Influence of strain rate on the beginning of instable deformation and failure behavior from shear to multiaxial loading for a DP1000

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Abstract. The influence of strain rate on the beginning of instable deformation and failure behavior of a DP1000 steel is investigated for a wide range of stress states with experimental methods. Therefore quasistatic and high speed tests have been performed for four different loading situations, shear loading, uniaxial tension loading, plane strain loading and equi-biaxial tension loading. The deformation of the specimens up to fracture in the highly deformed zones has been captured with high speed video recording and evaluated with digital image correlation (DIC). The beginning of instable local deformation behavior designated as beginning of instability has been detected with one uniform procedure. For tensile dominated loading situations the development of the local thinning rate in the necking zone on the surface of the specimen has been analyzed. For the determination of the beginning of shear instability, the development of the major and minor strain rate in the shear zone has been investigated. The difference between strain at beginning of instability and failure strain, determined as the largest strain at the location of failure prior to fracture, gives hints to the material’s crash performance under the investigated stress state. The largest difference has been observed for uniaxial tension loading and increases with increasing strain rate. However, under dynamic shear loading, fracture occurs without previous instability and at significant lower strains than under quasistatic shear loading. The proposed evaluation procedure to determine the beginning of instability for a wide range of stress states including shear loading is applied to the investigated DP1000 and strain rate effects are discussed.

1. Introduction
Dual phase steel sheets are frequently used in automobile crash components. Because of their sensitivity to edge cracking and their tendency for failure due to shear banding an accurate determination of the onset of plastic flow localization and failure initiation is important for component design [1, 2, 3]. Failure occurs as ductile fracture with previous plastic flow localization, either as shear banding or as internal necking [4]. This deformation process before fracture is strongly influenced by the stress state. Therefore the onset of localization and fracture should be investigated under different loading situations, either for forming processes but also for crash safety [5, 6]. Under crash loading the influence of strain rate should additionally be taken into account [7]. In forming processes the onset of instable deformation behaviour, designated as instability, leads to fracture and is usually described as forming limit in terms of major and minor strains. The commonly used method for the determination of forming limits is the section method proposed in DIN EN ISO 12004-2 [8], but also other methods based on the time history of the strain field and the strain rate field in the necking zone are frequently used [9, 10]. The experiments for the determination of forming limits are often Nakajima tests and cover stress states between uniaxial to equi-biaxial tension. For the specimens usually used for the crash characterization no established method for the determination of the beginning of instability from experimental data is known, but several theoretical investigations exist [11,12,13]. Especially under shear loading information about the beginning of instability are rare, because under pure shear loading no local necking occurs. Anyway shear failure occurs after previously established localized shear zones for the most advanced high strength steels including dual phase steels [4, 14, 15].
In this work the beginning of instability and failure is investigated solely by analyzing experimental results. Therefore quasistatic and high speed experiments have been performed for a dual phase steel DP1000 under four loading situations, shear loading, uniaxial tension loading, plane strain loading and equi-biaxial tension loading. The evaluation of failure strains from DIC of high speed videos has been performed in a generalized way for all specimen geometries and described in detail in a previous work in [16]. Now these tests are analyzed more deeply concerning the beginning of instability. A generalized approach to determine the strains at the beginning of instability has been developed and is discussed here in detail. For uniaxial tension loading, plane strain loading and equi-biaxial tension loading situations the beginning of instability has been determined as the onset of local necking by analyzing the development of the thinning rate in the highly deformed zone. The beginning of shear instability has been determined by analyzing the development of the major and minor strain rate. Therefore strains at the beginning of instability from shear loading up to equi-biaxial tension loading can be determined with one single evaluation procedure, which is applied to the investigated DP1000. Strain rate effects are analyzed to detect critical stress situations and to avoid too conservative component design.

2. Experimental program
The deformation and damage behavior of a dual phase DP1000 steel sheet with a thickness of 1.5 mm and with an ultimate strength of about 980 MPa and a fracture strain A20mm of about 20% is investigated. The characterization for quasistatic and dynamic shear loading, uniaxial tensile loading, plane strain loading and equi-biaxial loading is presented in detail in [16]. All tests were carried out at room temperature and the tensile direction was perpendicular to the rolling direction. The specimen geometries for the different tensile tests for shear loading, uniaxial tension loading and plane strain loading are given in Figure 1. The notched shear tensile specimen shown in Figure 1 is an optimized shear specimen for the investigated DP1000, because the shear specimen used in [16] didn’t lead to shear failure under quasistatic loading. Therefore additional experiments with the notched shear tensile specimen shown in Figure 1 were carried out in this work. The equibiaxial Nakajima specimen and the Nakajima test setup are shown in Figure 2.

