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Experimental Investigation of the Influence of Load Direction Changes on Damage in Dual Phase Steel and Aluminum Alloy

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Abstract. The influence of the stress state on damage evolution, fracture behavior, and component performance is well established for proportional loading conditions. In contrast, many industrial sheet-forming processes involve non-proportional loading paths, which can significantly alter material hardening and fracture responses. Recent results have shown, that a load direction change affects damage evolution in the dual-phase steel DP800. This paper aims to investigate to what extent these results can be transferred to the aluminum alloy AA6082-T6. Therefore, specimens are first prestrained in uniaxial tension and subsequently reloaded either in the same direction or orthogonally, using additional tensile tests. Fracture strains during the subsequent tensile tests are determined by Aramis Digital Image Correlation. An orthogonal load direction change leads to an increased fracture strain for DP800, but decreased fracture strain for AA6082. While the observed behavior of DP800 can be attributed to the void morphology, which is established during prestraining, the results of AA6082 indicate different damage mechanisms which cause this behavior.

Introduction

Dual-phase steels, such as DP800, are composed of martensite and ferrite and widely used in the automotive industry because of their excellent balance of high strength and good formability. The microstructure of DP800 is established during hot and cold rolling followed by intercritical annealing, which can result in anisotropic ductile behavior.

AA6082-T6 is a high-strength aluminum alloy widely used in automotive, aerospace, and structural applications due to its excellent strength-to-weight ratio and good corrosion resistance. However, the T6 temper, obtained through solution heat treatment and artificial aging, provides high strength at the expense of reduced work-hardening and formability.

In complex manufacturing routes, but also in simpler processes like deep drawing, different regions of a sheet experience a variety of stress conditions, including changes in hydrostatic and deviatoric stress. A key feature of these non-proportional load paths is the variation in the direction of the mean stress. This study aims to assess how changes in loading direction influence damage evolution.

Damage, in this study, refers to the nucleation, growth, and coalescence of voids within a material. Damage evolution is affected by the stress state (triaxiality η and Lode parameter L) during forming. Damage, as well as other forming-induced properties such as residual stresses and work hardening, influence fatigue life, Charpy impact toughness, and crash performance of the formed component [1]. Direct methods for the characterization of damage evolution are mass density measurements and 2D microscopic images. The specific mechanisms responsible for damage are material-dependent. Void nucleation can occur through the fracture of individual phases or non-metallic inclusions, as well as through decohesion either between two phases or between a phase and an inclusion. The precipitates in AA6082 form during quenching at low cooling rates and are distinguished from nano-scale precipitates which form during the ageing process and are desired for enhanced strength. The number and size of these precipitates is influenced by the chemical composition and the quenching rate and are therefore batch-dependent [2].

In dual-phase steels, the dominant damage mechanisms are martensite cracking and interfacial decohesion at martensite–ferrite boundaries [3]. During tensile loading, voids initially form with orientations perpendicular to the loading direction at small strains and subsequently grow in the direction of loading as deformation progresses [4].

Investigations into strain path changes have demonstrated that non-proportional strain paths generally result in higher fracture strains than proportional ones. Kestner and Koss [5] performed experiments involving sequential combinations of uniaxial and equibiaxial tension on titanium sheets, ultimately reaching a plane-strain condition. Their results showed that non-proportional strain paths yielded higher fracture strains than proportional ones. They attributed this behavior to a delay in void nucleation during multi-stage deformation, associated with strain paths characterized by relatively low maximum principal stresses.

Strain path changes can be classified using the strain path change indicator defined by Schmitt et al. [6]:

$$\kappa = \frac{\Delta\varepsilon_1^{\mathrm{pl}} : \Delta\varepsilon_2^{\mathrm{pl}}}{\left\|\Delta\varepsilon_1^{\mathrm{pl}}\right\| \cdot \left\|\Delta\varepsilon_2^{\mathrm{pl}}\right\|} \tag{1}$$

where $\Delta\varepsilon_i^{\mathrm{pl}}$ is the tensor corresponding to the plastic strain increment of load step i.

