Metallographic analysis of failure mechanisms during Nakajima tests for the evaluation of forming limits on a dual-phase steel

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Abstract. The material characterization is the first step for an accurate numerical design of forming operations. Since its first definition in the 1960s, the forming limit curve (FLC), usually evaluated with Nakajima or Marciniak tests, is still one of the most used criteria in the industrial and scientific field for the determination of the forming limits under different stress conditions. Despite the several signs of progress in terms of measurement techniques, thanks to the introduction of optical measurement systems, the European standard method for the evaluation of the FLC remains the cross-section-method of 2008. This method is basically suitable for materials with a pronounced necking evolution. For materials with an abrupt localization, like modern high-strength materials, the standard evaluation shows weaknesses. Investigations in 2015 based on pattern recognition on Nakajima tests show that the pattern evolution of the strain distribution during the test can be used for the prediction of the material failure. However, a definition of the pattern development is needed. In order to investigate new possibilities for the determination of the FLC, the knowledge about the failure mechanisms during Nakajima tests for these materials has to be increased. The aim of the present work is an analysis of the changes on the surface and the microstructure during the Nakajima tests at different stress states and drawing depths. The correlation between material modifications and failure behavior is conducted on the dual-phase steel DP800. For the analysis of the surface and the thickness, the scanning electron microscope (SEM) is employed. Moreover, considerations about the forming mechanisms of the DP800 at different stress conditions are given and compared with the forming limit prediction of the FLC.

1. Introduction
The forming limit curve represents the formability in terms of onset of necking as major and minor strain pairs for sheet metals. The concept of formability evaluation during stretching processes refers to the work of Keeler and Backofen in 1963 [1]. Their investigation was focused on biaxial strain conditions. With the study of Goodwin in 1968 [2] the concept of the modern forming limit curve (FLC) from uniaxial tension to the biaxial tension was developed. The test setups proposed by Nakajima [3] and Marciniak [4] are nowadays the most used setups for the FLC determination and part of the standard DIN EN ISO 12004-2 [5] in the regulation of the FLC evaluation. The standard not only prescribes the experimental condition but also the evaluation method. This is the so-called “cross-section-method” [6] that applies an interpolation of the second order on the strain distribution before crack initiation. The interpolation implies a pronounced development of the strain localization
and the possibility to fit it with a second order function. The cross-section-method achieves reliable results for ductile materials like conventional deep-drawing steels. However, for those materials with a brittle crack without a clear necking phase, the method shows weaknesses [7]. That is the case of lightweight materials such as aluminium alloys and high-strength steels. In the last 15 years, several evaluation approaches were proposed to overcome this problem. In the time-dependent evaluation methods the whole strain history of the necking zone is considered. The most used time-dependent evaluation method is the so-called “line-fit-method” proposed by Volk et al. [8]. A review of the principal time-dependent evaluation methods can be found in [9]. Nevertheless, the suggested methods are based on the strain development evaluated in a small area at necking. Thus, the material structure and in general the global development of the strain during forming are not considered. In 2015 the authors proposed a first approach based on the global evaluation of the forming history by using pattern recognition methods [10]. The results show that it is possible to predict the crack initiation by training the pattern recognition algorithm on the whole forming history. The pattern recognition analysis deals with the automatic evaluation of pattern. Prerequisite is the definition of the classes to analyze. The first approach was based on the recognition of the crack initiation, thanks to its easy definition. The challenge is to recognize and predict the onset of necking and thus a reliable definition is required. The possibility to find correspondence between the pattern on surface and changes in the material structure was investigated for a deep drawing steel DC04 [11]. The results have shown a good agreement with the experimental FLC. While the analysis of the DC04 was possible thanks to the marked necking phase, the investigation of high-strength steels or aluminium alloys can be more difficult. Tasan et al. investigated the damage evolution of a dual-phase steel and a high formability steel by analyzing the microstructure [12], remarking the importance of damage mechanism for microstructures with phases with different deformation characteristics. They also developed a miniaturized Marciniak setup [13] for in-situ investigations with scanning electron microscopy (SEM). The outcomes for dual-phase steels [14] reveal the relation between material structure and forming limits. Non-homogenous martensite distributions possibly cause earlier macroscopic strain localization. However, the scaled setup may cause some problems due to the severe contact condition. Furthermore, the smaller evaluation area on the scaled setup is not directly comparable with the standard configuration. In addition, a correlation of the changes in the material structure and surface should be investigated. The aim of the present work is the analysis of the surface and thickness changes during Nakajima test for a dual-phase steel DP800. The investigation is conducted for different stress states and drawing depths. The results are quantified and compared with the experimental FLC. The achieved information can be used for the evaluation of the FLC by reaching a more accurate class differentiation for the pattern recognition method.

