Bending dual-phase steel
A finite element analysis

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Bending of dual-phase (DP) steels has introduced new issues concerning the analysis by finite element (FE) modelling. During the investigation of the microstructure of a DP1000 steel, it is found that there is crack formation at lower bending angles and elongations than would be expected based on the forming limit curves (FLCs).

The results of an FE analysis with a continuum material model without taking into account damage formation and subsequent softening do not show behaviour similar to what is seen in actual microstructures. The prediction of the FE analysis will therefore not be a good representation of the bendability of the DP steel. An addition to the continuum analysis is made by implementing a damage and softening model. Localization effects due to the softening of the material arise in places similar to the real material. However, mesh sensitivity is still present for different mesh sizes, despite the addition of a delocalization parameter, and alter the results of the simulations.

To improve the analysis of DP steels, a new representation of the microstructure is implemented in the finite element model. A zone with a Voronoi diagram is used as a representative volume element (RVE) for the DP steel. The diagram is embedded in the continuum sheet analysed in the simulation and represents both the ferrite and the martensite phases. The interaction of the ferrite and martensite phase in the embedded Voronoi diagram determines the strain patterns that develop during the bending simulation.

An investigation of different Voronoi diagrams on the former force versus former displacement is made. It is not necessary to introduce damage and softening to create the strain patterns which are seen in the real material. However, material degradation is still required to obtain the softening behaviour at high former displacement.
1. Introduction

Bending and hemming of steel is an important step in the production of consumer products. During this production procedure the material may be deformed several times before the final form is achieved. Plastic deformation by bending and hemming is the main way to obtain the final form. These processes will induce plastic and elastic strains in the material, which can weaken and even break the product. The prediction of this behaviour by finite element (FE) modelling plays a role in the efficient development and implementation of new materials.

Due to demand of stronger materials in the automobile industry, driven by the continuing desire to decrease a car’s weight, the forming process has become more complicated. The modern materials that are used are more complex because they are composed of two or more phases, the so-called dual-phase (DP) or complex-phase (CP) steels. The interaction between phases during deformation is an important factor for the behaviour of the material. Compared to the predecessors, low carbon and high-strength low-alloy (HSLA) steels, the modern DP and CP steels show limited bendability. This introduces new complications, for example during bending over an insert to 180°. This often introduces a crack on the outer surface of the steel sheet, where it was not expected based on forming limit curves (FLCs).

The limited bendability encourages the steel industry to develop new high strength steels with increased bendability. An effective implementation of these new materials in industrial and consumer applications requires good understanding of the possibilities of the material. FE modelling may help in the understanding of the mechanisms which play a role in the bending of a steel sheet. Recent results indicate that FE modelling of these materials introduces new challenges: the modelling of damage and fracture in metallic alloys.
2. Theory

In this section a literature review will be presented on the main characteristics of dual-phase (DP) steels as well as the current status of the Finite Element (FE) analysis of DP steels.

2.1 DP steels

2.1.1 Historical development

In car manufacturing the demands concerning safety and fuel economy are getting higher due to government regulations. These developments ask for more advanced materials which can lower the weight of the car and thereby improve the efficiency, while maintaining or even increase the crashworthiness. As a result of that, the type of steel which was used shifted from the low carbon (LC) steels with good formability to the high strength low alloy (HSLA) steels. Because HSLA steels have a lower ductility, it caused many problems in metal forming. This delayed the usage of high strength steels (HSS) in the automotive industry and the search for ductile high strength steels continued. An overview of the different types of steel can be seen in Figure 1.

![Figure 1 – Strength vs. strain at fracture for various steels.](image)

DP steels belong to the first generation of the so-called advanced high strength steels (AHSS). The first report on the properties of DP steels dates back to the mid '70s by Rashid (1976). DP steels consists of two phases, namely a softer matrix and particles of a harder

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1 Horvath, (2010)
phase. The characteristic properties of the material depend on the fractions of the two phases and the morphology of the grains. In Figure 2 a typical microstructure of DP steel can be seen, where the matrix is shown in dark grey and the hard phase is represented by the light grey islands. The softer phase, in this case ferrite, gives the material its ductility. While the harder phase, martensite, improves the strength of the material. DP steels usually contain 10-70% volume fraction of martensite, where the increased martensite fraction leads to a higher tensile strength (Speich & Miller, 1979; Shaw & Zuidema, 2001). Based on simulations, the optimum between formability and strength is reached with a martensite fraction in the range of 20-30% (Uthaisangsuk, Prahl & Bleck, 2011).

![Microstructure of DP600 steel - Scanning Electron Microscope.](image)

### 2.1.2 Production

DP steels are manufactured by annealing of ferritic-pearlitic low carbon steels at intercritical temperatures, which lie between 723°C and 900°C. Equilibrium exists between the ferrite and austenite phase at these temperatures. After the heat treatment the material is rapidly cooled, this causes the austenite to transform into martensite. The fraction of both phases is controlled by the temperature of the heat treatment and the cooling rate to room temperature (Liedl, Traint & Werner, 2002). After the formation of martensite, an extra heat treatment can be executed to temper the martensite fraction.

As already mentioned before, the martensite fraction is an important parameter for the properties of the DP steel. However, the characteristics of DP steels depend on many other parameters, like the morphology of the grains of both the martensite and the ferrite phases.

### 2.1.3 Geometrically necessary dislocations

During the production of DP steels, transformation from austenite to martensite introduces stresses in the material. This is because the austenite fraction undergoes a volume expansion of approximately 3% due to the transformation from a face-centred cubic (FCC) to a body-centred cubic (BCC) structure, or with increasing carbon content in the martensite to a body-centred tetragonal (BCT) (Liedl et al., 2002; Tsipouridis, Koll, Krempaszky & Werner 2011; Sodjit & Uthaisangsuk, 2012; Paul, 2013). The ferrite matrix will therefore be compressed and as a consequence deform plastically which causes geometrically necessary dislocations (GNDs) to appear. The amount of hardening in the ferrite matrix is determined by the martensite fraction in the DP steel (Liedl et al., 2002).

Due to the GND phenomenon local hardening will occur in the ferrite matrix during the transformation of austenite to martensite. This will happen specifically near the grain boundaries between martensite and ferrite, so the dislocation density near phase boundaries is higher compared to the dislocation density near grain boundaries. Nanohardness testing showed that within 3 µm of the ferrite-martensite phase boundaries the hardness values in the ferrite are 30% higher than in the ferrite matrix and 10% higher compared to the ferrite-ferrite grain boundaries (Tsipouridis et al., 2011).

![Figure 3 - Engineering stress-strain curves of selected HSLA and DP steels.](image)

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2 General Motors Corporation, 2008 (Horvath, 2010)
2.1.4 Work hardening

The local hardening behaviour also has an effect on the work hardening rate seen in the material. The ferrite matrix acts as a work-hardened skeleton, due to the GND phenomenon (Tsipouridis et al., 2011). This alters the initial flow behaviour of the material, since yielding is more gradual as a result of the pre-strain in the ferrite matrix which causes the matrix to be more similar to the harder phase (Caballero, García-Junceda, Capdevila & García de Andrés, 2006; Paul, 2013). Because of the GNDs, the DP steels show higher initial work hardening rates with increasing martensite fraction compared to conventional HSS (Liedl et al., 2002; Sodji & Uthaisangsuk, 2012). The work hardening effect can be attributed to two contributions, namely work hardening caused by the mobile dislocations and work hardening by the GNDs (Tsipouridis et al., 2011).

In Figure 3 typical stress-strain curves of a uniaxial tensile test can be seen for conventional HSLA steel and several DP steels. The DP steels combine high tensile strengths with similar yield strength compared to HSLA steel, which is advantageous in formability processes. Also the high work hardening rates as well as the ability to absorb high amounts of energy makes DP steel a good candidate to be used in car bodies.

2.1.5 Processing difficulties

Stamping has been the most common process in car manufacturing for decades (Horvath, 2010). Stamping covers several sheet-metal forming processes like: bending, drawing and piercing. Although the elongation compared to other steels seems reasonable in Figure 1, there are some difficulties in the forming process of DP steels. The local formability of DP steels will cause the material to show cracks in areas where, based on the global formability using forming limit curves (FLCs) for the DP steel in question, cracking was not predicted (Horvath, 2010).

Four distinct damage mechanisms are seen in DP600 steel during tensile testing, namely: cracking of martensite, decohesion at ferrite-martensite phase boundaries, separation of martensite islands, and void nucleation on inclusions (Avramovic-Cingara et al., 2009). In another study, on transformation induced plasticity (TRIP) steels, two mechanisms were seen, dimple or ductile fracture and cleavage fracture. Cleavage fracture is the dominant mode in the harder martensite phase, as a result of the low ability to flow, which causes low ductility in the phase (Papaefthymiou, Prahl, Bleck, Van der Zwaag & Sietsma, 2006). The ductile failure was caused by a mechanism similar to the damage mechanisms in DP600, which are void initiation and growth in the ferrite phase (Prahl et al., 2007). According to numerical investigation of Kuroda and Tvergaard (2007) stable bending of sheets is hampered by the formation of shear bands, which is supported by the experimental work of Lievers, Pilkey and Lloyd (2003).

2.1.6 Localization effects

Second phase particles in a material are good nucleation sites for strain localization to occur (Lievers et al., 2003; Poruks, Yakubtsov & Boyd, 2006). Critical sites are identified in areas in the vicinity of hard second phase particles (Uthaisangsuk, Prahl & Bleck, 2009a). Voids nucleate at a low strain of ~0.2 at inclusions of second phase particles, compared to a strain of ~0.9 at phase boundaries (Poruks et al., 2006). These sites are therefore susceptible to crack initiation which leads to ductile failure (Papaefthymiou et al., 2006). Nevertheless, the volume fraction of inclusions is much lower than the volume fraction of martensite, and as a
consequence fracture is mainly caused by voids at martensite boundaries (Poruks et al., 2006). At the same time, hard particles, which are located beyond two times the grain size below the surface, show less influence on localization (Dao & Li, 2001). According to Uthaisangsuk et al. (2011), void growth is preferentially initiated in areas of high hardness gradient and the void growth will proceed along grain boundaries. This makes the boundaries between the hard martensitic islands and the soft ferritic matrix susceptible to the formation of microvoids (Prahl et al., 2007; Soyarslan, Malekipour Gharbi & Tekkaya, 2012).

### 2.1.7 Strain distribution

The difference in strength between phases will cause irregular strain behaviour in materials come to light when the material is deformed. With low fractions of martensite the ferrite matrix will accommodate the strain, while the strain in the martensite can hardly be measured (Shen, Lei & Liu, 1986; Al-Abbasi & Nemes, 2007). Kang, Ososkov, Embury and Wilkinson (2007) measured the local strain in the martensite and ferrite phase in a DP600 steel using digital image correlation (DIC) and found that the ferrite phase accumulates more strain compared to the martensite phase. At increasing martensite fraction, the ferrite has to accommodate more strain (Tsipouridis et al, 2011). This irregular strain distribution leads to shear localization and microvoid formation at the boundaries between the martensite and ferrite grains (Poruks et al, 2006; Hayashi, Miyata, Katsuki, Kojima & Nomura, 2009). Ultimate shear localization can form shear bands as shown in Figure 4. The shear localization and microvoid formation is seen earlier in multiphase material compared to a homogeneous material of one of the constituents (Batra & Love, 2004). According to Korzekwa, Lawson, Matlock and Krauss (1980), the void formation is analogous to fibre pullout, since the interface is not strong enough to load the martensite to its ultimate strength. The interfaces between phases are not strong enough to load the martensite to its ultimate tensile strength (UTS). Nevertheless, shear localization is not only seen in dual-phase material, but it is also a natural outcome of polycrystalline microstructures in single phase material (Dao & Li, 2001).

A parameter which delays the formation of shear bands is the work hardening rate. A higher work hardening rate will cause less strain localization during forming processes (Dao & Li, 2001). The work hardening rate in the ferrite phase near the phase boundaries is increased by the number of GNDs due to the phase transformation (Tsipouridis et al., 2011). A uniform distribution of the martensite particles will lead to an even distribution of the GNDs. Consequently void formation will be slower and more uniformly distributed which delays void coalescence, so a higher void density can be obtained at fracture. As a result finely dispersed martensite has a better combination of strength and ductility (Avramovic-Cingara et al., 2009). Still, the strengthening effect of second phase particles in general competes with the effect of inhomogeneity and at high strains the inequality between phases will dominate over the effect of strengthening.

In the automobile industry, surface finish is an important criterion for the outer panels of a car. Becker (1992; 1998) found that the inhomogeneous deformation in shear bands near the free surface are responsible for the surface to roughen, which was confirmed by Dao and Li (2001) who found surface roughening due to different crystal orientation of neighbouring grains. However, a random texture shows less strain localization compared to a texture with a preferential direction of the grains, for instance a rolling grain structure. The roughness of the surface is linearly dependent on the grain size and the applied strain (Becker, 1998). The surface roughness will introduce new points for strain localization and shear band formation.
According to several studies (Triantafyllidis, Needleman & Tvergaard, 1982; Tvergaard, 1987; Dao & Li, 2001) shear bands are likely to show up in the deeper parts of the waviness at the free surface.