The parameter κ can vary between $-1 < \kappa < 1$ and represents following strain paths:

$\kappa = 1$: monotonic strain path
$1 < \kappa < 0$: monotonic strain path change
$\kappa = 0$: orthogonal strain path change
$0 < \kappa < -1$: non-monotonic strain path change
$\kappa = -1$: strain path reversal

Recent investigations on DP800 show, that load direction changes influence damage evolution and finally the fracture strain [7]. This paper aims to find out to what extent those results are transferable to aluminum alloys from the 6xxx-series.

Firstly, the sheets are tested in monotonic tensile tests. The stress-strain curves and R-values will reveal, if the material's behavior depends on the rolling direction. The uniform elongation also shows to which level prestraining is possible to still obtain homogenously prestrained specimens.

Then, the 2-step tensile tests are conducted to investigate the effect of load direction changes on damage (Fig. 1). Therefore, smaller tensile specimens are extracted from larger, prestrained specimens. These smaller specimens are then loaded parallel to the prestrain - with a monotonic loading direction ($\kappa = 1$) – and another set is loaded orthogonally to the prestrain - with an orthogonal load direction change ($\kappa = -0.5$). The void morphology in DP800, which influences further void growth in the subsequent tensile tests is shown. The fracture strains in the subsequent tensile tests are determined by Aramis Digital Image Correlation (DIC) to indicate the influence of the load direction change on damage behavior.

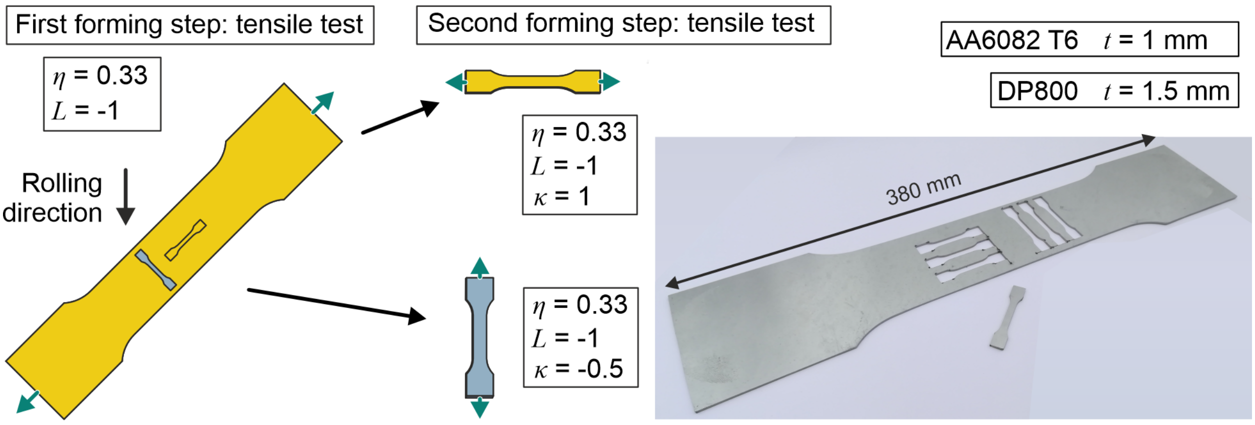

Fig. 1. 2-step tensile tests.

Monotonic Characterization in Standard Tensile Tests

Former investigations have shown, that the rolling-induced microstructure influences the behavior of DP800 sheet material since damage and fracture depend on the rolling direction. To see if this is also the case for the investigated aluminum alloy AA6082-T6, standard A80 tensile tests are performed with orientation in 0°, 45° and 90° to the rolling direction. All tests in this work are carried out on the universal testing machine Zwick Z250 with a quasi-static strain rate of 0.0067/s. The strains are measured by the contact extensometer makroXtens II HP by Zwick with an initial length of 80 mm. The stress-strain curves reveal similar hardening behavior of all specimens regardless the rolling direction with a yield strength of 275 MPa and an ultimate tensile strength of 310 MPa (Fig. 2). The uniform elongation ε_u is lowest at 0° (0.089±0.002) and similar for 45° (0.093±0.002) and 90° (0.093±0.001). The total elongation ε_f follows the same trend, since it is also lowest at 0° (0.121±0.003) and similar for 45° (0.135±0.004) and 90° (0.133±0.002). This shows, that the rolling direction influences the fracture behavior, which needs to separated from the effect of load direction changes. Therefore, the prestraining is applied in 45° to the rolling direction, because then both subsequent tests are loaded in 45° as well, which ensures the separation of the effect of the loading direction on damage and fracture from the effect of the rolling-direction-dependent behavior.