![Figure 1](image1.png)
![Figure 2](image2.png)

*Figure 1.* Specimen geometries for quasistatic and dynamic shear tension, smooth tension and notched tension tests

*Figure 2.* Nakajima test setup and equi-biaxial Nakajima specimen

All specimen geometries are tested under quasistatic loading. Additionally the different tensile specimens are tested with a test speed of 2.5 m/s leading to a nominal strain rate of 100/s for smooth tension tests and the Nakajima specimens are tested with a test speed of 5 m/s. High speed videos are performed and the strain and strain rate distributions in the localized zone on the surface of the
specimens have been analyzed by DIC evaluation with the software ARAMIS [17]. The DIC evaluations of the equivalent v. Mises strainfield in the last image before fracture are shown in Figure 3 for one quasistatic test for each specimen geometry. For the dynamic tests the corresponding images are shown in Figure 4. The stage point at the location of failure with the largest strain value before failure analyzed in [16] is marked in each image. It is well known, that the evaluated strains in the highly deformed zone depend strongly on the used strain gauge length $L_0$ [4,18,19]. In Figure 3 and Figure 4 the optimized optical $L_0$ - values are also given for each specimen.

![Figure 3](image)

**Figure 3.** Equivalent v. Mises strain evaluated by DIC in the last image before fracture for a quasistatic shear tension, smooth tension, notched tension and equi-biaxial Nakajima test

![Figure 4](image)

**Figure 4.** Equivalent v. Mises strain evaluated by DIC in the last image before fracture for a dynamic shear tension, smooth tension, notched tension and equi-biaxial Nakajima test

### 3. Analysis of the onset of instability

#### 3.1 Uniaxial tension loading, plane strain loading and equi-biaxial tension loading

Under tensile dominated loading local instability mostly occurs as internal necking and void coalescence [4, 20]. The macroscopic result for this physical mechanism is strain localization with local thinning in the necking zone. Experiences from forming technology in the determination of forming limits show that the local thinning rate in the highly deformed zone is a very sensitive parameter to detect the onset of local instability under tension dominated loading. [9, 10]. Therefore, the development of the local thinning rate in the highly deformed zone was analyzed for the smooth tension, the notched tension and the equi-biaxial Nakajima tests. Worth noting that local thinning evaluated by DIC is based on volume consistancy within the gauge length and gives a good approximation for metals.

For the quasistatic smooth tension test the local thinning rate in the necking zone is evaluated up to fracture for three different stage points shown in Figure 5 in the thinning rate field and in the equivalent v. Mises strain field in the last image before fracture. Stage point 0 with the largest equivalent v. Mises strain before failure and also marked in Figure 3, stage point 1 with the maximal value of the thinning rate in the necking zone before failure and stage point 2 with a lower value of the thinning rate in the necking zone. For these three stage points the development of the local thinning
rate is investigated and it’s moving average values over 7 points are plotted against time together with the engineering stress in Figure 6. All three stage points show about the same curve. Therefore all further evaluations are performed for the stage points with maximum equivalent v. Mises strain before fracture and marked in Figure 3 and in Figure 4. In Figure 6 the moving average values of the local thinning rate increase after ultimate strength. With the red box a time period for the onset of thinning in the necking zone is shown. At the left border of the box the thinning rate begins to increase and at the right border of the box the thinning rate curve shows a kink and the slope of the curve changes significantly.

Figure 5. Thinning rate and equivalent v. Mises strain in the last image before fracture for a quasistatic smooth tension test

Figure 6. Development of the local thinning rate for three different stage points in the necking zone for a quasistatic smooth tension test

For the dynamic smooth tension test the development of the local thinning rate in the necking zone, again as moving average value, and the global engineering stress are shown in Figure 7. The slight increase of the thinning rate after ultimate strength is less pronounced than for the quasistatic test in Figure 6 and the following kink in the thinning rate time curve is more pronounced than it is for the quasistatic test. The beginning of instability is determined for the marked time with the pronounced kink in the local thinning rate time curve in Figure 7. For the quasistatic smooth tension test the beginning of instability is also determined for the time with the kink in the local thinning rate time curve to get comparable results for quasistatic and dynamic loading. In Figure 6 this is the time at the right border of the red box. The notched tension tests show comparable thinning rate time curves and comparable thinning rate values than the smooth tension tests. Therefore the evaluation of the onset of instability is performed in the same way.

For the quasistatic equibiaxial Nakajima test the development of the local thinning rate in the necking zone is shown together with the global force in Figure 8. The local thinning rate in Figure 8 shows a round curve with a kink very near to fracture. The onset of instability is determined for the time with the kink. The forming limit values as major and minor strain determined by the section method [8] for this test are $\phi_1 = 0.25$ and $\phi_2 = 0.26$ and confirm the evaluated values based on the thinning rate. Without a kink the onset of instability would be difficult to determine. In such cases other time dependent evaluation methods like the linefit method [9] should be applied.
3.2 Shear tension loading