2. Experimental setup and procedure

2.1. Nakajima test

For the present analysis, the Nakajima test setup according to the DIN EN ISO 12004-2 is used (Figure 1). The blank holder clamps the specimen with a force of 500 kN without drawbeads. The punch has a diameter of 100 mm and a velocity of 60 mm/min. The strain distribution is measured with the optical measurement system Aramis (gmm GmbH). The cameras have a resolution of 1280x1024 pixels and the frame rate is set 40 Hz. The evaluation of the FLC is conducted with the cross-section-method according to the DIN EN ISO 12004-2. In order to reduce the friction between the specimen and the punch, a sandwich-type lubricant system is used. According to the DIN EN ISO 12004-2, it is composed of grease, Teflon foil and soft PVC. To focus the investigation on the most significant strain path and in order to limit the number of tests to a reasonable amount, the present investigation is focused on three stain paths: negative minor strain condition (S050: parallel width of 50 mm), plane strain condition (S110: parallel width of 110 mm) and the biaxial condition (S245: full test specimen). The used specimen geometry is schematically depicted in Figure 1. The geometries are cut with a CO2 laser system (TruLaser Cell 7020, Trumpf GmbH+Co. KG).
During the Nakajima test, the strain distribution progresses gradually and proportionally until instabilities occur. Generally, instabilities are observed in the last 2 millimetres of punch displacement before crack. Therefore, the metallographic analysis is focused on the last 2 mm of forming. Firstly, a test specimen is formed until crack and the maximal punch displacement is evaluated. Secondly, the different forming steps are achieved by stopping the punch stroke with steps of 0.2 mm from the maximal punch displacement. The steps are evaluated up to -1.6 mm from the maximum. Finally, a forming step at -4 mm is performed, in order to have a comparison with a lower forming condition. Table 1 gives a summary of the geometries and the investigated drawing depths.

### Table 1. Investigated drawing depth (mm) with the corresponding geometry.

| Drawing steps | fracture | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---------------|----------|---|---|---|---|---|---|---|---|---|
| S050          | 23.5     | 23.3 | 23.1 | 22.9 | 22.7 | 22.5 | 22.3 | 22.1 | 21.9 | 19.5 |
| S110          | 24.4     | 24.2 | 24.0 | 23.8 | 23.6 | 23.4 | 23.2 | 23.0 | 22.8 | 20.4 |
| S245          | 32.7     | 32.5 | 32.3 | 32.1 | 31.9 | 31.7 | 31.5 | 31.3 | 31.1 | 28.7 |

2.2. **Material**

The investigations are conducted on a cold-rolled high-strength steel DP800 with a sheet thickness of $t_0 = 1.00$ mm. It is a galvanized dual-phase steel with about 90% ferrite, leading to sufficient ductility for sheet metal forming. Martensite islands located at grain boundaries lead to high-strength and hardness.