Figure 4 – Shear band formation in DP600 steel - Scanning Electron Microscope.

The interactions between the two phases in DP steel seem to play a very important role in the formability. A good understanding and representation of the microstructure is necessary to predict the possibilities of DP steels. In the next section an overview will be given on research in FE modelling.

2.2 Modelling of DP steels

2.2.1 Development tool

In the course of the developmental stage of a product FE software is an important tool in order to realize and give dimensions to the final concept. Possibilities of a mechanism and the performance of the design can be explored without the requirement of a working prototype. The FE analysis will give the opportunity to make adjustments to the design and test these, without having to manufacture new parts. However, the data which is obtained by computer simulations needs to be handled with care. This is due to the fact that the analysed model is a representation of the reality; therefore the model can behave differently compared to the real world. The consequences of misinterpreting the simulated data can be very unfortunate. Therefore the aim of researchers and engineers is to represent the actual microstructural mechanics of materials in order to get the best prediction of the behaviour of a design.
With the introduction of the AHSS new guidelines and techniques for manufacturing have been developed due to the difference in behaviour compared to the conventional HSS. The issues with forming of these steels are well known from practise, but not all the mechanisms are yet fully predictable (Horvath, 2010). The complex deformation mechanism makes the predictability of failure of DP and multiphase (MP) steels difficult, which impedes the implementation of these steels on a larger scale.

### 2.2.2 Simulation

Many investigations on material behaviour during deformation processes using numerical or FE analyses have been done in the past, either in 2D or 3D, in order to get a prediction of the response of the material. The simulation in 2D is faster than a simulation in 3D, because there are fewer elements used in the 2D simulation. However, the model is a representation of the real material and therefore a 2D model includes more presumptions, since a real world system will usually comprehend a third direction. The response in the third direction is determined in a 2D representation based on assumptions. This can be plane strain (no strain in the third direction) or plane stress (no stress in the third direction). In the bending process, plane strain may be assumed when the thickness of the plate is eight times smaller compared to the width of the sample (ASM Handbook, 2000). In a 2D model phases in the microstructure are assumed to be infinitely large in the third direction. This will cause each phase to act as an elongated grain. The martensitic islands will therefore act as long cylinders, instead of spherical particles. In 2D plane strain this leads to a lower predicted flow stress and therefore a lower stress-strain curve. The 3D simulation shows a better resemblance to the experimental findings (Uthaisangsuk et al., 2011).

The representation on a macro scale shows good results for the behaviour of materials, since the homogeneous properties can be captured well. However, on a local scale complex interactions between the phases govern the formability, which makes it more difficult to predict the response. Based on the experiments by Dao and Li (2001), Lievers et al. (2003) and Prahl et al. (2007), intense strain localization in bending is responsible for void formation in regions with high strength difference. The strain localization can be seen at second phase particles like inclusions. The localized strain and voids play an important role in failure of multiphase materials, because ductile failure is preceded by strain localization (Prahl et al., 2007; Avramovic-Cingara et al., 2009, D’hers & Dvorkin, 2011). Several models have been used in the past to predict the mechanics on a micro scale.

### 2.2.3 Shear bands

Triantafyllidis et al. (1982) used the J
\(_2\) corner theory to investigate the influence of surface imperfections on the formation of shear bands. An investigation of a pure bending process was done using FE modelling with small undulations at the free surfaces. A homogeneous material was chosen and represented by three models, namely: two elastic-plastic models and a nonlinear elastic solid. Shear bands start to appear first at the compressed free surface and will grow to the neutral axis against an opposing deformation gradient (Becker, 1992). This results in small strains at the neutral line and as a consequence, shear bands will not develop and will not cause damage near the neutral line (Hambli, Mkaddem & Potiron, 2004; Kuroda & Tvergaard, 2004). After shear band initiation on the tensile surface, little growth of the shear bands at the compressed surface is seen. Because the shear bands start to form at the deeper parts of the surface undulations, it is demonstrated that the
imperfections at the surface are responsible for the formation of shear bands (Triantafyllidis et al., 1982; Tvergaard, 1987).

### 2.2.4 Polycrystalline modelling

Becker (1992) used a Taylor-like slip-based polycrystalline model to capture different orientations between the grains in FE modelling. This means the grains are subjected to equal strain during a step and twelve slip planes are considered within the grains. The model consists of quadrilateral elements and each element is governed by a different crystal orientation. Due to the inhomogeneity between the elements, shear bands arise in pure bending deformation in a material without initial surface imperfections. The Taylor-like polycrystalline model is also used by Kuroda and Tvergaard (2007) to investigate the influence of texture on the formation of shear bands in a bent specimen. It was found that during tensile testing the textures with higher tensile stresses lead to shear band formation at a lower strain, while textures with lower tensile stresses showed no shear band formation. A more random texture also leads to less shear band formation (Dao & Li, 2001).

A similar experiment with the use of a crystal-plasticity-based model resulted in the same observations. Shear bands start to form near the free surface at the deeper parts of the undulations formed by the bending process. This phenomenon is seen at the convex and the concave surface at approximately the same bending deformation (Dao & Li, 2001).

### 2.2.5 Gurson-Tvergaard-Needleman

Further investigation on the shear band formation at the free surface was done by Tvergaard (1987), who implemented the Gurson-Tvergaard-Needleman (GTN) model in a pure bending problem. The GTN model takes into account formation, growth and coalescence of voids, which are important phenomena in ductile fracture of metals (Uthaisangsuk, Prahl & Bleck 2008; Sun, Choi, Liu & Khaleel, 2009). The model considers an initial volume fraction of voids, which will grow under the influence of hydrostatic stress. Additional voids will emerge based on the equivalent plastic strain. After significant deformation, voids will coalesce and the material will lose load-carrying capacity until failure occurs.

### 2.2.6 Oyane

Another void-growth-based model is the damage model by Oyane (1972) which takes into account the appearance of microscopic holes and growth under the influence of plastic strain. This ultimately leads to separation of the material due to the coalescence of voids which appear near each other in shear bands. The criterion which is used to determine the strain at fracture is as follows:

\[
\int_0^{\varepsilon_{eq, f}} \left(1 + \frac{1}{a_0} \frac{\sigma_m}{\sigma_{eq}}\right) d\varepsilon_{eq} = b_0, \tag{1}
\]

where:
- \(\varepsilon_{eq, f}\) equivalent fracture strain,
- \(a_0\) constant,
- \(\sigma_m\) hydrostatic stress (MPa),
- \(\sigma_{eq}\) equivalent Von Mises stress (MPa),
- \(b_0\) constant.
The constants are found experimentally using two stress states with constant triaxiality factor \((\sigma_m/\sigma_{eq})\) during the experiment until fracture occurs. The maximum strain at fracture is assumed to be reached when the integral corresponds with the constant \(b_0\). Although the model shows good agreement for many materials, under certain circumstances the predicted fracture strain will not correspond to the experimental value. This can be ascribed to the assumption that fracture occurs if the volumetric strain reaches a certain value. In order to accommodate the increase in dislocation density and the corresponding decrease in strength during plastic deformation, an extra parameter is added (Oyane, 1972).

\[
\int_{c_0}^{c_0} \left(1 + \frac{\sigma_m}{a_0 \sigma_{eq}}\right) c_0 d\varepsilon_{eq} = b_0, \tag{2}
\]

where:

- \(c_0\) constant.

The formula reduces to the first Oyane criterion when \(c_0\) is chosen to be zero, which rules out the influence of the plastic strain factor as it is reduced to 1. With \(c_0\) larger than zero, the influence of the plastic strain will become more important at larger strains compared to smaller strains. This represents the influence of local necking and crack propagation in the material (Oyane, 1972). Also increased void formation which is due to the higher dislocation density at larger strain will cause faster material degradation (Goijaerts, 1999).

### 2.2.7 Mesh dependency

The shear band formation in FE modelling shows a shortcoming of FE analyses, namely the mesh dependency of localization effects. Several studies (Triantafyllidis et al., 1982; Tvergaard, 1987; Tvergaard & Needleman, 1997; Reusch, Svendsen & Klingbeil, 2003; Sun et al., 2009; Bettaieb, Lemoine, Duchêne & Habraken, 2010; D’hers & Dvorkin, 2011; Uthaisangsuk et al., 2011) report on the mesh sensitivity of localization phenomena, since the shear bands are as narrow as can be accommodated by the size of the elements (Nielsen & Tvergaard, 2009). As a result, critical damage is reached faster in a finer mesh compared to a coarser mesh.

Modelling of localization effects therefore require different length scales to model deformation on a macroscopic level and deformation on a microscopic level (D’hers & Dvorkin, 2011). Nonlocal damage parameters have been applied in order to overcome the mesh sensitivity of FE analyses and decouple the local scale from the global scale. Various models are introduced to overcome the mesh dependency by adding a local length scale \(L\) to the model to control the width of the localization bands and thereby the macro-scale failure mechanism (Reusch et al., 2003; Wisselink & Huëtink, 2008).

### 2.2.8 Representative volume elements

In order to simulate multiple phases in a material, often representative volume elements (RVE) are used to apply the properties of separate phases to various elements in FE modelling (Al-Abbasi & Nemes, 2003, 2007; Sun et al., 2009; Uthaisangsuk et al., 2009, 2011; Soyerslan et al., 2012; Paul 2013). Each phase is represented by a number of elements with the properties of the particular phase. In Figure 5 an example of a 2D RVE mesh is shown for a DP steel, where the green triangles represent martensite, the blue
triangles represent ferrite and the red triangles represent the properties of both phases combined as a continuum. The mesh describes a DP zone embedded in a mixed zone to prescribe the appropriate boundary conditions. Depending on the simulation, the elements can either be 2D or 3D and also different form factors can be used, like triangular or quadrilateral shaped and at the same time the elements can be linear or quadratic.

An RVE can be created using multiple techniques and according to Socrate and Boyce (2000), the behaviour of an RVE is dependent on the accuracy of capturing the actual microstructure of the material. A method to obtain an RVE mesh is DIC, where software can transform an image of a real microstructure into elements which can be used in FE analysis (Sun et al., 2009; Sodjit & Uthaisangsuk, 2012). In this manner, the RVE resembles the real microstructure of a material quite good for a DP steel, since the different phases can be distinguished from each other. However, in MP steel it can be more difficult to distinguish the several phases like bainite, ferrite, martensite, pearlite and retained austenite. The DIC procedure is mostly used for 2D microstructures, but it can also be used to capture 3D microstructures. In order to obtain a 3D microstructure, a layer of material is removed after imaging and a new image is taken. Multiple 2D RVE layers based on the taken images are combined to obtain the 3D RVE microstructure.

![RVE representation of a DP600 steel.](image)

Another method to acquire the microstructure of DP or MP steels is assuming the random distribution of grains of the several phases based on the volume fractions in the real material (Prahl et al., 2007; Uthaisangsuk et al., 2009, 2011; Uthaisangsuk et al., 2011a; Paul, 2013, 2013a). In this case the material will have an almost uniform distribution of the phases in the RVE due to the randomly distributed elements. The representation of the material using the random distribution might not capture the real microstructural mechanics, because segregation and clustering of particles are not implemented in RVE simulations. Though, this is frequently found in real materials, due to reheating and slow cooling. The clustering and segregation of particles play an important role in the failure behaviour of DP and MP steels on a local scale, since clustered particles cause high localization effects and damage nucleates in between closely spaced particles (Uthaisangsuk et al., 2009). Uthaisangsuk et al. (2011a) found earlier microcrack formation in materials with martensite segregated into bands, which causes the load-carrying capacity to go down up to 20%. Randomly distributed particles are found to be less prone to damage formation (Schmauder, Weber & Soppa, 2003).
Results obtained by RVE simulations based on either of the two methods show a qualitative similarity in behaviour (Paul, 2013a). The irregular strain distribution between the martensite and ferrite phase is captured by the FE analysis independent of the morphology of the elements used in the analysis. The ferrite phase will be constrained by the martensite and the ferrite matrix will accommodate most of the strain due to the lower yield stress (Paul, 2013). As a consequence of yielding of the ferrite matrix, the martensite fraction will keep on carrying higher stresses during deformation (Sun et al., 2009). Strain localization will occur at increased deformation and will lead to the formation of shear bands between the martensite grains. The onset of shear bands in uniaxial tensile loading of DP980 is found at a uniform strain level of 0.115 by Sun et al. (2009). At this uniform strain level in the RVE, the average strain in a shear band can already reach levels of 0.3 with even higher peak strains. During subsequent deformation, shear bands will grow and eventually connect to form a larger shear band. The localization sites which are formed can be initiation points for void nucleation and growth, which is in accordance with Uthaisangsuk et al. (2011a) who found crack initiation in the ferrite matrix at an artificial notch root in an RVE.