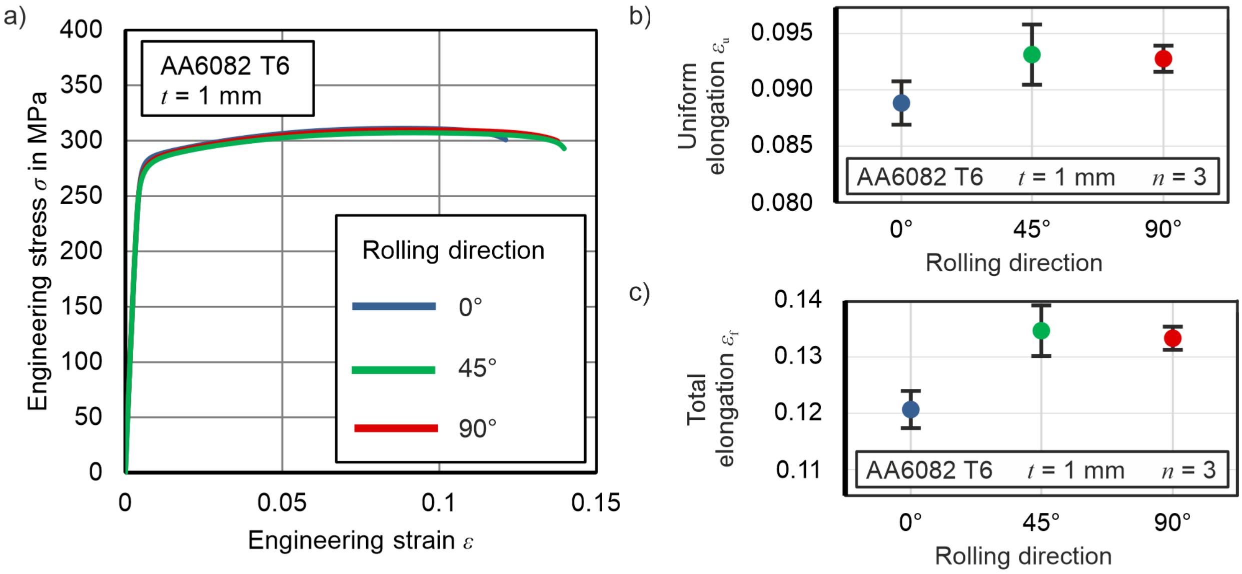

Fig. 2. AA6082-T6 – a) Stress strain curve; b) Uniform elongation; c) Total elongation.

Prestraining of the Specimens

The testing area of the large specimens for prestraining has a width of 60 mm and a length of 120 mm (Fig. 3a). The strains are measured with a contact extensometer with an initial length of 14 mm. The aim of the prestrain is to induce damage evolution due to tensile strain. Therefore, higher strains are preferable since damage evolves at positive triaxialities with an increasing strain. On the other hand, the prestrain should not exceed the uniform elongation, as a heterogenous strain distribution would influence the subsequent tensile tests by making them not comparable. To balance these goals, the prestrain is chosen to be 0.074 ($\varepsilon_p = 0.07$), since necking sets in at a strain of approximately 0.09. Since the DP800 material started necking at 0.108, the prestrain for these specimens was chosen to be 0.098 ($\varepsilon_p = 0.09$).

After forming, the specimens for the subsequent tensile tests are extracted from the testing area by laser cutting. To compare the material behavior and damage evolution under monotonic loading and after an orthogonal change of loading direction, one set of secondary specimens is extracted parallel to the prestraining direction and another set is extracted in orthogonal direction (Fig. 3b).