2.3. **Metallographic analysis**

The scanning electron microscope (SEM) Gemini II optics (Merlin, Zeiss GmbH) is employed for the investigation of the surface. The measuring distance is set to 50 mm with a magnification of 30x and a current intensity of 2 nA. Due to the surface curvature and the limited measuring volume of the SEM, the measured area is limited to 9.2 mm x 6.7 mm at the specimen center. The area of interest, named the area of instabilities, is well covered since the tribological system assures the crack initiation at the center of the specimen. The 3D measurements are achieved by collecting two pictures with a tilt angle of 6°. The merging of the pictures is fulfilled with the software MeX 6.1 (Alicona Imaging GmbH). The effect of the curvature is adjusted by the least square method. Furthermore, the surface texture is analyzed with pictures with magnification 200x, in order to observe additional patterns such as micro-cracks initiation. The surface analysis is followed by the thickness analysis. The specimens are water-
cooled cut in three sections perpendicular to the forming zone as depicted in Figure 2 (a). The sections are then embedded (see Figure 2 (b)), grounded, polished and etched in 3% nital solution. With a magnification of 2500x, pictures of the whole sheet thickness are recorded with the SEM.

![Figure 2](image)

**Figure 2.** Experimental procedure: (a) cutting sections in the center of an S050 specimen and (b) associated embedding.

3. Results and discussion

3.1. Surface analysis

For all the investigated geometries the crack initiates in the center of the specimen. The major strain distribution one drawing step before crack evaluated during the test with the optical measurement system is depicted in Figure 3. The S050 geometry shows a local necking, also visible in the strain distribution before crack, at 23.3 mm drawing depth. The maximum value of reached major strain is about 0.36. In contrast, in the geometry under plane strain (S110) several local maxima can be observed at 24.2 mm drawing depth. The reached major strain value is about 0.24. The geometry under biaxial condition (S245) develops with a diffuse necking distribution and a severe thinning. At 32.5 mm drawing depth, the diffuse major strain reaches the value 0.24 and no strain localization is observed.

![Figure 3](image)

**Figure 3.** Major strain distribution one drawing step before fracture for the investigated geometries.

Even if the investigation of the strain distribution during the test shows some important information and typical patterns related to the strain forming history, for a better understanding of the surface changes of the material an additional analysis of the surface is needed. The 3D measurement of the surface structure with the SEM measurement reveals different outcomes for the different strain histories (see Figure 4). For the geometry S050, a significant development of the surface is detectable. By increasing the drawing depth a thickness reduction in the center of the specimen parallel to rolling direction occurs. The height difference reaches 200 µm at 0.4 mm drawing depth before fracture. At 0.2 mm drawing depth before fracture the height difference is about 250 µm.
Figure 4. 3D surface evolution for the investigate geometries detected with the SEM measurements and analyzed with the software MeX 6.1.

The height difference for lower drawing steps remains under 50 µm. The surface structure of the S110 and S245 geometries are more heterogeneous. The geometry S110 depicts a height difference of 150 µm at 24.2 mm drawing depth just before crack initiation. Lower drawing steps show a heterogeneous distribution. Comparable results are observed for the geometry S245. The diffuse necking and the thinning cause multiple peaks on the surface and a clear pattern cannot be observed. The inhomogeneous failure behavior and the multiple peaks on the surface suggest a sudden local change on the surface. Therefore, SEM measurements with a higher magnification (200x) are recorded in the zone of interest. The outcomes are depicted in Figure 5.

Figure 5. Surface SEM investigation at 200x magnification reveals micro-cracks 0.2 mm before crack.
As expected, for all three geometries micro-cracks are observed at 0.2 mm drawing depth before crack. This failure has to be considered as the previous state before crack and is responsible for the sudden crack initiation without necking phase. In particular, the geometry S110 shows multiple micro-cracks in consecutive zones. This outcome is in accordance with the multiple local peak strain distribution observed during the test.

3.2. Texture analysis
Observing the structure along the thickness at different drawing depth steps, the presence of voids was observed. An example is depicted in Figure 6 (a). The voids occur on the grain boundaries due to martensitic fracture and decohesion. The results are in accordance with the observation in Tasan et al. [12]. In order to quantify the development of the void growths, the pictures are processed with the open-source software ImageJ. The voids are evidently darker than the material structure. Therefore the level of darkness can be used for the quantification of the area of voids with respect to the material grains.