2.2.9 Material models

In FE modelling not only the grain distribution plays an important role, but also the material parameters which are used are of great significance for the behaviour of the system. The stress-strain curves can be obtained using tensile tests or hydraulic bulge tests and represent the macroscopic behaviour of the material. The work hardening behaviour of materials during plastic deformation can be described in FE software by several hardening laws. The parameters are chosen to get the best fit of the empirically obtained stress-strain curves. A few examples of hardening laws are as follows:

Linear hardening:

\[ \sigma = \sigma_y + K \varepsilon_p, \]  
(3)

Power-law hardening (Hollomon):

\[ \sigma = K \varepsilon_p^n, \]  
(4)

Power-law hardening with initial yield strength (Ludwik):

\[ \sigma = \sigma_y + K \varepsilon_p^n, \]  
(5)

Power-law hardening with initial plastic deformation (Swift or Nadai):

\[ \sigma = K (\varepsilon_p + \varepsilon_p^0)^n, \]  
(6)

Dislocation based hardening (Kocks-Mecking):

\[ \sigma = \sigma_y + \Delta \sigma + \alpha M \mu \bar{b} \sqrt{\frac{1 - \exp(-M k \varepsilon_p)}{k L}}, \]  
(7)

where:

- \( \sigma \) true stress (MPa),
- \( \sigma_y \) initial yield strength (MPa),
- \( K \) hardening constant (MPa),
- \( \varepsilon_p \) true plastic strain,
- \( n \) strain hardening exponent,
- \( \varepsilon_p^0 \) initial plastic strain,
- \( \Delta \sigma \) additional strengthening by precipitates (MPa),
- \( \alpha \) material constant,
The representation of DP steels in FE modelling by a single material, which contains the macroscopic behaviour based on the Ludwik hardening law like in Grujicic, Er turk & Owen (1986), or represented by an experimentally obtained flow curve (Soyarslan et al., 2012), is in good agreement with experimental data. However, in FE modelling of multiphase systems on a local scale, the macroscopic response of the material will not capture all the facets of the microscopic behaviour. Each phase has its own characteristics and needs to be represented by its appropriate properties in order to simulate the interactions between both the phases, as the interaction between the phases will determine the stress and strain behaviour of the RVE.

In several studies the Ludwik hardening function is used with different parameters for the separate phases (Sun et al., 2009; Uthaisangsuk et al., 2011, 2011a; Paul, 2013a), as is the hardening function according to Swift (Al-Abbasi & Nemes, 2003, 2007) and the dislocation hardening law (Uthaisangsuk et al., 2009a, 2011, 2011a; Sodjit & Uthaisangsuk, 2012; Paul, 2013). Uniaxial tensile tests are used most often to obtain or verify the parameters which are used for the hardening functions of each phase (Al-Abbasi & Nemes, 2003, 2007; Sun et al., 2009; Uthaisangsuk 2009a, 2011, 2011a). In this case, macroscopic behaviour is used to represent the material at a microscopic level. Sun et al. (2009) used an in-situ measurement of the strain by using a high energy X-ray diffraction (HEXRD) technique to obtain the flow data for the ferrite phase of a DP980 steel. Here, the actual microscopic behaviour is captured for the ferrite phase.

Experimental uniaxial tensile data of macroscopic behaviour of DP steels is used to compare to uniaxial tensile simulations using RVEs (Sun et al., 2009, Uthaisangsuk et al., 2011a; Sodjit & Uthaisangsuk, 2012). Also additional hydraulic bulge tests are used to obtain data for higher strains compared to tensile testing (Uthaisangsuk et al., 2009, 2009a, 2011). The macroscopic behaviour of the RVEs show roughly the same tendency compared to the experimentally obtained data.

2.3 Three-point bending

The bending process is a widely used operation in metal forming. There are several types of bending; in this work three-point bending will be used to evaluate the properties of DP steels. The three-point bend test setup consists of two supporting rolls and a former, as shown in Figure 6. The supporting rolls for the test are built up using ball bearings and as a consequence the sheet does not experience friction with the supporting rolls. The test piece is subject to plastic deformation by the displacement of the former up to a specified bend angle without unloading during the process (International Organization of Standardization [ISO], 2005).

Because in three-point bend testing only a former is used and there is no supporting die to form the sheet metal, the material is able to flow freely between the former and the supporting rolls. The former force will therefore be lower compared to die bending, but it will
cause more springback compared to die bending and there is also an increased chance of free surface cracks (Soyarslan et al., 2012).

Figure 6 - Three-point bend testing\(^3\).

The geometrical angle upon loading which is obtained by the bended sheet is linked to the former displacement using the following formulas:

\[
\sin \frac{\alpha}{2} = \frac{p \times c + W \times (f - c)}{p^2 + (f - c)^2},
\]

where:

\( \alpha \)  bend angle (degrees),  
\( p \)  roll radius + half the gap width (mm),  
\( f \)  displacement of the former,

with:

\[
W = \sqrt{p^2 + (f - c)^2 - c^2},
\]

\[
c = r + a + \frac{D}{2},
\]

where:

\( r \)  roll radius (mm),  
\( a \)  sheet thickness (mm),  
\( D \)  former diameter (mm).

\(^3\) NEN-EN-ISO 7438:2005
During the bending process, the former displacement and the force which is applied to the former are monitored to give information about the sheet which is processed; this is visualized in Figure 7. The curve which is obtained is a measure for the strength of the material and it can also give an indication of the ductility of the material. This is due to the fact that fracture of the material can occur in the form of cracks, which is caused by void formation and coalescence, and as a consequence there is a loss in load-carrying capacity. This loss in load-carrying capacity can be recognized by premature decrease in force on the former, with increasing bend angle. However, a loss in load-carrying capacity is also seen at large former displacements due to the geometry. The DP600 sample in Figure 7 shows this behaviour at a former displacement of 13 mm and beyond. The steel sheet loses its load carrying capacity as a result of the bending angle which increases beyond 140 degrees.
3. Finite element modelling

In this section the modelling using a finite element analysis will be explained.

3.1 DiekA

To investigate the bending process with an FE analysis, the software package DiekA is used. The program is in development since the beginning of the 1980s by the University of Twente. DiekA is designed to solve non-linear plasticity problems. Particular problems which can be investigated by DiekA are deep drawing, rolling, extrusion, bending and injection moulding, which all have in common intense nonlinearities (DiekA development group, 2008). DiekA is therefore chosen to solve the bending of a steel specimen, involving large angles and strains which will be achieved during three-point bending. The version which is used to run the simulations is the latest developer edition (14th June 2013).

The program is run using a DiekA input file, which is composed as a plain text file. This file contains the various parameters that describe the analysis. All possible commands can be found in the full DiekA manual (DiekA development group, 2008) which is provided with the program. DiekA will run in a command line window and is available for multiple platforms. Direct and iterative solvers can be used to calculate the bending process, depending on the stiffness matrix the best solver will be chosen.

Post processing is done using external post processing software or software provided with DiekA for displacement and contour plots. An example of results from postprocessor Dipp can be seen in Figure 8, where the strain distribution is shown of a DP600 steel sheet.

Figure 8 – Plastic strain distribution in a bend specimen.
3.2 Bending simulation

As shown in Figure 8, the finite element simulation of the three-point bend test contains a 2D symmetric setup with the symmetry axis in the direction of the former, representing the y axis. In this manner the calculation time for simulations is reduced, compared to simulations which contain the full experimental setup. Another advantageous effect is the possibility to increase the accuracy of the data obtained by the simulation by using smaller finite elements while maintaining a low calculation time compared to a simulation with the full setup.

3.2.1 Equipment setup

To simulate the three-point bend test by FE analysis, the test bench is modelled to represent the bending equipment which is used during the experiment. The tools are shown in black in Figure 8. The support rolls and the former will not deform during the analysis as they are modelled as undeformable bodies. This is due to the fact that the experimental equipment is made of tool steel, which has a high hardness and also a high stiffness due to the second moment of area. Therefore the tools will show a negligible deformation during the course of the bending experiment.

As can be seen in Figure 8, only a quarter of the curve of the supporting roll is modelled. This is because during the experiment it is the only part of the roll which comes into contact with the metal sheet, so it is not essential to model the entire roll. The elongated part to the left of the roll is modelled to support the sheet in its initial state. When the simulation is started the sheet will only come into contact with the curved surface of the roll. Contrary to the experimental setup, the roll will not rotate during the experiment. However, there is no friction defined between the surface of the roll and the sheet, and therefore the steel sheet is able to slide freely over the surface. This is done to imitate the bearings which will rotate during the experiment and will make the friction negligible, as they move with the steel sheet.

The roll is built up using 500 elements to model the curvature with a radius of 15 mm accurately, corresponding to the radius of the experimental setup. A gap between the symmetry axis and the roll is maintained which resembles the gap of the experimental setup and corresponds to 1.85 mm. The roll is represented by quadrangle plane strain elements to be used in the 2D environment which will be used during the simulation.

The former, unlike the experiment where the former is stationary during the test, will move downward in the y direction to create the bending conditions to deform the modelled sheet. Similar to the support roll, the former is constructed using quadrangle plane strain elements. 50 elements are used to create the corresponding curvature. The radius of the former is equal to the radius used during the experiment, which is 0.393 mm.

3.2.2 Metal sheet

The model of the metal sheet can be seen in Figure 9. The different colours represent the various regions of the mesh. The elements which are used are of the plane strain type and triangular in shape with quadratic sides, so a single element is built up out of six nodes. Because the width to thickness ratio for the plate used in the experiment is at around 20:1 and is therefore smaller than 8:1, plane strain elements can be used to model the experiment (ASM Handbook, 2000). Because of this, the simulation can be carried out in 2D and the strain in the third direction is assumed to be zero. However, to maintain zero strain in the
third direction, the stress in the third direction is dependent on the strain in the other two directions via the following formula:

\[
\sigma_3 = \frac{E \nu}{1 + \nu} \left( \epsilon_1 + \epsilon_2 \right),
\]

where:
\( \sigma_3 \) stress in the third direction (MPa),
\( E \) Young’s modulus (MPa),
\( \nu \) Poisson’s ratio,
\( \epsilon_{1,2} \) principle strains.

The size of the elements is varied in the different regions of the sheet; in total there are six regions defined. As a result the total number of elements can be decreased, since the elements can be coarse in areas with low strain compared to areas where severe deformation takes place. In this way the calculation time which is necessary can be as low as possible, while maintaining accuracy in areas with high strain.

\[\text{Figure 9 - Steel sheet mesh.}\]

The mesh size for the symmetric sheet ranges from 1 mm edges in the coarsest regions to 1 \( \mu \)m edges in the region where the largest deformation takes place. In Figure 9 the left upper side of the sheet, which is shown in orange, does not make contact with the tools and there is no significant deformation and therefore a mesh size of 1 mm is chosen to keep the number of elements low. The lower left side, which is shown in green, comes into contact with the support roll, so it is necessary to have a high mesh density. Otherwise the curve of the force versus displacement will have a stepped character, due to sudden changes of the position where the sheet is supported. Therefore a mesh size of 50 \( \mu \)m is chosen, which results in a smooth force versus displacement curve. The mesh density will decrease from the bottom side of the region to the upper part of the region to keep the number of elements low, without affecting the force versus displacement curve.

In Figure 10 a detailed view of the side along the axis of symmetry can be seen. The two left regions are already explained in the previous subsection. The two regions which are positioned in the middle, shown in light green and light orange, are transition regions to connect the side of the sheet which comes into contact with the roll and the regions where the most deformation takes place. These regions do not come into contact with the modelled equipment and are exclusive for connecting the other regions. The mesh size in both regions varies and corresponds to the neighbouring areas on the right and left side with a gradient in the middle. In this way the number of elements can be kept low, because the regions where
minimal deformation takes place can be separated from areas where large deformations takes place.

Figure 10 - Steel sheet mesh – Detail.

The yellow region in Figure 10 is similar to the green region on the bottom on the left side, this is because it is a contact surface between the sheet and the tools. Therefore, the same mesh density is used for the outer surface of this contact region, which results in a mesh size of 50 μm. The lower side of the yellow region is given the same mesh size as the adjacent region, as the bottom right area will provide data about the bending process.

The region where the most severe strain is experienced is shown in Figure 10 in turquoise and is positioned at the lower right corner. The mesh size can be altered between different simulations to enhance the accuracy of the deformed mesh and can be as small as 1 μm. As opposed to the other regions, the mesh size is kept homogeneous throughout the zone, because in this area the most important data is collected. Due to the high strain in this area, the damage is likely to form in this region. The dimensions of this region are chosen in such a way that the area where high strains are experienced is covered. The width of the region is approximately three times as wide as the former radius at 1 mm, and the height is chosen to be 1.1 mm to also cover the neutral line during bending. In this way, no import data will be lost due to low density of the mesh.
3.2.3 Material model

During the analysis the Von Mises yield criterion is used to determine the yield behaviour of the finite elements. Plastic deformation will take place when the calculated equivalent stress exceeds the yield stress which is calculated as follows:

\[
\sigma_{eq} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}},
\]

where:
- \(\sigma_{eq}\) equivalent Von Mises stress (MPa),
- \(\sigma_{1,2,3}\) principal stress (MPa).