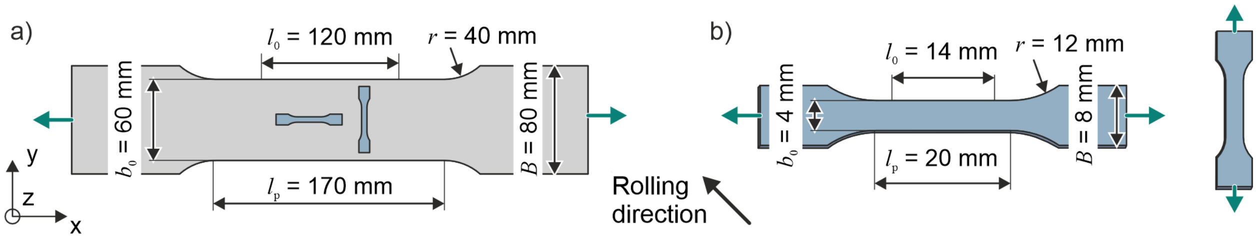

Fig. 3. Specimen geometry for the tensile tests: a) specimens for prestraining; b) specimens for subsequent tensile tests.

Void Morphology in DP800

The void morphology after prestraining was investigated for DP800 [7]. Damage analysis of the prestrained specimens by SEM shows that voids most often form between two martensite islands, likely due to martensite cracking or ferrite failure in these narrow regions. These voids are bordered by hard martensite along the prestrain direction and by softer ferrite orthogonally. An illustrative simulation was conducted to demonstrate the effect of this microstructural configuration, considering the different hardening behaviors of ferrite and martensite. The model consists of two martensite islands embedded in a ferritic matrix with a void positioned between them, oriented orthogonal to the initial tensile loading direction (Fig. 4a). The numerical results show, that after monotonic loading, the void grows, whereas an orthogonal change in loading direction causes the void area to decrease (Fig. 4b).

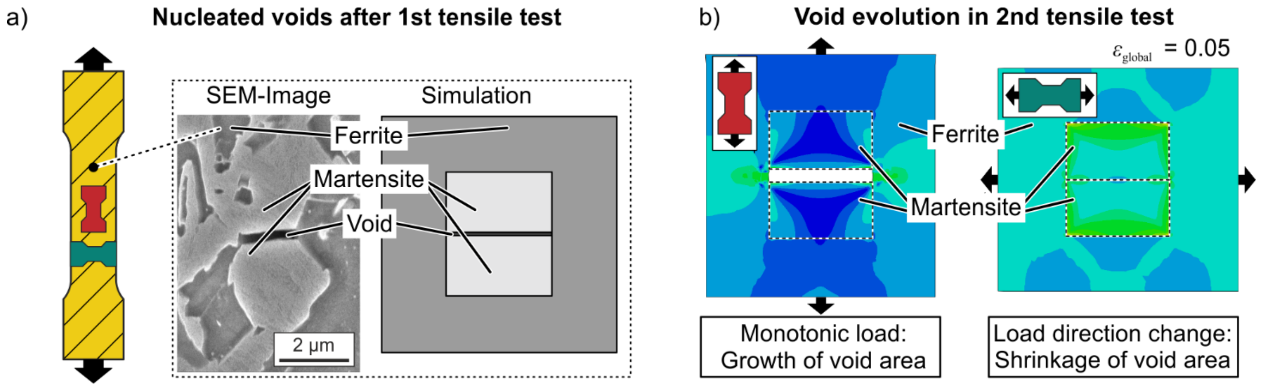

Fig. 4. DP800 – a) Voids after first tensile; b) Void evolution in subsequent tensile tests [7].

Fracture Strains in Subsequent Tensile Tests

The fracture strains are determined with Aramis DIC during the subsequent tensile tests. The DIC system has a frame rate of 5 Hz. The equivalent strains are measured in the last frames before fracture is visible in the DIC-system. The results reveal, that an orthogonal load direction change leads to a decrease in terms of the fracture strain for the aluminum alloy, while the fracture strain is increased after the orthogonal load direction change in DP800 (Fig. 5). For DP800, the fracture strain increases about 10% from 0.5 to 0.55 after an orthogonal load direction change in comparison to a monotonic load. For AA6082-T6 the fracture strain decreases about 6% from 0.5 to 0.47 after an orthogonal load direction change in comparison to a monotonic load.

The manufacturing of the specimens by laser cutting might influence the results quantitatively due to heating in the cutting area. Anyway, this does not influence the comparative nature of the results, since all specimens were manufactured with the same methods.