![Figure 6. SEM micrograph showing voids (a), influence of drawing depth on void area fraction (b) and sheet thickness (c).](image)

The results for the different strain conditions and drawing depths are summarized in Figure 6 (b). For all geometries four significant steps are analyzed: the step 1 (0.2 mm before fracture), the step where it is supposed that instabilities start, a drawing step 0.4 mm before the supposed onset and the drawing step 9, where the strain distribution is still homogeneous. Since for the geometry S050 a local necking was observed, a further step between step 1 and the onset of instabilities was considered. The void area fraction in as-received state material is 0.005 %. The percentage of the area of voids increases by increasing the forming independently on the strain path history. Nevertheless, for the full geometry, the reached void fraction is two times greater than for the other strain histories. The results partially confirm the outcomes of Tasan et al. [12] that observed that in the full geometry the damage mechanism is more active. However, the percentages reached in the present study are different to the results of the above-mentioned investigation. It can probably depend on the differences in the dimension of the considered area. It should be noted, that the material thickness obviously decreases.
The thickness measurements for different steps are shown in table (c). At step 9, the thickness is about 0.88-0.86 mm for the geometry S050 and S110. The full geometry shows a visible thinning with a thickness of 0.68 mm. Nevertheless, the results in diagram (b) do not change significantly if normalized to the thickness, confirming a general increase of voids nucleation by higher drawing depths. The increase of voids nucleation seems to develop gradually and continuously during the test and there is not a limit value that causes the crack initiation.

4. Comparison of the results with the forming limit curve
Finally, in Figure 7 the surface and micrograph results are compared with the experimental FLC points. The steps in which some instabilities were detected, namely necking, micro-cracks and fractures, are compared with the evaluation of onset of necking from the classic FLC. The outcomes show that in presence of a local necking, this can be detected with the SEM surface analysis. For example, the geometry S050 shows a gradual failure development with an onset of necking, that correlate with the FLC evaluation. For strain paths in which micro-cracks on the surface are basically responsible for the crack initiation, the FLC does not match properly the onset of instabilities. Regarding the quantification of micro-voids nucleation, the gained knowledge shows a proportional increase of the voids area fraction from beginning to crack. Therefore, this damage mechanism does not give further information for a phase's classification. It can be concluded, that the surface analysis has given additional information about the material instabilities for the dual-phase steel. Thus, the outcomes can be used for a more precise definition of forming limit for materials without a clear necking phase.

![Figure 7. FLC with strain paths and investigated steps.](image)

5. Conclusion and outlook
In the present study, the failure mechanisms of the dual-phase steel DP800 during Nakajima tests have been analyzed for three different strains paths. The analysis has been conducted on the surface and the thickness with the help of SEM analysis. The results have been compared with the experimental FLC in order to achieve a better understanding of the meaning of instability for this material. The SEM 3D surface analysis detects the onset of necking. However, a localization was observed only for the geometry under uniaxial tensile strain condition. In addition, even if all geometries show micro-cracks on the surface and thickness, these failures are more important in the crack initiation of the geometries under plane and biaxial strain. For the geometry under plane strain, the failures on the surface can be considered as responsible for the crack initiation. The damage to the geometry under biaxial stretching is ruled by the nucleation of micro-voids in the thickness. Nevertheless, this damage mechanism
increases proportionally with the forming to fracture. The classification of instability for the full geometry cannot be based on the quantification of micro-voids. A possible way should be found by using the maximum achievable thinning. The gained information can be used for the classification of “onset of instabilities”. The results suggest a different definition according to the stress conditions. For negative minor strain conditions (uniaxial tensile stress up to plane strain), the onset of necking has to be considered. For positive minor strains (plane strain up to biaxial strain) the metallographic analysis can be used for the determination of onset of surface damage and maximal thinning. The pattern recognition method can then be applied for the automatic detection of those point by Nakajima tests. The reliability of the definition should be investigated also for different geometries as well as for material with similar material structures.

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