As already mentioned in section 2.2.9, the hardening behaviour of a material can be represented by various models during FE analysis. The constitutive formula which is used during the analysis in DiekA is based on the Nadai hardening law, which is one of the power-law hardening models. This model is capable of representing the work hardening behaviour which is seen in DP steels (Grujicic et al., 1986). A characteristic graph of stress versus strain which makes use of the Nadai hardening law is shown in Figure 11. The corresponding formula which is used to calculate the stress at the corresponding strain is as follows:

\[
\sigma = \sigma_0 + K(\varepsilon_0 + \varepsilon_p)^n,
\]

where:
- \(\sigma\) true stress (MPa),
- \(\sigma_0\) yield strength offset (MPa),
- \(K\) hardening constant (MPa),
- \(\varepsilon_0\) plastic strain at yield point,
- \(\varepsilon_p\) true plastic strain,
- \(n\) strain hardening exponent.

Although the yield strength offset is implemented in the formula in DiekA, it is not used in this case, because the initial strain (\(\varepsilon_0\)) in combination with the hardening constant (\(K\)) and exponent (\(n\)) will control the transition between the elastic and plastic material behaviour.

The parameters which are used to determine the work hardening properties of the material are the hardening constant (\(K\)) and hardening exponent (\(n\)). Up until the initial yield point stress (\(\sigma_{y0}\)) the behaviour of the material is considered elastic. Therefore stress versus strain response of the material is dependent on the Young’s modulus (\(E\)) via Hooke’s law, which is simplified as follows:

\[
\sigma_t = E \varepsilon_t,
\]

where:
- \(\sigma_t\) true stress (MPa),
- \(E\) Young’s modulus (MPa),
- \(\varepsilon_t\) true strain.
In Figure 11 the following symbols are used:

\( E \)  
Young’s modulus (MPa),

\( \sigma_0 \)  
yield point stress (MPa),

\( \sigma_{y0} \)  
initial yield point stress (MPa),

\( \varepsilon_0 \)  
initial strain.

### 3.3 Determination of the material parameters

For the determination of the material parameters of DP1000 which are used to represent the material during the damage analysis, an analysis is run which does not take into consideration damage formation. This approach is chosen due to the fact that during the first stage of deformation hardening of the material is the dominating factor. This can be recognized in the force versus displacement curves as a continuing increase in force concurrent to an increase in displacement. Therefore the hardening parameters are determined before damage and softening will start to degrade the material. Therefore the material will be investigated up till a former displacement of 8 mm, which can be deduced from Figure 12, as it is well before a drop in the force occurs.
For the analysis of the hardening parameters the Young’s modulus of the material is chosen to be 210 GPa, which is a common value for steels. The Poisson’s ratio which is used during the analysis is 0.28, as this is a common value for cold-rolled steel sheet products. During the analysis, the material is assumed to be homogeneous. This reduces the number of parameters for investigation to only two variables, because only the two hardening parameters $K$ and $n$ have to be determined. This is different from the actual material, because DP steel consists of two or more phases, all with different properties for each phase. This way of representing a material is often referred to as the continuum approach.

The parameters for the hardening law which correspond to the material are determined using the least squares error. This error is calculated between the obtained force versus displacement curve during the experiment and the force versus displacement curves which are acquired during the simulation runs with the different parameters. To compare the acquired data, the curves are normalized so the former displacements of both curves match each other. This is done by interpolating between data points which are obtained experimentally and by simulation.

The mesh size which is used, for the area with a variable mesh size between different simulations (turquoise region in Figure 10), during the simulations for determination of the $K$ and $n$ parameter will be 5 μm. This value is chosen in order to be in agreement with the magnitude of the mesh size which will be used during the damage analysis. The total number of elements of the symmetric sheet will therefore be 126645. During the simulations, the increment of the former displacement will be 0.01 mm to ensure enough data points are collected to compare the experimental curve with the simulated characteristics.
The two parameters are not completely independent, but each of the parameters has its own main influence on the force versus displacement characteristic. The main influence of the $K$ parameter is shown in Figure 13. It can be seen that the slope of the curve does not significantly change under the influence of the varying $K$ value. The height of the curve however, is changed under the influence of the $K$ value beyond a former displacement of approximately 2 mm. The change of force at a former displacement of 8 mm is shown in Table 1. It can be seen that the difference in force scales linearly with the difference of the $K$ value which is used to run the simulation. Therefore, an estimate can be made for the appropriate $K$ value, which will be between 1085 MPa and 1105 MPa, because the force at 8 mm during the experiment is 133.7 N. The investigation of a range is necessary due to the fact that the $n$ value also has an effect on the force at a displacement of 8 mm.

As mentioned above, the $n$ value also has an influence on the force at former displacements beyond 1 mm. However, the main effect of the $n$ value is on the slope of the force versus displacement curve, as can be seen in Figure 14. The slope of the experimentally obtained force versus displacement curve at a former displacement of 8 mm is approximately 4.9 N/mm.

<table>
<thead>
<tr>
<th>$K$ (MPa)</th>
<th>$n$</th>
<th>Force at former displacement of 8mm (N)</th>
<th>Change in $K$ (MPa)</th>
<th>Change in force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1050</td>
<td>0.055</td>
<td>129.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1085</td>
<td>0.055</td>
<td>133.3</td>
<td>35</td>
<td>4.3</td>
</tr>
<tr>
<td>1120</td>
<td>0.055</td>
<td>137.6</td>
<td>70</td>
<td>8.6</td>
</tr>
</tbody>
</table>
Figure 14 - Force vs. displacement - Simulated and experimental data - Various \( n \) values.

Table 2 - Slope development at different \( n \) values.

<table>
<thead>
<tr>
<th>( K ) (MPa)</th>
<th>( n )</th>
<th>Slope at former displacement of 8 mm (N/mm)</th>
<th>Change in ( n )</th>
<th>Change in slope (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1085</td>
<td>0.010</td>
<td>3.88</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1085</td>
<td>0.055</td>
<td>4.82</td>
<td>0.045</td>
<td>0.94</td>
</tr>
<tr>
<td>1085</td>
<td>0.100</td>
<td>5.53</td>
<td>0.090</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Table 2, the effect of the hardening exponent on the slope of the force versus displacement curve is shown: a higher \( n \) value will lead to a higher slope. The relation between this parameter and the difference in slope is not as straightforward as the linear dependency of the force and the \( K \) value. The dependency can be seen in Figure 15 and is linear, although there are fluctuations. However, it can be recognized that the hardening exponent should be close to 0.055, because then the slope is almost similar to the slope of the experimental curve.

Multiple simulations lead to hardening constant of 1095 MPa and a hardening exponent of 0.058 to optimally match the force versus displacement curve of the experiment. Figure 16 shows this optimum curve, and the two curves are similar from a former displacement higher than 3 mm. However, the curves do not match during the initial displacement less than 3 mm which is mainly during the elastic deformation of the material. This is due to the fact that the chosen Young’s modulus does not match the elastic properties of the material during the bending process. Nevertheless, the initial behaviour does not affect the material behaviour during plastic deformation, because the Nadai hardening law will determine the yield behaviour of the material. The initial response will not have an influence on the formation of
cracks and degradation of the material, as severe damage formation and degradation will not act below a displacement of approximately 9 mm.

Figure 15 - Slope vs. $n$-parameter.

Figure 16 - Force vs. displacement – Optimally simulated and experimental data.
4. The continuum simulation

In this section the provisional results for the continuum simulation will be evaluated.

4.1 Force versus displacement

In the previous section the material parameters were determined using a maximum displacement of 8 mm. An analysis of the degradation of the material found experimentally can now be made using an FE analysis to review the force versus displacement curve, which is shown in Figure 17. The initial behaviour of the simulation differs from the experimental curve, which was already addressed in the previous section as the Young’s modulus which does not correspond to the experimental value. From a displacement of 3.5 mm till 8.5 mm the correspondence of the curves is very good, as the simulated curve is fitted according to this range.

In the final stage of the force versus displacement curves the experimental curve drops below the simulated curve, because degradation starts in the metal sheet in the form of shear bands and void formation. However, the continuum simulated sheet shows a different behaviour, since the material will work harden during deformation. This causes the force versus displacement characteristic to increase up till the force drops due to geometric effects, because the sheet will lose load-carrying capacity as a result of being bend 180°. The loss in load-carrying capacity will not happen up till a former displacement of approximately 15 mm.

![Force vs. Displacement Curve](image)

Figure 17 - Force vs. displacement – Optimally simulated and experimental data.

The discrepancy in behaviour beyond 8.5 mm of former displacement is due to the fact that no material degradation is implemented. This means that the only factor which affects the
material behaviour is work hardening. Therefore, the material will only get stronger during the course of the simulation.

4.2 Strain distribution

In Figure 18 the plastic strain distribution during the bending simulation is shown. It can be seen that beyond a former displacement of approximately 4.5 mm the region next to the symmetry axis is completely plastically deformed, as the colours represent a plastic deformation between 0.001 and 0.750. This causes the force versus displacement characteristic to behave according to the Nadai hardening law, because the region where most of the deformation takes place will behave according to the Nadai hardening law.

A detailed view of the material at a displacement of 9.0 mm, which is presented in Figure 19, gives an overview of the plastic strains at the symmetry axis and shows a smooth surface on both the upper and lower surface. The contact area where the former touches the sheet is the only transition in the surface. Also the equivalent plastic strain is distributed fluently without localized strain patterns, such as shear bands, which is seen in scanning electron microscopy (SEM) images of the real bent material.

The highest equivalent plastic strain is seen at the contact with the former. This area will be highly compressed due to the former which presses on the surface, as well as the material that moves inwards due to the geometric deformation. High plastic strains are also encountered at the outer surface as the material is exposed to tensile stresses below the neutral line, which lies in the dark blue part next to the symmetry axis.
In Figure 20 the strain at the outer surface is shown for two different former displacements. It is clear that the strain is fluently distributed. The plastic strain increases as the former displacement increases. At a distance of approximately 1.5 mm from the symmetry axis the strain is almost similar for both former displacement cases. Therefore it can be said, that the most significant part of the deformation takes place close to the symmetry axis and the calculation time can be kept low by using small elements for that specific region only.
5. Damage

In this section an addition is made to the simulation model, the damage formation which is seen in the scanning electron microscopy (SEM) images is implemented using the Oyane damage model.

5.1 DiekA

From the previous section it becomes clear that there is a need to implement an effect which causes the material to deteriorate. The damage model which will be implemented is the Oyane model. As already described in section 2.2.6, the Oyane damage model is based on growth and coalescence of voids based on the plastic strains which are encountered during bending.

The Oyane damage which is implemented in DiekA consists of three components which can be altered to influence the magnitude of damage formation which is encountered during the simulation. The three different components are as follows:

- Oyane damage parameter
- Material softening parameter
- Nonlocal parameter

5.1.1 Oyane damage parameters

The Oyane damage parameter is based on an integral of the positive plastic strains and comes in two variants. The formula which is chosen is slightly different compared to the original formula. Although the constant $a_0$ is not placed in the denominator but in the numerator, the constant is able to acquire equal behaviour, as follows:

$$
\int_{\varepsilon_{eq}}^{\varepsilon_{eq,f}} \left( 1 + a_0 \frac{\sigma_m}{\sigma_{eq}} \right) \frac{b_0}{\sigma_{eq}} d\varepsilon_{eq} = z, \quad (15)
$$

where:

- $\varepsilon_{eq}$ equivalent plastic strain,
- $\varepsilon_{eq,f}$ equivalent plastic fracture strain,
- $a_0$ constant,
- $\sigma_m$ hydrostatic stress (MPa),
- $\sigma_{eq}$ equivalent Von Mises stress (MPa),
- $b_0$ constant,
- $z$ damage integral.

In this way the damage formation during plastic strain and the exponential damage formation, which is seen during high plastic strains, can be taken into account (Oyane, 1972). The constants $a_0$ and $b_0$ can be adjusted to change the magnitude of the damage which is formed. The $z$ parameter is introduced as outcome of the damage integral, which contradicts the original Oyane model. The outcome of the integral in the original model was the criterion for fracture in the material. For the simulation run in DiekA, the calculated $z$ parameter will be used as an input parameter for the softening which is coupled to the material model during the simulation.
The evolution of the $z$ parameter as a function of the equivalent plastic strain will depend on the variables which will be used during the simulation. In Figure 21 several functions of the $z$ parameters are shown with an assumed triaxiality factor of 0.75. It can be seen that for a higher $b_0$ parameter, high strains will have higher damage accumulation. However, for low strains the damage development is lower, which can be deduced from a lower $z$ value at an equal strain.

\[ \frac{\sigma_y}{h(\varepsilon_p)} = (1 - \omega)h(\varepsilon_p), \]

\[ \omega = \frac{z - a_1}{b_1 - a_1} \quad \text{for} \quad z > a_1, \]

\[ \omega = 0 \quad \text{for} \quad z < a_1, \]

where:
- $\sigma_y$ yield strength (MPa),
- $h(\varepsilon_p)$ hardening function (see section 3.2.3),
- $z$ damage integral,
- $a_i$ softening parameter,
- $b_i$ softening parameter.

