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Damage Evolution in Nakajima Tests of DP800 Dual Phase Steel

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Abstract. In order to extend the understanding of damage evolution in sheet metal forming, standardized Nakajima tests are carried out on a DP800 dual phase steel. Sample geometries for characteristic stress-strain states are drawn in incrementing stages and their damage states are analyzed using light and scanning electron microscopy as well as micro hardness measurements. Numerically analyzed load paths are correlated with the respective damage states to allow prediction of damage evolution in deep drawing processes. The influence of anisotropy is investigated by testing samples cut at various angles to the rolling direction of the sheet material. The result of the conducted research is the understanding of interactions between load paths and damage evolution in sheet forming. These results will later be used to optimize load paths in a deep drawing process, taking into account Lode parameter and stress triaxiality to produce damage controlled parts.

1. Introduction and state of the art

Human-made climate change has been identified as one of the most urgent threats to the environment [1]. One way to reduce carbon dioxide emissions and thereby global warming is the reduction of vehicle mass. This can be achieved by lightweight design using advanced high strength steel [2]. Vehicle body parts are primarily made in forming processes. However, service properties of formed parts depend strongly on the damage state after forming. Material discontinuities such as voids, inclusions, or precipitations, act as damage initiation locations and undergo evolution with respect to stress states during forming processes. An increased damage state after forming facilitates damage evolution and, eventually, failure in service. [3]

Damage models are categorized into two distinct approaches. Cockcroft and Latham [4], and Bao and Wierzbicki [5] proposed models that quantify damage through a scalar parameter and predict failure at a critical value for that parameter. Lemaitre [6] proposed a microstructural approach which takes into account softening and allows relation of damage to plastic properties. Both types of models are primarily designed to predict failure in the manufacturing process. To be able to reliably model damage evolution and thereby control damage during forming processes, closer examination in specific forming processes is necessary. Li has shown that the investigation of damage evolution requires the regard of not only an equivalent stress, as used in flow curves, but of the actual stress state, characterized by the von Mises equivalent stress σ_{eq} , the Lode parameter L and stress triaxiality η , which are invariants of the stress



tensor [7]. The value of these invariants can be identified with certain stress states. The von Mises equivalent describes the magnitude of the stress state. The Lode parameter L is a normalized value and takes values of $L = -1 \dots 1$. A Lode parameter of $L = -1$ describes biaxial tension with uniaxial compression, $L = 0$ describes pure shear stress and $L = 1$ describes uniaxial tension. Stress triaxiality η takes values of $\eta = -\infty \dots \infty$ with $\eta = -2/3$ describing plane compressive stress, $\eta = -1/3$ uniaxial compressive stress, $\eta = 0$ pure shear stress, $\eta = 1/3$ uniaxial tensile stress and $\eta = 2/3$ plane tensile stress [8]. Yin has identified positive values of stress triaxiality η as an indication of damage critical stress states in in-plane torsion tests of DP600 dual phase steel [9].

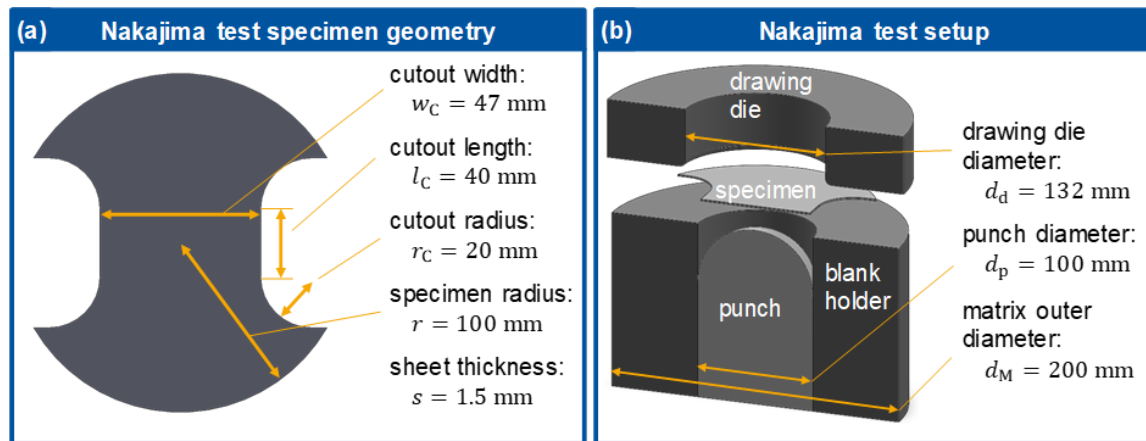


Figure 1. Nakajima test principle: (a) specimen geometry; (b) test setup.

