation, wire electrical discharge machining (WEDM) was used. The amount of damage was measured on polished samples, as a function of thickness reduction at different distances from the fracture surface and analyzed with Northern Eclipse image analysis software [30]. Consecutive fields along the same thickness strain were measured optically in order to determine the average through-thickness void data. The accuracy of small voids characterization by optical metallography was verified for DP600-B at higher magnification using a JSM-7000F FESEM. The SEM analysis of void nucleation mechanisms was carried out on the same samples etched later in 2.5% nital. For DP600-A, SEM in situ analysis was conducted by a screw-driven mini-tensile SEM stage (Ernest F. Fullam Inc., Lantham, NY) installed inside an environmental SEM (Electroscan

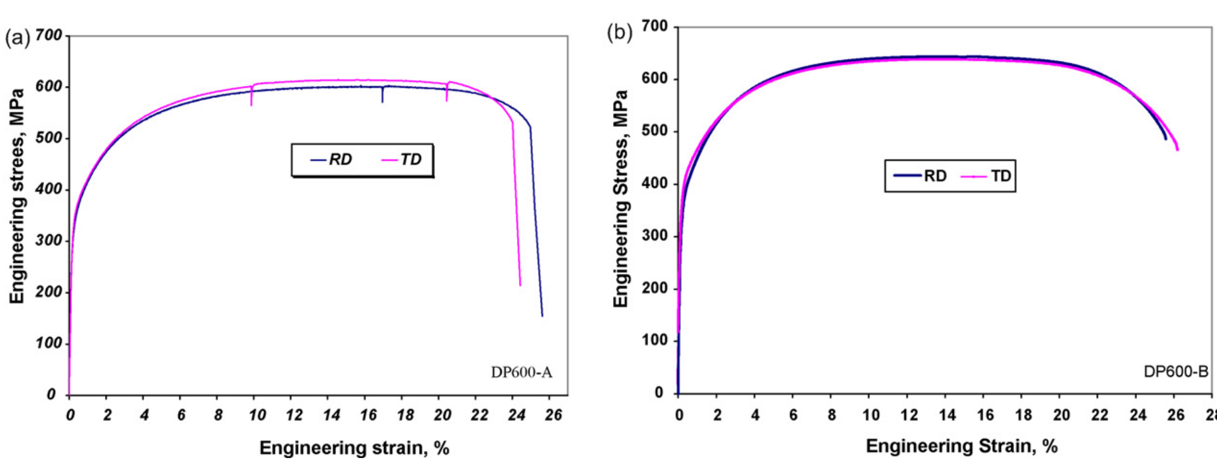

Fig. 1. Engineering stress–strain curves for (a) DP600-A and (b) DP600-B steels.