Figure 21 - $z$ vs. equivalent plastic strain - Various $b_0$ values.

5.1.2 Softening

The material deterioration which is seen during the experiment is implemented during the FE simulation by the usage of a softening model. The softening model makes use of the $z$ parameter as the determining factor. The formulas which are used to determine the material parameters are as follows:
From the formulas it can be derived that when $\omega(z)$ equals 1, the material degradation will be 100% and the material will lose all load-carrying capacity. This is due to the fact that the yield strength will be reduced to 0 MPa and therefore will yield upon any applied load. The degradation according to the formula is linear and is visualized for $a_1=0.1$ and $b_1=3$ in Figure 22. The softening will not act up till the damage integral reaches a value greater than softening parameter $a_1$. Complete degradation will be encountered when the value of the damage integral is greater than the second softening parameter ($b_1$).

5.1.3 **Nonlocality**

The dependency of the outcome of an FE analysis on the mesh size is already discussed in section 2.2.7. A smaller mesh size will lead to faster localization, because of smaller length scale at which the localization takes place. This is due to the fact that the strain will be accommodated on a smaller area of the sheet, which makes the strain more severe in certain elements, while the average strain is similar. With the implementation of damage it will be more critical due to the fact that in case of localization of strain, damage formation will also be localized as strain is the governing factor. Therefore, hardness gradients will come to light due to degradation of the material, which in their way will increase the rate for further localization and degradation. So the effect of degradation will amplify itself by additional localization and faster degradation.

In order to overcome the dependency of the mesh size an extra parameter is used to control the magnitude of localization. The parameter is an extra length scale in order to spread the strains which are encountered during bending. The parameter will control the localization by
spreading the damage integral by making use of a Helmholtz partial differential equation as follows:

\[ \bar{z} - l^2 \nabla^2 \bar{z} = z, \]  

(17)

Where:
- \( \bar{z} \): nonlocal damage integral,
- \( z \): local damage integral,
- \( l \): nonlocal parameter (mm).

The nonlocal parameter determines the length scale at which localization can take place. With the delocalization by the nonlocal parameter the width of shear bands can be indirectly controlled, as the damage integral in the nodes is distributed over the nodes within the nonlocal parameter length scale of a node. As a consequence more elements will degrade during the simulation, but the degradation will be less severe. The macroscopic strains and stresses will be similar to simulations done without the nonlocal parameter.

Because of the ability of the nonlocal parameter to influence the distribution of the damage integral, the stresses and strains will also be distributed differently. This is due to softening of the material, which will also be spread due to the redistribution of the damage integral. The stresses and strains will be spread out, as a result of the softening of the elements over a length scale of the nonlocal parameter. Because the stresses and strains are altered by the nonlocal parameter, the fracture mode will also depend on the minimum length scale. This minimum length scale at which stresses and strains can localize is similar to the largest value of either the mesh size or nonlocal parameter. However, the effect of the nonlocal parameter will be negligible if the chosen parameter is smaller than the mesh size. This is a result of the spreading which will not have an influence, because the nodes of the element will be further apart than the length of the nonlocal parameter.

5.2 Damage analysis

In order to obtain an indication of the influence of a parameter and in which range an optimum can be found, a sensitivity analysis is done. The material parameters which are used are similar to the parameters found in section 3.3 \((K = 1095, n = 0.058)\). The damage parameters are kept constant, except for the parameter which is tested during the particular sensitivity analysis. The values which are chosen to represent the parameters which are constant during the sensitivity analysis are as follows:
- \( a_0 \) 3.0,
- \( b_0 \) 0.0,
- \( a_1 \) 1.4,
- \( b_1 \) 4.5,
- \( l \) 0.015 mm.

To investigate the sensitivity, the force versus displacement curves and the strain distributions in the material will be considered. The force versus displacement curve will provide information about the magnitude of the maximum force, as well as the former displacement which correspond to that value. Furthermore, the quickness of degradation can be derived by comparing the former displacement at the maximum force and the moment of full degradation.
The distribution of the strain in the sheet provides information about the damage mode which acts in the sheet. An indication can be made of the magnitude of the shear localization and from there a conclusion can be drawn about the shear band formation, or other damage modes like necking.

5.2.1 Oyane parameters

The Oyane damage integral consists of two individual damage parameters, namely the multiplier, \( a_0 \), which controls the magnitude of the triaxiality factor on the development of the damage integral, and the exponent, \( b_0 \), which raises the equivalent plastic strain to a power. In Figure 21 the development of the \( z \) parameter as a function of several \( b_0 \) parameter values is shown. The exponent will affect the curvature of the \( z \) parameter in the sense that higher values will increase the significance of high strains and decrease damage formation at lower strains.

![Figure 23 - z vs. equivalent plastic strain - Various \( a_0 \) values.](image)

In Figure 23 the influence of the \( a_0 \) parameter is shown. The parameter is responsible for the change in slope which is seen in the three curves: the slope increases at higher values of the \( a_0 \) parameter. In this way, the magnitude of the damage integral can be controlled and the curvature up to a small degree since it will only change due to a different multiplier. The base curvature is controlled by the \( b_0 \) parameter, which was shown in Figure 21.

During the sensitivity analysis of parameter \( a_0 \), the value is varied in a range from 0 to 25. The simulations are run until 100% degradation is encountered or numerical problems occur. In both cases the simulation will automatically be stopped, due to the fact that 100% degradation of an element will cause numerical problems. The problems indicate an impossibility to reach the lower yield strength in accordance with the amount of degradation.
and the strain. So no convergence is reached for the yield strength and the strain in an element in the multiple iteration steps of which a former displacement increment consists.

The maximum former displacement versus the $a_0$ parameter is shown in Figure 24. It can be seen that a higher $a_0$ value leads to earlier loss in load-carrying capacity, because the former displacement at the maximum force decreases. The trajectory of the force versus displacement curve does not change, so a lower displacement at maximum force leads to a lower maximum force. For $a_0 = 0$ the material shows little degradation which translates into a high displacement and a corresponding bend angle of nearly 180 degrees.

The influence of the $a_0$ parameter shows an inversely proportional like relation, since the displacement at the maximum force shows asymptotic behaviour for higher values of $a_0$. The limit cannot be lower than a former displacement of a few millimetres. This can be explained on the basis of elastic and plastic strains, since the damage integral is based on strains. As a consequence of the small strains during the first stage of deformation, the development of the damage integral will be slow. This will cause a delay in degradation, due to the fact that softening will not start until the damage integral reaches a value higher than softening parameter $a_1$.

![Figure 24 - Displacement at maximum former force vs. $a_0$ value.](image)

Another observation which can be made when plotting the difference in former displacement between maximum force and maximum displacement is the fact that the degradation is more severe at higher $a_0$ values, as shown in Figure 25. This can be explained by the fact that the difference in former displacement between maximum force and maximum displacement decreases for increasing $a_0$ values. The discrepancy for $a_0 < 2$ is due to geometrical reasons, since the simulation will reach a maximum displacement of 15 mm. So not only will the degradation start at lower former displacements, but also the maximum former displacement
at 100% degradation will be lower. Since after initiation of damage, degradation will be more severe and accumulate faster.

The zero difference at an \( a_0 \) value of zero is due to the fact that there is little degradation and the sheet can bend by almost 180 degrees. The force will therefore increase up till the maximum former displacement and thus there will be no difference in former displacement between the maximum force and the maximum former displacement. Similar to the former displacement in Figure 24, the curve shows an inversely proportional relation with the \( a_0 \) parameter for values higher than 2.0.

The analysis of the \( a_0 \) parameter, for the constants which are used during the sensitivity analysis, leads to a range where the optimum can be found. According to Figure 24 this range is between 2 and 4, since the displacement at the maximum force for the experiment is at a former displacement of 9.5 mm.

![Figure 25 - Difference in former displacement between maximum force and maximum displacement vs. \( a_0 \) value.](image)

For the \( b_0 \) parameter a similar sensitivity analysis is done as for the \( a_0 \) parameter. The value for the \( b_0 \) parameter should be found close to 1 (Oyane, 1972; Goijaerts, 1999), so the range in which the parameter has to be sought for is chosen to be from 0 to 2. The result of the analysis can be seen in Figure 26, where the force versus displacement curves are presented. From these curves an interesting phenomenon comes to light, namely the increase in load-carrying capacity when the \( b_0 \) parameter increases.

This is due to the nature of the parameter, since the parameter decreases the influence of low plastic strains and increases the growth of the damage integral at high strains. As a consequence, there will be less development of the damage integral at low former...
displacements and degradation will be delayed due to the low value of the damage integral which triggers softening. From Figure 18-Figure 20 the main cause for this behaviour can be deduced, since for former displacements lower than 10 mm the plastic strain does not reach a value higher than 1. As the plastic strain is raised to the power of the $b_0$ parameter, the value will become smaller as a result of the exponentiation.

For the $b_0$ parameter values above 0.8 the various former force versus former displacement curves show comparable behaviour during the analyses. This is a consequence of the degradation which is very small in the material. Therefore it leads to former force versus former displacement curves which are similar to the curves which are obtained during simulations without using a damage model. This can be recognized in Figure 26, where the curve for $b_0 = 1.0$ shows an increase in force during most of the simulation and a slight drop in former force due to geometrical nonlinearity, whereafter the former force increases significantly due to another geometrical occurrence. Also the maximum displacement which is reached corresponds to an analysis which is carried out without the implementation of a damage model, due to the low damage development.

![Figure 26 - Force vs. displacement - Simulation - Various $b_0$ parameters.](image)

The implementation of the $b_0$ parameter for the continuum analysis does not give a satisfactory result. Due to the nature of the parameter and the low plastic strain encountered at small former displacement, the effect is opposite to what is intended. The degradation is delayed and for higher values of the parameter the delay will cause no degradation upon maximum former displacement. So the $b_0$ parameter will not be used during the parameter analysis.
5.2.2 Softening parameters

Similar to the Oyane damage integral, the softening model which is used during the analysis consists of two parameters, namely $a_1$ and $b_1$, as explained in section 5.1.2. The $a_1$ parameter should be smaller than the $b_1$ parameter in order to obtain useful data. This is due to the fact that the softening will act as a discontinuous function. The material will have an ordinary behaviour until the damage integral is larger than $a_1$. Thereafter, if $a_1$ is larger than $b_1$, the material will immediately be degraded as a consequence of the smaller $b_1$ value and the simulation will encounter numerical problems. The range in which the $a_1$ parameter can be chosen is therefore determined by the value of the $b_1$ parameter. That is why the range which is used for the $a_1$ parameter is set to 0.5 up to 4.0 during the sensitivity analysis, as a higher parameter will probably delay degradation to a too big degree.

It can be seen in Figure 27 that the displacement at which the material starts to lose its load-carrying capacity is influenced by the value of the $a_1$ parameter. A lower value of the parameter will lead to earlier degradation in the material and therefore a quicker loss in load-carrying capacity. This behaviour is opposite to that of the $a_0$ parameter which causes earlier degradation when the value is increased. All $a_1$ values beyond 2.9 will give a similar behaviour, since the degradation will start at a former displacement beyond the maximum former displacement in the experiment and simulation. This causes the force versus displacement characteristic to behave like a material which does not have damage implemented.

![Figure 27 - Force vs. displacement - Simulation - Various $a_1$ values.](image)

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However, the difference in former displacement at maximum force and the maximum former displacement of the simulation which is achieved does not change in the way the $a_0$ parameter did, as is presented in Figure 28. The difference fluctuates around 0.8 mm for the parameter range of 0.5 up to 2.5, instead of decreasing during the increase of the parameter. Due to the delay in degradation for an $a_1$ parameter beyond 2.9 the difference will be reduced to zero, since then the maximum force will be obtained at the maximum displacement which is encountered during the simulation.

The former displacement where the material starts to degrade can therefore be altered, without significantly changing the magnitude of the degradation. According to Figure 27 the value for the $a_1$ parameter should be close to 1.5 for the given constants of the sensitivity analysis. Therefore the range in which $a_1$ will be sought for is estimated to be 1 till 2 to take into account the variation, and as a result different response, of the other parameters.