Evolving stress states are described using load paths. These show the evolution of loads, in this case of the three invariants, over time [10]. To achieve different load paths, Nakajima tests are executed. These were originally developed to record forming limit diagrams, which help in predicting failure in sheet metal forming. Nakajima tests use specimens with varying cutout widths (Figure 1 (a)) to achieve different stress-strain states. These specimens are clamped using a circular blank holder and then drawn until fracture through a drawing die using a hemispherical punch (Figure 1 (b)). Major and minor strains on the specimen surface are recorded when fracture occurs and plotted in the forming limit diagram, resulting in a curve representing the limit of formability of the sheet material [11].

Pathak [12] investigated damage evolution in DP780 dual phase steel during Edge Stretching. Holes were alternatively reamed and sheared into a tensile test specimen and the specimen was then drawn. Experiments were interrupted at different strains and the damage states were analyzed. Void nucleation, void growth and void coalescence were investigated as damage mechanisms. Void density, as an indicator for void nucleation, showed a strong increase with increasing strain. Both average void diameter and void orientation did not change significantly with increased strain [12].

2. Methods and materials

In the context of this work, specific stress states are created in a DP800 dual phase steel using Nakajima tests. These stress states are correlated to damage states in the material. The specimens were water jet cut, which has been determined to prevent both excessively frayed edges and heat influence. Frayed edges might lead to premature failure at the edges while heat influence would change the steel micro-structure, especially the damage state.

2.1. Load paths

Specimens with cutout widths $w_c \in \{11 \text{ mm}; 47 \text{ mm}; 83 \text{ mm}; 107 \text{ mm}\}$ were produced. Finite Element simulations of the Nakajima tests on these specimens were carried out in previous work using Abaqus/Explicit with solid three-dimensional reduced integration 8-node hexahedral elements (type

C3D8R). Convergence analysis has shown element lengths of $l_p = 0.3$ mm in the sheet plane and $l_s = 0.5$ mm in sheet thickness direction to give consistent results. The simulations have yielded load paths for various cutout widths [12]. The simulations were validated with strain fields obtained from physical Nakajima tests. While a significant drop-off in strain towards the specimen center could be observed in the simulations that did not occur in physical experiments, strain results starting at 20 mm from the center were consistent with the fields observed in experiment. Load paths were therefore extracted for elements at the center line of the specimen, at the end of the cutout (see Figure 2 (a)). The extracted load paths are shown in Figure 3. Specimens with cutout width $w_c = 47$ mm were selected to use in experiments since their load paths show gradually increasing values of the Lode parameter L at the top surface and a steep increase to the maximum value at the bottom surface.