Under pure shear loading no necking occurs, therefore the thinning rate is no appropriate parameter to evaluate the beginning of shear instability. Under shear loading plastic flow localization occurs as shear banding [4, 15]. Parameters to quantify shear deformation are the shear angle or the shear strain. They depend on the coordinate system used for evaluation, therefore the maximal shear angle or the maximal shear strain should be investigated. As the more sensitive parameter the development of the maximal shear angle rate was analyzed. For a quasistatic shear tension test the moving average value of the local maximal shear angle rate is plotted against time together with the global force in Figure 9. After the elastic line with strongly increasing maximal shear angle rate the maximal shear angle rate decreases continuously up to a point near maximum of force and failure. From that point up the maximal shear angle rate increases again strongly up to failure and that point is determined as the onset of shear instability. As the maximal shear angle $\theta_{\text{max}}$ can be calculated by the major strain $\varepsilon_1$ and the minor strain $\varepsilon_2$ using Mohr’s Circle for strain analysis in formula (1) [21], the main parameters influencing the maximal shear angle rate are major strain $\varepsilon_1$, minor strain $\varepsilon_2$, major strain rate $\dot{\varepsilon}_1$ and minor strain rate $\dot{\varepsilon}_2$.

$$\theta_{\text{max}} = \frac{(\varepsilon_1 - \varepsilon_2)}{(\varepsilon_1 + \varepsilon_2 + 0.5)}$$  \hspace{1cm} (1)

The sensitive parameters for the detection of the onset of shear instability are the major strain rate and the minor strain rate, because major strain and minor strain are increasing more or less
continuously. In Figure 10 the development of the moving average value for the local major strain rate in the shear zone is demonstrated. The major strain rate curve also shows a significant kink near to maximum of force and near to fracture for the same time as the maximum shear angle rate does. Also the development of the minor strain rate shows this kink for the same time.

To show the development of the shear band evolution for the investigated quasistatic shear test a section perpendicular to the shear band is drawn. In Figure 11 the major strain rate is plotted against the position on the section for several stages before failure. The evaluated stage for the onset of shear instability is marked in red. Major strain rate increases significantly from this stage on while for the stages before nearly a constant major strain rate is evaluated over the whole section. The requirement for using major or minor strain rate to detect the onset of shear instability is no overlayed tension loading and therefore no thinning. This can be investigated by analyzing the local thinning rate in the shear zone, which should be nearly constant zero up to failure. For this investigated shear test this requirement is fulfilled. The dynamic shear tension test with a test speed of 2.5 m/s shows no kink neither in the maximal shear angle rate nor in the major or minor strain rate. This is a hint for fracture without previous local instability. Under dynamic shear loading, very thin localized shear bands occur with adiabatic heating and shear failure strains are much lower under dynamic loading compared with quasistatic loading [16]. Probably those reduced shear failure strains under dynamic loading are responsible for fracture without previous local instability.

3.3 Influence of the strain rate on the onset of instable deformation behavior

The evaluated onsets of instability for the different quasistatic and dynamic tests are shown as major and minor strains together with the strain paths in Figure 12. For the smooth tension and the notched tension tests instability under dynamic loading begins at lower strains than under quasistatic loading. For equi-biaxial tension loading instability under dynamic loading begins at higher strains than under quasistatic loading. The largest strain rate effect occurs under shear loading. Under dynamic shear loading fracture occurs without previous instability and at significant smaller strains than under quasistatic loading. The largest difference in strain between the onset of instability and failure occurs for the dynamic smooth tension test.

![Figure 11](image1.png)  
**Figure 11.** Major strain rate for a section perpendicular to the shear band for the last stages before failure for a quasistatic shear tension test

![Figure 12](image2.png)  
**Figure 12.** Strain paths up to fracture and evaluated major and minor strain at the beginning of instability in the highly deformed zone for quasistatic and dynamic tests for each specimen geometry
4. Conclusions
An experimental program was carried out for a dual phase steel DP1000 with quasistatic and dynamic tests under four different loading situations, shear loading, uniaxial tension loading, plane strain loading and equi-biaxial tension loading. Fracture strains were determined at the location of fracture with DIC evaluations from high speed video recording in a previous work [16]. Here the onset of instable deformation behavior was investigated with DIC evaluations for all loading situations. It is found that the local thinning rate in the highly deformed zone is an adequate parameter to determine the beginning of instability for uniaxial tension loading, plane strain loading and equi-biaxial tension loading. For equi-biaxial tension loading, the evaluated strains at the beginning of instability were confirmed by forming limit values determined by the section method in DIN EN ISO 12004-2 [8]. For shear loading the major and minor strain rate in the shear zone is found to be suitable to determine the beginning of shear instability. For the quasistatic shear test instability begins shortly before maximum of force and fracture. The dynamic shear test leads to fracture without previous instability and at significant lower strain values than under quasistatic loading. Under uniaxial and plane strain loading instability begins at lower strains under dynamic loading than under quasistatic loading, while under equi-biaxial tensile loading it begins at higher strains than under quasistatic loading. The largest difference between strains at the beginning of instability and fracture strains occurs for dynamic uniaxial tensile loading. For this stress state the investigated DP1000 shows the largest ductility and best crash performance.

The presented evaluations for the determinations of the onset of instable deformation behavior are suitable for the DP1000 steel under the different investigated quasistatic and dynamic loading situations. Statistical verification and user independency can be improved in the future. Further advanced high strength steels are under investigation.

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