The second softening parameter, $b_1$, is responsible for the maximum value which the damage integral may reach before the material will lose all its load-carrying capacity. The parameter will thus also have an influence on the severity of the softening response. This is due to the formula which is described in section 5.1.2: since the parameter is in the denominator it reduces the magnitude of softening at equal values of the damage integral. An increase of the $b_1$ value will therefore lead to a material which can resist higher values of the damage integral before it is fully degraded.

Figure 28 - Difference in former displacement between maximum force and maximum displacement vs. $a_1$ value.
In Figure 29 the influence of the second softening parameter $b_1$ on different displacements is shown. It can be seen that a higher value leads to higher displacements due to the ability to absorb more damage. For both the displacement at maximum force and the maximum displacement a linear increase is seen for increasing $b_1$ values. The change in slope of the maximum displacement curve is due to the fact that the maximum displacement of the equipment setup is reached and the sheet is bend by almost 180 degrees. Since the experiment does not reach former displacements with the same magnitude, it is assumed that the displacement scales linearly with the $b_1$ parameter for former displacements in the range which is experienced during the experiment. The appropriate range for $b_1$ will be between 3 and 5.

Due to the tempering effect on the degradation by the $b_1$ parameter, not only will the displacements which belong to the maximum force and the maximum displacement change, but accordingly also the difference between both displacements. This can also be seen in Figure 29.

### 5.2.3 Nonlocal parameter

The nonlocal parameter itself does not modify the damage development in the material. However, it controls the ability of the damage integral to localize in a single element and thus the potential to avoid local degradation. The average strain on the macro scale will therefore not change and is similar to simulations without taking nonlocality into account, only the distribution within the material will be changed. However, due to the spreading of the damage integral over larger volumes of material, differences in the force versus displacement curve can occur. This is a result of the redistribution of the damage integral in parts of the material where the strain was in the elastic region, because the maximum absorption of energy is not
achieved in material which experiences elastic strain or is not 100% degraded yet. The effect of the nonlocal parameter on the force versus displacement characteristic is visualized in Figure 30. It becomes clear that a higher nonlocal parameter leads to a stronger material which can carry a higher load and also can sustain the high loads for higher former displacements.

![Graph of Force vs. Displacement with different nonlocal parameters](image)

**Figure 30 - Force vs. displacement - Simulation - Various nonlocal parameter values.**

In Figure 31 plastic strain distributions for several values of the nonlocal parameter can be seen. The displacement of the former is different for each nonlocal value, since the displacement is just before 100% degradation in the material. It can be seen that the strain is able to act on a smaller length scale at lower values of the nonlocal parameter. As a consequence, different patterns can be observed in the plastic strain distribution close to the symmetry axis. A smaller nonlocal parameter leads to narrower shear bands; these can be identified as the high plastic strain regions at a 45 degree angle with the lower surface.

Not only will the shear localization bands be narrower, also the pattern is different as can be seen when both the left-hand figures are compared. In the lower image, only one shear band can be identified as opposed to the upper image, where several shear bands are connected and form a diamond pattern. This is also visible at a nonlocal parameter of 0.025 mm, but beyond a nonlocal parameter of 0.025 mm only a single shear band can be identified near the symmetry axis. Another thing which can be deduced from Figure 31 is the mode of failure for the material. This can be recognized as the thinning of the material in the y direction at the symmetry axis. This is especially visible for a nonlocal parameter beyond a length of 0.020 mm. The thinning shows similarities to the necking phenomenon during a uniaxial tensile test. And although the phenomenon of the material becoming less thick during a bend test is to be expected, it should not show the same behaviour as necking during a tensile
test. Instead, thinning is expected to be seen over a larger area of the outer surface. Note, that as a consequence of the thinning the neutral line will shift during the bending experiment.

Figure 31 - Plastic strain distribution – Simulation – Various nonlocal values – Upper left: nonlocal = 0.010 mm, upper right: nonlocal = 0.025 mm, lower left: nonlocal = 0.050 mm, lower right: nonlocal = 0.100 mm.

In Figure 32 the maximum displacement of the former is shown for different nonlocal values. From the image the difference in damage mode is also visible, since this can be recognized as the change in slope of the maximum former displacement at a nonlocal value of 0.020 mm which is approximately the same value as what can be deduced from the plastic strain distributions in Figure 31. So not only can the difference be seen in the plastic strain distribution, but also in the maximum displacement which the former reaches before numerical problems occur. Similar behaviour is seen when the maximum force which is reached during the simulation is plotted versus the nonlocal parameter.

The behaviour of the material during the simulation for a nonlocal parameter beyond 0.020 mm is not what is seen in actual material. The shear band formation which is seen in dual-phase material is explained in section 2.2.3. The shear band formation for nonlocal values lower than 0.020 mm are more in agreement with the behaviour of dual-phase materials compared to larger values for the nonlocal parameter. Therefore, the nonlocal parameter should not be chosen larger than 0.020 mm. For this reason, the nonlocal parameter is chosen to be 0.015 mm, as the resemblance with the real material is good and the parameter is comparable with the grain size of the material, which is in the range of 5-15 μm.
5.2.4 Step size

The size of the displacement per increment during the simulation also has an influence on the damage formation in the material (Wisselink & Huétink, 2007). Therefore an investigation of the displacement step size is done to ensure that there is no dependency. The influence is caused by the fact that the damage which is used to calculate the increment step is fixed at the beginning of the step and is not changed during the calculation step. This will cause the damage to be delayed by one step, and as a result damage formation and development will be slower at larger displacement increments per step.

Several force versus displacement curves are shown in Figure 33 for different values for the displacement increment per step. A larger value of the displacement increment will lead to less damage formation and therefore to higher forces and displacement for the former. The increments of displacement smaller than 0.002 mm show similar behaviour and have force versus displacement characteristics within 1% difference. In order to have the smallest possible calculation time which is independent of the increment step size, a former increment step size of 0.002 mm per step is chosen for the simulation.
5.3 Optimum parameters

The analysis of the material parameters found for the simulated force versus displacement curve which are in consensus with the experimental values which are described in the following section for several mesh sizes.

The range in which the different parameters are sought for are described in the previous subsection and are as follows:

\[
\begin{align*}
&a_0 & 2-4, \\
&b_0 & 0, \\
&a_1 & 1-2, \\
&b_1 & 3-5, \\
\text{nonlocal parameter} & 0.015 \text{ mm}.
\end{align*}
\]

During the analysis combinations of the three variable parameters \((a_0, a_1, \text{ and } b_1)\) will be used to obtain the force versus displacement curve. The optimum will be determined using the method of least squares, which compares the obtained curve with the characteristic which was obtained experimentally. The most relevant part of the characteristic is at a former displacement between 9 mm and 10 mm, since degradation will occur and show differences.

In contradiction to the sensitivity analysis where the simulations are stopped due to numerical problems or 100% degradation, the analysis for the optimum parameters only have to run till a former displacement of 10 mm. This is due to the fact that beyond 10 mm there is no experimental data available.

The optimum parameters which are found for a mesh size of 0.010 mm are shown in Figure 34. Except for the force at former displacements lower than 4 mm, where a difference in the
curves is present due to the elastic response of the material, the curves are very close to the curve which is obtained during the experiment. The parameters which are found can thus represent the material for the bending process.

![Graph](image)

**Figure 34 - Force vs. displacement - Simulation - Optimum - Mesh size 0.010 mm – Nonlocal parameter = 0.015 mm.**

In subsection 2.2.7 it was addressed that mesh sensitivity is the main complication of FE analyses. The nonlocal parameter was introduced to reduce the influence of the mesh size. In order to see if there is still an effect of the mesh size during the optimization process, more simulations are carried out. Therefore the optimization is run for multiple values of the mesh size in the area closest to the symmetry axis and the outer surface, as shown in Figure 10 represented by the turquoise region.

In Figure 35 the optimum curve and the second best fit with the corresponding parameters can be seen for a mesh size of 0.009 mm. The optimum curves have the same values as obtained in the analysis which was run using a 0.010 mm mesh size. However, the second best curve which corresponds to the experimental characteristic is different from the second best curve which is found in the analysis using a mesh size of 0.010 mm. Nevertheless, both curves do appear as the third best fit of the analysis of respectively 0.010 mm and 0.009 mm. So although there are some differences, the values of the optimal curves are in close proximity of each other. It could be possible that these optimums are part of a local optimum and there are other ranges in which similar curves can be obtained.
For simulations done at smaller mesh sizes the values start to differ from the values found at 0.010 mm and 0.009 mm. This is an indication that the mesh size still has an influence on the result of the simulations, despite of the nonlocal parameter which was introduced to counteract the mesh sensitivity of the FE analysis. In Table 3 the several optimal results of the analyses are shown for mesh sizes in the range of 0.005 mm up to 0.008 mm.

<table>
<thead>
<tr>
<th>Mesh size (mm)</th>
<th>Optimal fit</th>
<th>Second best fit</th>
<th>Third best fit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a_0$</td>
<td>$a_1$</td>
<td>$b_1$</td>
</tr>
<tr>
<td>0.008</td>
<td>3.05</td>
<td>1.4</td>
<td>5.0</td>
</tr>
<tr>
<td>0.007</td>
<td>3.3</td>
<td>1.5</td>
<td>5.0</td>
</tr>
<tr>
<td>0.006</td>
<td>3.2</td>
<td>1.45</td>
<td>5.0</td>
</tr>
<tr>
<td>0.005</td>
<td>3.0</td>
<td>1.45</td>
<td>4.5</td>
</tr>
</tbody>
</table>

The sensitivity to mesh size is also confirmed by the force versus displacement curves which are shown in Figure 36, where it becomes clear that the simulations done at a mesh size of 0.010 mm and 0.009 mm are similar. The simulation with a mesh size of 0.008 mm and 0.007 mm are also similar to each other, but clearly different from the curves which are obtained using a mesh size of 0.010 mm. If the mesh size is decreased further to 0.006 mm and 0.005 mm, the obtained characteristics lie in between the curves obtained with a mesh size of 0.010 mm and 0.009 mm and the curves obtained with a mesh size of 0.008 mm and 0.007 mm. There is not yet a clear tendency in the positions of the former force versus former displacement curve. The position of degradation alternates randomly for the mesh sizes which are used.
Figure 36 - Force vs. displacement - Simulation – $a_0 = 3.15$, $a_1 = 1.5$, $b_1 = 4.5$, nonlocal parameter = 0.015 mm - Various mesh sizes.

Figure 37 - Plastic strain distribution – Outer surface - Simulation – $a_0 = 3.15$, $a_1 = 1.5$, $b_1 = 4.5$ nonlocal parameter = 0.015 mm - Various mesh sizes.
The plastic strain distribution at the outer surface is shown in Figure 37. The figure confirms the dependency of the obtained results on the mesh size in the region next to the symmetry axis. Not only do the positions of the peaks change, which is an indication that the underlying shear band also shifts position, also the magnitude of the peaks is different. This will result in a different damage development in the material and therefore a deviation of the force versus displacement curve, as well as a different surface roughness. Even for simulations where the force versus displacement curve is almost identical, there is a difference seen in the plastic strain distribution, albeit small.

![Figure 38 - Plastic strain distribution – Simulation – Various mesh size – Upper left: mesh size = 0.002 mm, upper right: mesh size = 0.005 mm, lower left: mesh size = 0.008 mm, lower right: mesh size = 0.010 mm.](image)

The difference in the plastic strain distribution does not disappear at smaller values of the mesh size, although the nonlocal parameter is several times larger than an edge of an element. And due to the usage of quadratic triangular elements, nodes in the neighbourhood are half the edge length apart and therefore the redistribution which takes into account the nonlocal parameter as a length scale is provided twice as much nodes as the mesh size suggests. However, due to calculation time which is needed, smaller mesh sizes are not possible. In Figure 38 several plastic strain distributions are shown with different values of
the mesh size while using the optimum settings which are obtained from the analysis run at a mesh size of 0.010 mm. Similar to the plastic strain distribution at the surface shown in Figure 37, the plastic strain distributions in the sheet show a different pattern for different mesh sizes.

To conclude the continuum simulation, the simulations with the implementation of damage and softening are able to match the experimentally obtained curve. The softening can be altered in combination with the damage integral and is able to fit the degradation of the DP1000 material. The optimization of the damage and softening parameters can be obtained in a reasonable timeframe of five days when ten calculation units are used. However, the optimum parameters which are found are only valid for the given mesh size and nonlocal parameter and it cannot be assured it will be representative for other forming processes.
6. Representative volume elements

In the coming section, the implementation of a Voronoi diagram (section 6.2), which will be embedded as a representative volume element (RVE) in the modelled sheet, is discussed.

6.1 Embedded Voronoi diagram

In the previous subsection, the main shortcoming of finite element (FE) analyses came to light, which is the sensitivity of the result to the mesh size used during the simulation, even though the nonlocal parameter was introduced to overcome this main imperfection. There were still discrepancies between simulations with similar nonlocal parameters and a different mesh size. To reduce the sensitivity of the analysis to the mesh size of the region near the symmetry axis, an RVE is introduced in this region. This RVE is based on a Voronoi diagram which in this case is a description of both the hard and the soft phases of the dual-phase (DP) steel, as explained in subsection 2.2.8.