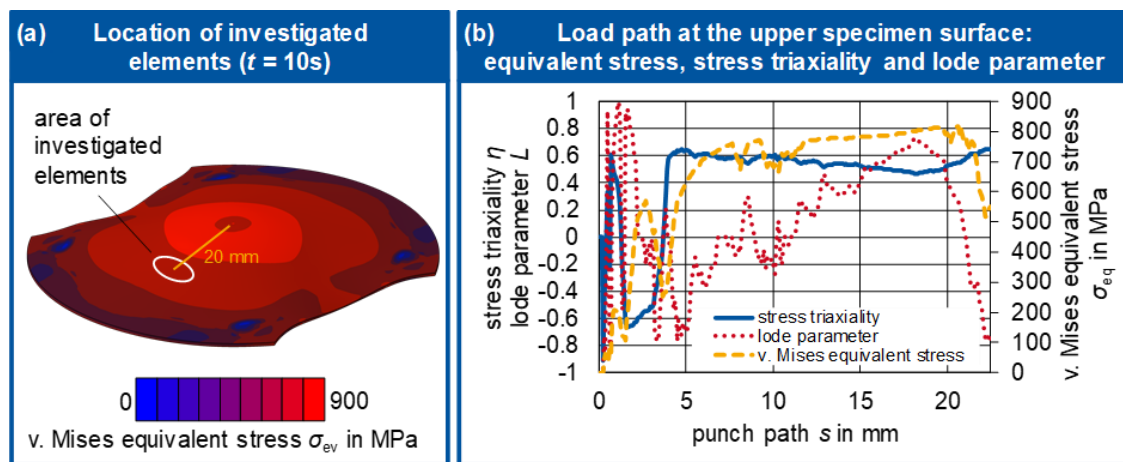


Figure 2. Finite Element model of a $w_c = 95$ mm Nakajima test: (a) location of investigated elements at $t = 10$ s; (b) load paths at the upper specimen surface.

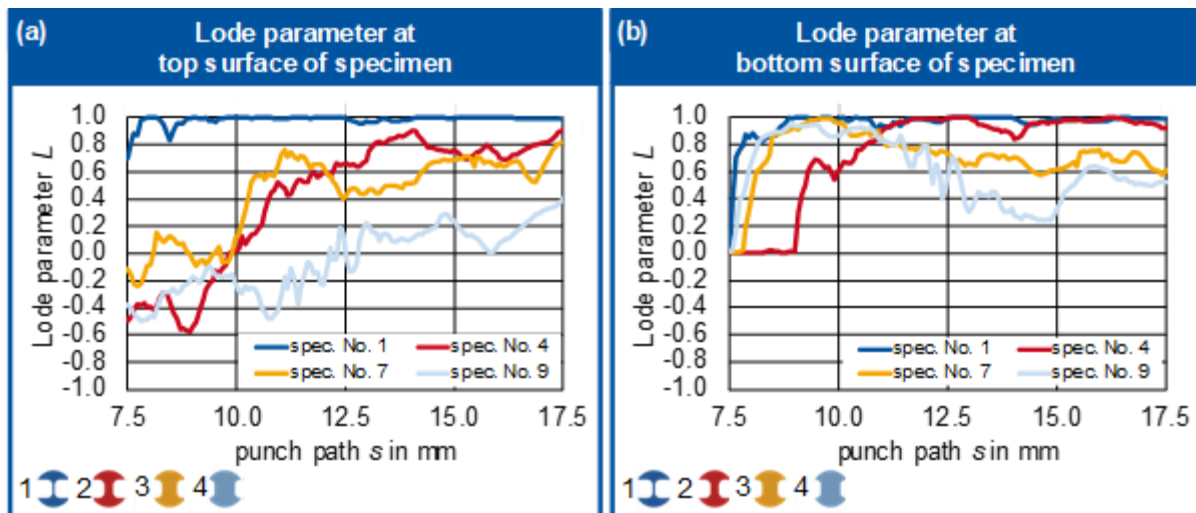


Figure 3. Load paths with respect to Lode parameter (a) at top surface, (b) at bottom surface for various cutout widths.

