Ductile Damage Evolution and Strain Path Dependency

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Abstract. Forming limit diagrams are commonly used in sheet metal industry to define the safe forming regions. These diagrams are built to define the necking strains of sheet metals. However, with the rise in the popularity of advance high strength steels, ductile fracture through damage evolution has also emerged as an important parameter in the determination of limit strains. In this work, damage evolution in two different steels used in automotive industry is examined to observe the relationship between damage evolution and the strain path that is followed during the forming operation.

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INTRODUCTION

Forming limit curves (FLC) are generally used in the industry to define the safe forming strains for any given forming operation. In these diagrams, localized necking of the sheet is the criteria for determining the safe forming regions.

However, it is also known that sheet metals may fail due to one or the combination of three different mechanisms. These are instability with localized necking (followed by ductile or shear fracture inside the neck area), shear fracture (based on shear band localization) and ductile fracture (based on initiation, growth and coalescence of voids) [1]. For bending operations, excessive roughening observed in hemming processes can also be regarded as a failure mechanism that limits the straining limits of sheet metals.

With the rise of the popularity of advanced high strength steels in the last decade in automotive industry, ductile fracture has evolved as an important factor in determining the limits of formability. It is known that damage evolution affects the mode of failure very significantly, especially in the biaxial strain paths where void growth is more relevant [2].

The goal of this work is to examine and compare the FLC’s, fracture limit curves (FrLC) and fracture surfaces of an interstitial-free (IF) steel and a dual-phase (DP) steel, in order to analyze the relationship between ductile damage and the strain paths followed.
EXPERIMENTAL METHODOLOGY

Determination of FLC’s are carried out according to the principle of Nakajima test using a hemisphere punch. A measurement grid of 0.5mm spacing is applied to the surface of the undeformed blanks and the blanks with different geometries are deformed until the point of fracture. The displacements of the grid points on the samples are measured in the major and minor directions by the use of the image correlation software PHAST. Local strains at which necking starts are calculated by extrapolating the strain profile of each sample over the crack. For the calculation of the major strains at fracture, the crack opening is measured by a measuring microscope and this distance is subtracted from the distance between grid points. To visualize the path followed by each geometry, specimens of the same geometry are deformed to different amount of final deformation values, and local strain values are measured and marked on the strain diagram.

To characterize the failure modes of the different geometries of IF and DP steels, uniaxial and biaxial specimens from each are cut and metallographically prepared in different directions to be examined under SEM.

RESULTS

Obtained FLC and FrLC curves of IF and DP600 steels are given in Figures 1.

It is seen for all geometries of both steels that the deformation occurs through a linear path up to the point of necking, and above this point the sheet follows a somewhat plane strain path to up to fracture. However, on uniaxial paths this behaviour is somewhat less pronounced. Another interesting point is the difference of fracture behaviour of the two alloys with different formability. Whereas the FrLC of the very formable IF steel is a linear curve, it is observed that the FrLC of the less formable DP600 steel has the same shape with the FLC.

The uniaxial IF specimen fails through shear band localization as shown in Figure 1-a. The crossectional morphology is shown in Figure 1-b. The SEM micrographs of
of the crack reveal three different microstructural zones. In the center of the crack (Figure 1-c: right) a severely deformed morphology is observed which shows extensive energy dissipation and also varying sizes of voids. Next to this zone is a region with a relatively less deformed surface and smaller sized void formation (Figure 1-c left). The neighbouring region is a region of extensive shear, which shows oriented dimples and a highly deformed morphology (Figure 1-d).

**FIGURE 2.** IF specimen which follows the uniaxial path. (a) Macroscopic view of the crack (b) Thickness crossection of the shear region (c) Fracture surface at the center of the specimen (d) Fracture surface at the shear zone.

The biaxial IF specimen fails through excessive thinning which is followed by necking and cup-cone type of ductile fracture (Figure 3). The thickness crosssection of the fracture surface is shown in Figure 3-b. Following the formation of the cup-cone in the center of the crack, the material fails by shearing towards the surfaces. It is possible to see some void formation on shear-edges (Figure 3-d)
FIGURE 3. IF specimen which follows the biaxial path. (a) Macroscopic view of the crack. (b) Thickness crosssection of the fracture surface. (c,d)

Uniaxially deformed DP600 sheet fails by necking and through thickness shear-fracture (Figure 4). The investigation of the microstructure of the crack reveals excessive plastic deformation and damage evolution (Figure 4-a). It is also possible to see examples of void coalescence mechanism (Figure 4-c, right insert picture). Another interesting morphology to point out is the local microcracks formed by the coalesence of voids. (Figure 4-d, left insert picture). Analysis in the transverse direction also reveals ductile damage evolution (Figure 4-b).

Biaxially deformed DP600 sheets fails in a similar fashion to the uniaxial DP600, although excessive thinning is observed in this case (Figure 5-a). The crack morphology shows a through-thickness shear fracture, with some local swifts in shear direction (Figure 5-b). As in the uniaxial DP600 specimen, void formation and local microcracks formed through void coalescence is also observed here; however, number of voids is observed to be higher (Figure 5-c,d).
FIGURE 4. Uniaxial DP600 specimen (a) Macroscopic view of the crack. (b) Thickness crosssection. (c) Fracture surface

FIGURE 5. Biaxial DP600 specimen (a) Macroscopic view of the crack (b,c,d) Fracture surface
DISCUSSION

When the damage evolution in the uniaxial and biaxial IF specimens are examined by the SEM micrographs, it is seen that void nucleation, growth and coalescence plays different roles in these two paths. In the uniaxial path, a region with large voids forms in the middle of the specimen, where failure is initiated. The crack then propagates in a localized shear band to the edge of the specimen. In the biaxial specimen however, a severely damaged zone running all through the center of the specimen is responsible of a cup-cone type of failure, shearing off to the surface. Although larger voids are observed in the fracture surface of the uniaxial specimen, due to the excessive thinning in the biaxial path prior to the neck formation, biaxial specimens require much less straining after necking to fracture.

In the DP600 specimens the fracture surface morphologies are very similar. However, it is noticed that in the biaxial specimen both the void density and the number of microcracks formed due to void coalescence are higher (Figure 4-c vs Figure 5-c,d). The fractographic comparison of damage evolution in these two specimens is currently still underway.

When the uniaxial IF and DP600 specimens are compared with each other, it is seen that although damage occurs in both of these steels, DP600 fails in a through-thickness shear fracture, whereas the IF steel, due to its high formability, resist fracture to higher strains before failing with a shear band localization. In the biaxial case, both specimens go through excessive thinning. IF specimen fails by a cup-cone type of ductile fracture, initiated with void coalescence in the center of the specimen whereas the DP600 specimen fails again by through-thickness shear fracture.

The analysis of all specimens, also involving the plane strain specimens are still being carried out. A more detailed damage analysis will be obtained when examination of the thickness crosssection specimens are done.

CONCLUSIONS

Nakazima strips of IF and DP600 steel sheets are tested to the point of fracture to obtain both FLC’s and FrLC’s. The fracture surfaces are also examined to investigate the differences in damage evolution in different strain paths. The analysis are still underway, however preliminary results show clearly the involvement of strain path and ductile damage in the failure mechanisms observed.

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