Since a Voronoi diagram is not symmetric like a continuum, a new model of the sheet is introduced to accommodate the RVE during the FE analysis. Due to the non-symmetric Voronoi diagram, the sheet covers the full length with the RVE embedded into the sheet at the surface loaded in tensile, as is shown in Figure 39. Similar to the sheet which is used during the symmetric analysis, the mesh consists of several regions to strive for an as low as possible number of elements in order to keep the calculation time as short as possible. Therefore the regions at the left and right (shown in green and orange) are built up using coarse elements. The elements which come into contact with the supporting rolls of the simulation have an edge size of 50 μm to ensure there is no discontinuous force versus displacement curve, as a result of the position where the sheet is supported. The mesh size will increase in the positive y direction lowering the number of elements by increasing the edge size to 250 μm on the top of the sheet.

Figure 39 - Steel sheet mesh with RVE.

The yellow and blue region which can be seen in Figure 39 and Figure 40 on the left and right of the RVE are the transition zones. The regions will accommodate the mesh size difference introduced to minimize the number of elements. The edge length therefore varies to connect the region with a small mesh size (Voronoi diagram) and the zone with a large mesh size (support mesh), which will make the mesh size vary between 1 μm and 250 μm. The middle top region which is shown in Figure 40 as the orange area makes contact with the former, so for this area a mesh size of 50 μm is chosen, equal to the surface which comes into contact with the supporting rolls.

6.2 Voronoi diagram

The multicoloured area situated in the lower part of Figure 40 is the RVE built with a Voronoi diagram which represents the DP structure of the material. The different coloured areas each
represent a different grain to which a particular material characteristic can be assigned. In this case this will be the soft ferrite phase combined with the hard martensite phase. The distribution of the hard and soft phase will be based on the fractions of each phase in the actual DP1000 material. The number of generated grains depends on the average grain size and the area which is covered by the Voronoi diagram. As can be seen in Figure 40, the area of the Voronoi diagram consists of a rectangle of 2.0 mm wide and a height of 1.0 mm. This covers the area where the highest deformation takes place, which can be seen in Figure 20, where the highest strains are close to the symmetry axis.

**Figure 40 - Steel sheet mesh with RVE – Detail.**

The Voronoi diagram gives a distribution of cells from a given amount of distributed points in the prescribed area. Given the total number of grains, an equal amount of points is distributed randomly over the area of the RVE. The area of the RVE will be divided around the points which are distributed over the area using the Euclidean distance as measurement. The area will be assigned to the point which is nearest to that particular area. An example is shown in Figure 41, where fifteen points are distributed over an area. The area is divided among the points up till there is no undivided space left, using a perpendicular bisector construction.

As the number of grains in the RVE increases, the size of the grains decreases, since the mean grain cross sectional area is calculated as the total area divided by the total number of grains. The average grain size is the square root of the mean grain cross sectional area and decreases with the increase of the number of grains. Another result of an increase of the number of grains is the change in edge length of the grains. This will lead to edges smaller than the mesh size and as a result of that, elements will have an unfavourable aspect ratio to be used during FE analysis. This is the case if one of the edges of a triangular element is much smaller than the other edges to accommodate the outline of a grain. To prevent the mesh to contain elements with an undesirable aspect ratio, the edges which are shorter than the mesh size are removed from the Voronoi diagram. The Voronoi diagram will therefore be
slightly altered and some grains will be changed to ensure that there are no inconsistencies in the grain perimeter.

Figure 41 - Voronoi diagram.

During the creation of the Voronoi diagram, each individual grain is assigned either the characteristics of martensite or of ferrite. This is done randomly while keeping in mind the volume fraction of both phases in the real material. Since the grain size is approximately evenly distributed among the grains of both phases in the Voronoi diagram, the fraction of grains which are assigned to a particular phase fraction is similar to the volume fraction of this phase in the material. For the RVE a fraction of approximately 40% martensite is desired, since this is the corresponding fraction in the actual material. Therefore 40% of the generated grains are assigned randomly across the grains to martensite. The value of the martensite fraction in the Voronoi diagram is equal to the area fraction of grains in the diagram which are assigned with the martensitic material characteristic.

The mesh size in the Voronoi diagram will be altered in a similar way as that in the region of high deformation close to the symmetry axis during the continuum simulation. However, the maximum mesh size is determined by the shortest edges in the Voronoi diagram, since the mesh needs to accommodate all the features without having elements with undesirable aspect ratios in the Voronoi diagram. The edge length of the mesh will therefore be smaller or equal to the shortest edges in the Voronoi diagram.

Figure 42 - Stress vs. strain – Ferrite, martensite and dual-phase - Experimentally and numerically obtained characteristics.
6.3 Material parameters

Since the material in the embedded Voronoi diagram consists of two phases, the material also has to be represented by two sets of material characteristics. In this case martensite and ferrite characteristics are used to represent the phases of DP1000, as was already pointed out in subsection 2.1.2. The characteristics for the stress versus strain behaviour are obtained from uniaxial tensile experiments. The martensite and ferrite are individually tested to obtain data for the single phase. This is visualized in Figure 42, where also the characteristic is shown which will be used for the material that surrounds the Voronoi diagram during the bending analysis (DP1000). The characteristic of this surrounding material is similar to that used during the continuum analysis ($K = 1095$ MPa, $n = 0.058$). This is because this material should show similar behaviour compared to the continuum to achieve the same bending boundary conditions in the embedded Voronoi diagram.

During the bending analysis of the sheet with the embedded Voronoi diagram a shortcoming of the method for determining the material parameters arises. Using the material characteristics obtained during the uniaxial tensile test, the force versus displacement curve shows an undesired behaviour. This is shown in Figure 43, where it can be seen that the force versus displacement characteristic does not reach the values of the experiment. This is because the hardening of the material in the RVE is insufficient to match the behaviour of the material during the experiment.

![Figure 43 - Force vs. displacement - Embedded Voronoi diagram.](image)

This behaviour can be explained by the interaction of the two phases during the production of the actual steel sheet. As explained in subsection 2.1.3, austenite undergoes an expansion during the transformation to the martensite phase. This results in geometrically necessary dislocations (GNDs) and this causes the ferrite to behave as a stronger phase, due to a higher dislocation density, compared to undeformed ferrite. The extra strength in the matrix
of the material leads to a stronger material and therefore a higher force versus displacement response during bending. This strengthening effect of the GNDs is not considered in the embedded Voronoi diagram, since the ferrite grains themselves are represented by undeformed ferrite, with a material characteristic obtained with a uniaxial tensile test.

In order to make the force versus displacement curve, obtained with the use of the embedded Voronoi diagram, correspond to the experimentally obtained curve, the work hardening function representing the ferrite phase is altered. At the same time the material behaviour of the martensite phase is kept constant during the optimization of the ferrite phase. This method of working is chosen because the matrix phase is decisive for the behaviour of the material during the bending process, with the ferrite being the matrix material. Since the ferrite phase accommodates almost all the strain, while the martensite phase hardly deforms (Shen et al., 1986; Al-Abbasi & Nemes, 2007) and due to the fact the GNDs are not yet considered in the material model for the ferrite phase, an adjustment of the ferrite phase is justified. Other adjustments like the change of martensite hardening parameters and martensite fraction do not give satisfactory results, since the martensite grains only show a minimal deformation.

The optimal set of parameters for the ferrite phase is found using a method similar to the optimization of the material parameters of the continuum DP1000 phase, namely using the method of least squares. The martensite phase is described by the hardening response which was obtained by uniaxial tensile testing of 100% martensite. The optimal characteristic for the ferrite phase will be sought-after in the range between the hardening curve found by the uniaxial tensile test and the hardening curve found for DP steel in the continuum sheet, which are both shown in Figure 42. The reason is that the uniaxial tensile characteristic of ferrite is insufficient to match the experimental force versus displacement curve and the continuum optimum from subsection 3.3 will show a response which is too strong due to the influence of the included martensite phase. The work hardening function has the same form as the work hardening function of the continuum approach, represented by equation (13).

The Young’s modulus \(E\) is represented by 210 GPa, since this is the common value for steel and has the same value for the three materials used during the analysis. The elastic stress versus strain response will therefore be identical for the used materials. The range in which the \(K\) parameter is sought-after is from 850 MPa up till 920 MPa and for the hardening exponent \(n\) the range is chosen to vary between 0.03 up till a value of 0.3.

The Voronoi diagram which is used during the optimization of the ferrite phase consists of 1000 grains in order to keep the calculation time during the optimization process low, since the mesh size can be similar to the mesh size used during the continuum analysis at 10 \(\mu\)m. This leads to an average grain size of 44 \(\mu\)m, which is large compared to the actual grain sizes of 5 to 15 \(\mu\)m. The optimization is run up till a former displacement of 8 mm which is equal to that used for the material parameter optimization of the continuum simulation. Since the force versus displacement characteristic starts to degrade beyond a former displacement of 9.5 mm, the material has to be determined before degradation occurs.

The optimum \(K\) and \(n\) values which are found during the analysis are 870 MPa for the hardening constant and a hardening exponent of 0.06. This is consistent with the material characteristic that was expected, given that the stress versus strain characteristic was expected between the optimum of the continuum and the uniaxial tensile experimental data.
In Figure 44 this is visualized, and as can be seen, the response of the ferrite phase is stronger at all given strains, compared to the uniaxial tensile data for pure ferrite.

![Figure 44 - Stress vs. strain – Ferrite phase and DP1000 – Experimentally and numerically obtained.](image)

The force versus displacement curve shows a similar response compared to the optimal characteristic obtained by the continuum simulation, which is shown in Figure 16. The initial response does not completely match the experimentally obtained curve, due to the elastic material properties which do not match the response of the real material. However, the resemblance at a former displacement beyond 3 mm is in good agreement with the experimental bend test characteristic, as can be seen in Figure 45.

![Figure 45 - Force vs. displacement - Embedded Voronoi diagram.](image)
6.4 Plastic strain distribution

The plastic strain distribution in the Voronoi diagram shows an irregular pattern with shear bands at an angle of 45 degrees relative to the surface, as can be seen in Figure 46. This is in accordance with the actual material which shows shear band formation upon deformation. Compared to the shear pattern found by the continuum approach the plastic strain distribution of the embedded Voronoi diagram shows a more capricious pattern. This is due to the random distribution of the hard and soft phase which will divert the strain from the hard phase to the soft phase and will meander between the grains. In contrast to the continuum simulation, which shows a gradual progression of the plastic strain without the use of a damage model, the simulation with an embedded Voronoi diagram brings out shear localization during the analysis without a damage model. The strain is concentrated in the softer ferrite phase similar to the strain distribution in DP steel (Shen et al., 1986; Al-Abbasi & Nemes, 2007; Kang et al., 2007). The shear bands fade out closer to the neutral line, similar to the fade out of the shear bands which arise during the continuum simulation.

![Figure 46 - Plastic strain distribution - Former displacement 8.0 mm - DP1000 – Embedded Voronoi diagram 1000 grains.](image)

The outer surface of the sheet shows an irregular pattern, as can be seen in Figure 46. The roughening of the surface is consistent with that in the actual material, since the irregular strain pattern in the material will cause undulations in the surface to occur during the bending process. While the shear bands which are seen in the continuum simulation show a fluent behaviour, the strain localizations which arise in the Voronoi diagram show an unpredictable pattern. This behaviour is shown in Figure 48 where the equivalent plastic strain at the outer surface of the material is shown at a former displacement of 5 mm. However, it can be seen...
that the strain localization is not dependent on the edge size of the elements. This is a consequence of the embedded Voronoi diagram, which imposes the strain distribution onto the elements in the RVE. The peak strains show up at equal horizontal distances from the centre, which is where the former makes contact with the sheet.

Although the former displacement is similar for all the strain curves (Figure 48) and also the strain pattern in the material is similar for all the mesh sizes, the force versus displacement curve for the different mesh sizes differ from each other. This can be seen in Figure 47, a smaller mesh size leads to less load-carrying capacity, which can be identified as a lower force at an equal former displacement. Also numerical convergence is becoming a problem during simulations which are run at a small edge size. This is due to the inability to obtain convergence of stress and strain in the nodes, as a result of the large deformations in the shear bands. Due to localization, the strain will be concentrated in a small amount of elements which are within the shear bands, as a result there will be excessive deformation of these elements and this leads to divergence in the simulation and bring the simulation to an end.

![Figure 47 - Force vs. displacement - Embedded Voronoi diagram 1000 grains– Various mesh size.](image)

Another phenomenon which stands out is the magnitude of the equivalent plastic strains which are obtained during the simulations using a different mesh size, as is shown in Figure 48. The peak equivalent plastic strain is higher in simulations when the mesh is built up using smaller elements. This is in correspondence with numerical difficulties to find convergence during these simulations, since a higher strain in the mesh will cause elements to experience higher deformation. Due to localization some elements will therefore experience even more
severe deformation, which can cause the elements to get an unfortunate aspect ratio, and as a result numerical convergence will be more difficult.