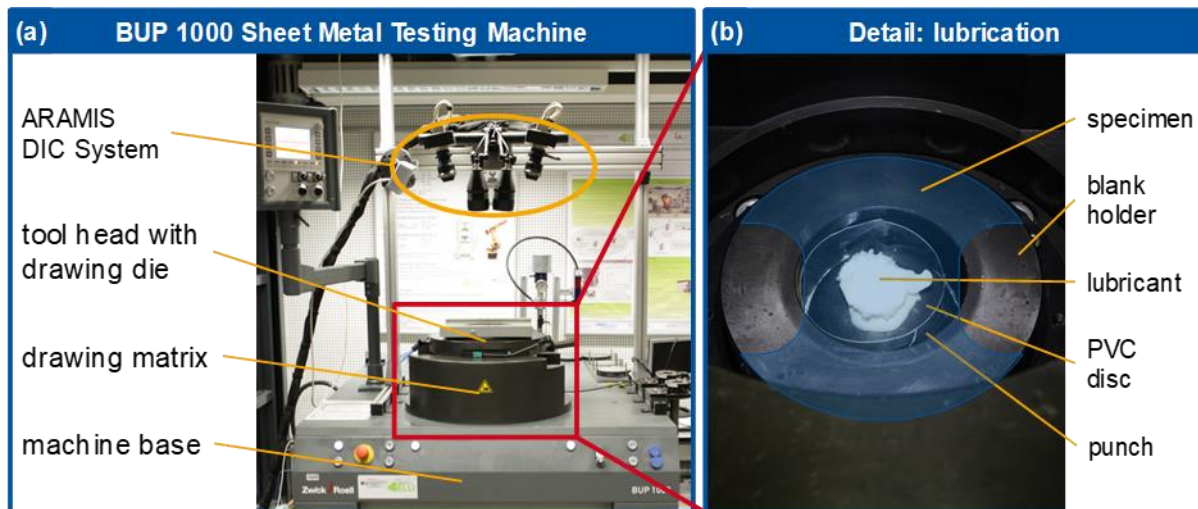


Figure 4. BUP 1000 Sheet Metal Testing Machine: (a) machine setup; (b) lubrication detail.

2.2. Experimental approach

The tests mentioned before were executed on a Zwick Roell BUP 1000 Sheet Metal Testing Machine (see Figure 3). The machine provides a maximum force of $F_{\max} = 1,000$ kN, which is available for both clamping and forming. A Nakajima tool was used with a punch diameter of $d_p = 100$ mm, a drawing die diameter of $d_d = 132$ mm and a forming matrix diameter of $d_M = 200$ mm. The testing machine is fitted with a GOM ARAMIS digital image correlation (DIC) system, which can be used to record strains during forming. However, since the focus of this work lies on the damage evolution in relation to the specific stress state and stress history, strains were not recorded.

Nakajima tests are ideally executed without friction in the contact zone between punch and specimen. To reduce friction as far as possible, a layered lubrication system was used (see Figure 3 (b)). Beruforge 170 from Bechem Lubrication Technology, a MoS_2 based coating lubricant, was first applied to the punch. The lubricant was then covered by a PVC disc with a diameter of $d_{\text{PVC}} = 90$ mm and another layer of lubricant was applied onto this disc. Experiments at the Institute of Forming Technology and Lightweight Components (IUL) at TU Dortmund have proven this combination to be effective in reducing friction to near-zero.

To investigate damage evolution during forming, stopped tests are undertaken. Specimens are drawn to depths of $s_d \in \{7.5 \text{ mm}; 12.5 \text{ mm}; 17.5 \text{ mm}\}$. These are then cut along the line at the end of the cutouts and their microstructure is analyzed, specifically with regard to voids. Specimens are grinded and polished with grain sizes of 6, 3 and 1 μm . To remove caps from the voids that result from material being smeared over them, the polished specimens are etched in a 3% Nital solution for 5 s. To remove the etched structure from the metal matrix, a polishing step of 1.5 min with 1 μm grains is used. The extent of damage in the specimens is identified through the area of voids that can be seen in the micrograph.

3. Results and Discussion

Sample micrographs of a $s_d = 17.5$ mm specimen both near the top and the bottom surface are shown in Figure 5 (a). The DP800 steel matrix is seen as a uniform, light gray area. All black areas are regarded as voids, with their percentage used as a measure for damage. Light pink inclusions are not counted towards the damage estimation.

3.1. Void percentage

Average void percentages v for the investigated specimens are displayed in Figure 5 (b). While top surface values increase from $v = 0.047$ % at $s_d = 7.5$ mm through $v = 0.052$ % at $s_d = 12.5$ mm to $v = 0.075$ % at $s_d = 17.5$ mm, this is entirely within the standard deviation of the sample. For the

bottom surface, average void percentage increases slightly from $v = 0.058\%$ at $s_d = 7.5\text{ mm}$ to $v = 0.060\%$ at $s_d = 12.5\text{ mm}$ and then decreases to $v = 0.053\%$ when the drawing depth is increased to $s_d = 17.5\text{ mm}$. Again, regarding standard deviation, no effect of larger drawing depths can be seen.