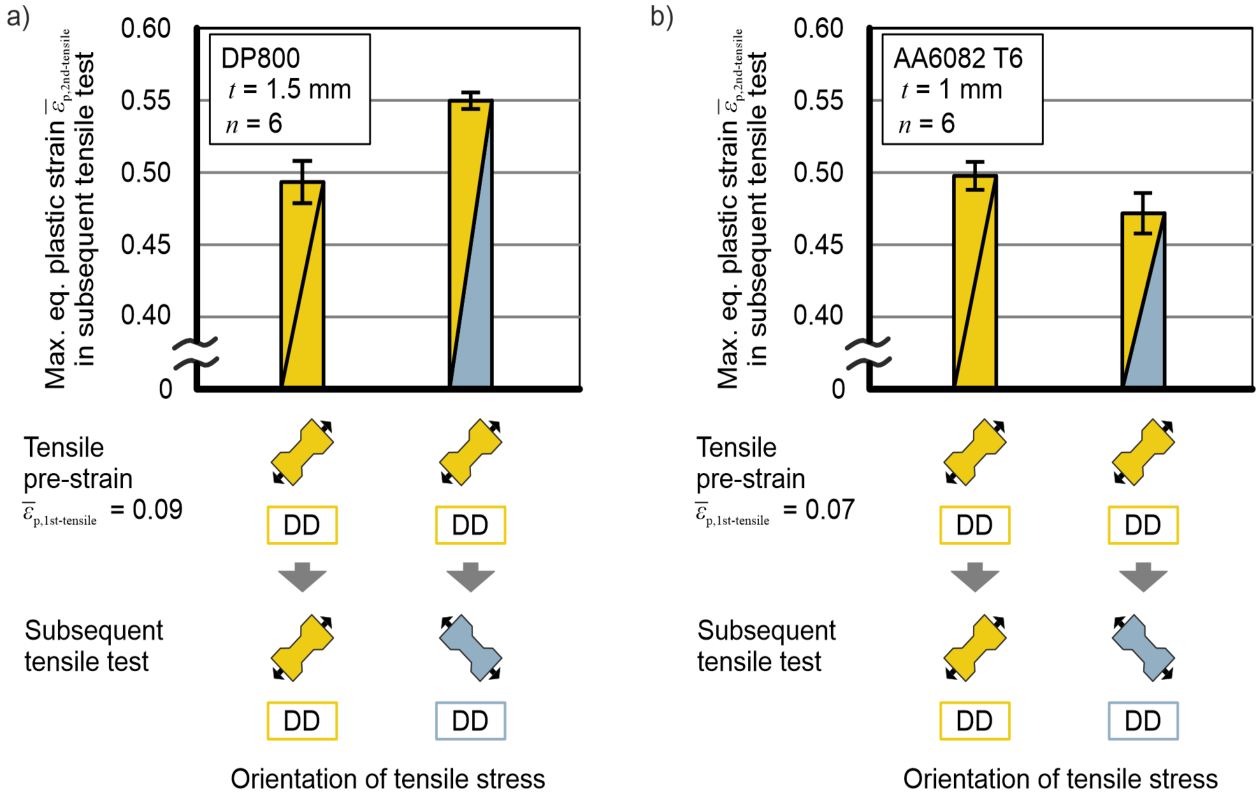

Fig. 5. Fracture strains in subsequent tensile tests – a) DP800; b) AA6082-T6.

Conclusion

The dual phase steel DP800, as well as the aluminum alloy AA6082-T6 have been tested in monotonic and 2-step tensile tests with a continuous load path and an orthogonal change of loading direction. Standard, monotonic tensile tests have shown, that the forming behavior of both materials depend on the rolling direction.

For DP800, orthogonal load direction changes lead to an increase in fracture strain. This can be explained by the void morphology, since voids shrink after orthogonal load direction changes due to their nucleation in between martensitic phases. On the other hand, for AA6082-T6, the fracture strain decreases after an orthogonal load direction change.

It can be concluded, that the damage mechanisms of AA6082-T6 seem to differ from DP800, since the fracture behavior under a non-monotonic load is opposite. While for DP800 the fracture of martensitic phases has been identified as the dominant damage mechanism in uniaxial load, the behavior of aluminum alloy AA6082-T6 in contrast might be governed more by decohesion of inclusions and precipitates from the matrix. Therefore, further investigations will aim at the identification of damage mechanisms in AA6082-T6 after a monotonic load and after orthogonal load direction changes.

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