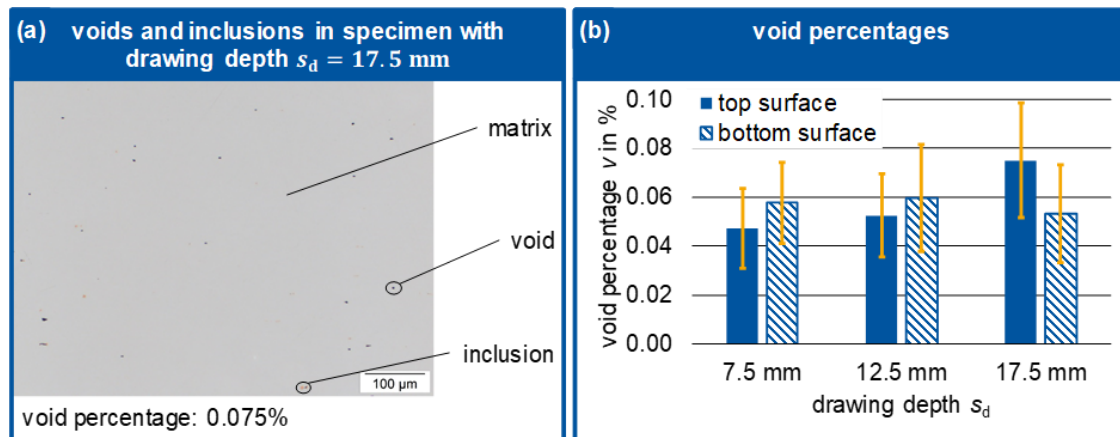


Figure 5. Void percentage in specimens: (a) void identification in micrograph; (b) void percentage averages for different drawing depths.

Possible reasons for the lack of effect on measured damage are issues with the evaluation procedure, a lack of resolution with the light microscope, or an actual lack of detectable effects. Damage initiation in the form of void generation happens through brittle fracture of the martensite phase, through ductile deformation of the ferrite phase or through stress concentration at inclusions or precipitations [13]. These effects occur at a scale that cannot be investigated using light microscopy. Continued deformation of the specimen does eventually lead to voids that can be detected with a light microscope, but these deformations were not achieved in the experiments.

Due to symmetry, the direction of the maximum principal stress at the investigated location is expected to be perpendicular to the plane in which the micrograph was taken. Since voids will grow primarily in the direction of the maximum principal stress, detection of growth is difficult.

4. Summary and Outlook

The drawing of the selected $w_c = 47\text{ mm}$ specimen to depths of $s_d \in \{7.5\text{ mm}; 12.5\text{ mm}; 17.5\text{ mm}\}$ has proven to not produce sufficiently significant damage in the form of voids to analyse the influence of load paths on damage evolution using light microscopy. Although an increase in the average void percentage at the top surface can be seen, this is entirely within the standard deviation of the measurement.

The cited study by Pathak [12] found void percentages of around $v = 0.2\%$ in reamed hole specimens at equivalent strain $\epsilon_{eq} = 0.05$. These grew to around $v = 0.8\%$ at $\epsilon_{eq} = 0.4$. While potentially different initial material states and different testing methods prevent a direct comparison, similar magnitudes can be seen.

Further experiments need to be undertaken to analyse damage evolution. The drawing depths at failure are known from experiments executed in order to validate the numerical model of the Nakajima tests. Drawing specimens to a depth just before failure will create a state of maximum damage. Furthermore, the numerical model must be refined in order to correctly predict strain not only at the location investigated here, but specifically at the center of the specimen, where failure does eventually occur. This will allow the investigation of load paths at a location where damage is expected to be more pronounced.

The results of the presented work and further investigations will be used in subprojects within the Collaborative Research Center CRC/Transregio 188 Damage Controlled Forming Processes that are specifically concerned with damage modelling to extend and calibrate various damage models for the specific dual-phase steel used within the CRC.

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