Figure 48 - Plastic strain distribution – Outer surface – Former displacement = 5.0 mm – DP1000 - Embedded Voronoi diagram 1000 grains – Various mesh size.

6.5 Voronoi diagram variance

Due to the random distribution of grains in the Voronoi diagram, different created diagrams will have a different grain morphology. However, the main characteristics for the Voronoi diagrams are similar to the Voronoi diagram which was used during the material optimization, given that the same material has to be represented. The features which are similar for all the Voronoi diagrams are a martensite fraction of approximately 0.4 and an average grain size of 44 μm, and a corresponding number of grains of 1000. The mesh size in the region of the Voronoi diagram is 10 μm in order to keep the calculation time low. As a result of the randomness of the Voronoi diagrams, there is some dispersal in the martensite fraction between the diagrams. The fraction of martensite between the different Voronoi diagrams varies between 0.37 and 0.40, with the majority within the range of 0.39 and 0.40.

As a result of the randomly distributed grains, the equivalent plastic strain distribution of the sheet will differ for every created Voronoi diagram. Several obtained plastic strain distributions are shown in Figure 49 for different Voronoi diagrams with little variation in the fraction of martensite. Several strain localizations can be identified in every strain distribution, all showing similar behaviour as the angle of the shear bands relative to the surface is approximately 45 degrees. The number of shear bands differs between the different Voronoi diagrams and also the magnitude of the maximum strain varies. The roughening therefore shows different behaviour between the Voronoi diagrams. Some of the shear bands
Figure 49 - Plastic strain distribution - Former displacement 9.0 mm - DP1000 – Embedded Voronoi diagrams 1000 grains – Upper left: martensite fraction = 0.3719, upper right: martensite fraction = 0.3910, middle left: martensite fraction = 0.3942, middle right: martensite fraction = 0.3959, lower left: martensite fraction = 0.4028.

will accommodate more strain compared to other shear bands and by doing so also unload these shear bands which will therefore be less pronounced. The number of strain peaks at the surface is a measure for the number of strain localizations in the material. The number of peaks for the tested Voronoi diagrams is of the same order of magnitude as the number of peaks on the surface and lies between 28 and 42.
Although the strain distribution in different Voronoi diagrams will be different, the behaviour of the material and the macroscopic response should ideally be similar, as they represent the same material. However, the force versus displacement curves which are obtained using various Voronoi diagrams show discrepancies to the curve which was obtained during the optimization of the material parameters. Figure 50 shows various force versus displacement characteristics, where it can be seen that the curves differ from the experimentally obtained data. This is in contrast to experimentally obtained curves, since these characteristics match each other during the initial response of the bending experiment up to a former displacement of 8 mm when cracks start to form and degradation takes the upper hand.

![Force vs. Displacement Curve](image)

**Figure 50 - Force vs. displacement - DP1000 - Embedded Voronoi diagram 1000 grains – Various Voronoi diagrams.**

The symptom of the discrepancies in the force versus displacement curves becomes worse upon the implementation of a damage model and softening of the material. Similar damage variables will lead to a significant change in the trajectory of the force versus displacement curve. However, some Voronoi diagrams show a higher sensitivity to the addition of the damage model, which can be identified as a larger difference between the force versus displacement curves obtained with and without the damage model implemented. While some simulations show little difference up to a displacement of 10 mm, other Voronoi diagrams already show large deviations at former displacements of 7 mm. Although the degradation and the severity of loss in load-carrying capacity varies between samples during the experiment, the force versus displacement curves follow equal trajectories up to former displacements of 9 mm. From here damage formation starts in some samples, quickly altering the slope of the force versus displacement curve which then lead to the rapid break down of the sample. In the simulation, small changes in slope are seen which do not lead to quick degradation. This is not seen during the experiment, as degradation causes a significant change in slope, since the response changes from strengthening to degrading.
A peculiar phenomenon which is visible in the force versus displacement curves is the fact that the embedded Voronoi diagram with the highest martensite fraction does not provide the simulated data with the strongest response. So the martensite fraction is not the only factor that determines the response of the simulation, but microscopic features in the Voronoi diagram also have an influence on the macroscopic behaviour of the sheet. This is most probably the cause for the high discrepancies in the force versus displacement curve, since the martensite fraction for the Voronoi diagrams are very similar to each other. Since the number of grains in the Voronoi diagram is small, it is possible that the morphology of the grains in the diagram have favourable features which show a higher response in the force versus displacement characteristic. The discrepancies which arise when implementing a damage model combined with a softening function could be traced back to the features which are represented in the morphology of the grains being prone to faster degradation. Due to the low number of grains the response of these features have a high influence and are not balanced with a grain morphology which possesses opposite characteristics and as a result some Voronoi diagrams will not be an average representation of the material.

6.6 Smaller grain size

In order to reduce the influence of the strengthening and softening features the number of grains in the Voronoi diagram has to be increased. This will decrease the average grain diameter so it will be closer to the values of the real material. Due to the random distribution and the larger number of grains, the morphology of the grains will bring forward a larger variety of features. Since the response of the grains is dependent on the morphology, a larger variety will lead to a more balanced distribution of strong and weak features. As a result the macroscopic response of the simulations in the form of the force versus displacement curve will behave in a more similar way, independent of the morphology of the grains in the Voronoi diagram.

Due to the decrease of the average grain diameter, the edges of the grains in the Voronoi diagram will also become smaller, since the circumference of a grain will also decrease. As a result, the shortest edges of the grain boundaries in the Voronoi diagram will also become shorter. This is an unwanted side effect, as the mesh size within the Voronoi diagram is dependent on the shortest edge of the grain boundaries. Since the elements within the Voronoi diagram need to maintain a proper aspect ratio, otherwise numerical problems are prone to occur, which lead to early halt of the simulation. In order to maintain this proper aspect ratio of the elements within the grains, the element size which is used is similar to the shortest edge length. As a consequence of the quadratic scaling of the area with the edge length of the elements, the number of elements will also increase quadratically during the decrease in length of the edges in the mesh. Since the Voronoi diagram is accountable for the vast majority of the elements in the simulation, the decrease of the edge size of the mesh in the Voronoi diagram will have a significant influence on the calculation time of the simulation. This will decrease the efficiency of the FE analysis for the bending experiment with DP material drastically, as the number of elements will increase beyond a million and accordingly the number of nodes in the mesh will increase beyond two million.

The force versus displacement characteristics which are obtained by using different number of grains within the Voronoi diagram show the differences of the various grain distributions with similar martensite fraction. While the difference between the force versus displacement curves was visible at a low number of grains, the discrepancies become lower at an increase
in the number of grains in the Voronoi diagram. The deviation of the obtained force versus displacement curves is an indication of the variance of the material behaviour resulting from the randomly generated Voronoi diagrams. A high standard deviation of the force versus displacement curve suggests that single microscopic features have a big influence on the macroscopic behaviour of the simulated sheet.

The experimentally obtained curves have very little deviations from each other with a standard deviation of the force of 0.34 N/mm at a former displacement of 8 mm and an average value of the former force of 133.32 N/mm. For the five randomly generated Voronoi diagrams with 1000 grains the standard deviation has a much higher value at 3.64 N/mm. If the number of grains in the Voronoi diagram is increased to 2000 grains within the same area, the standard deviation for five randomly created diagrams decreases to 1.35 N/mm. Although being significantly lower, the standard deviation is still high compared to the value which is found during the experiments. The mean force at a former displacement of 8 mm is 132.90 N/mm, which is more in accordance with the experimentally obtained values.

By further reducing the average grain diameter to 20 µm by making use of 5000 grains, the standard deviation of the former force at a former displacement of 8 mm decreases to 0.86 N/mm. This is a result of a distribution with more grains and therefore the Voronoi diagram contains a larger variety of strong and weak features, which leads to a more balanced representation of the material. However, the average value of the former force at a displacement of 8 mm does increase significantly to 136.17 N/mm. The average plastic equivalent peak strain does also increase to a value of 7.3, due to the fact that space between the martensite grains is on a smaller length scale as a result of the finer partition of the Voronoi diagram. Since the majority of the strain will be accommodated in a few shear bands only due to unloading of surrounding shear localizations in the ferrite, the strain acts on a smaller scale and has a higher magnitude compared to coarser grains, i.e. 6.6 and 6.8 for Voronoi diagrams with 1000 and 2000 grains, respectively.

The strain distribution for the simulations with a larger number of grains shows similarities to the strain distributions which are obtained using Voronoi diagrams with a lower number of grains. This can be seen in Figure 51, where the plastic strain distribution is shown. Strain is accommodated in the ferrite phase and shows localization in shear bands. These shear bands have an angle to the surface of around 45 degree similar to the Voronoi diagrams with lower number of grains. Although the behaviour of the shear bands is similar, the number of strain peaks visible at the surface is larger due to increased number of grains which are adjacent to the surface. As a consequence the number of phase boundaries on the surface increases and acts as additional initiation points for strain localization.

Another difference which comes to light is the surface roughness which is caused by the strain distribution among the martensite and the ferrite phase, since almost the entire strain is accommodated in the ferrite matrix. An increased number of grains within the Voronoi diagram lead to a higher number of peaks on the surface, since the number of grains on the surface is also increased. However, based on the outline of the plastic strain distributions shown in Figure 49 and Figure 51, the roughening of the surface is less severe for the Voronoi diagram with an increased number of grains. This is due to the fact that the scale at which the strain acts is smaller and is distributed among more shear bands compared to the Voronoi diagrams which contain less grains.
A further decrease of the grain size leads to results which are similar to the simulation run with a larger grain size. A Voronoi diagram with 10000 grains leads to a former force at 8 mm displacement of 135.65 N/mm, which is in accordance with the simulations run with 5000 grains. However, compared to the experimentally found value and the values found with a lower number of grains it is still higher. The maximum strain which is found in the simulated sheet again shows an increase, compared to the maximum strain in a Voronoi diagram with fewer grains, to a value of 8.2 equivalent plastic strain. This is expected to be due to the
further reduction of the spacing between martensite grains as a result of the smaller grains. Also the edge lengths of the elements are reduced as a result of the usage of smaller grains in order to accommodate the features of the grains within the Voronoi diagram. The standard deviation of the former force of the obtained curves is higher compared to the standard deviation of the simulation run with 5000 grains in the Voronoi diagram, with a value of 1.27 N/mm.

When the grains within the Voronoi diagram are increased in number to match the average grain diameter of 10 µm, which resembles the grain size in the actual material, the total number of grains will be 20000. Similar to the simulations with the Voronoi diagram with fewer grains, the strain acts in shear bands at an angle of 45 degrees to the surface. A further increase in the peak strain within the sheet is seen, as a result of the smaller martensite spacing and the smaller edge length which is used to accommodate all the features of small grains due to the large number of grains. However, the increase in equivalent plastic strain to a value of 13.16 is not in line with the linear increase which was seen between the increase in number of grains from 1000 to 10000 in the Voronoi diagrams, this is shown in Figure 52.

\[ \text{Figure 52 - Maximum equivalent plastic strain within the Voronoi diagram vs. number of grains.} \]

The average former force for the simulations with 20000 grains at a displacement of 8 mm is 133.67 N/mm, which is in good agreement with the force found during the experiment at a former force of 133.32 N/mm. Also the standard deviation of the former force at a former displacement of 8 mm of the simulations with 20000 grains decreased to a level which is more in accordance with the experimental results, with a value of 0.77 N/mm. This makes the simulation with a Voronoi diagram of 20000 grains more consistent compared to a lower value of grains, since the deviation between the different Voronoi diagrams is less. This can
also be seen in Figure 53, where the force versus displacement characteristics for Voronoi diagrams with 20000 grains are shown, since the difference between the curves is less than in Figure 50.

Figure 53 - Force vs. displacement - DP1000 - Embedded Voronoi diagram 20000 grains – Various Voronoi diagrams.
7. Damage

In this section the implementation and results of damage and softening during the usage of the representative volume element (RVE) with a Voronoi diagram is discussed.

7.1 Oyane

Since the material now consists of two different phases and will be represented by different material parameters for both phases, also the damage implementation will be different from the simulation with the continuum approach. As already mentioned in section 2.1.7, the majority of the strain within the dual-phase (DP) steel is accommodated in the ferrite phase and very little deformation of the martensite fraction is seen. Therefore the damage and softening model within the Voronoi diagram will be implemented only in the ferrite matrix. The implementation of damage into the ferrite phase is similar to that in the continuum sheet, and will make use of the Oyane damage function equal to equation (15).

However, the parameters which will be used to control the development of damage in the ferrite will be different from the parameters found for the continuum sheet which were found in section 5.3. This is due to the fact that the ferrite has a different response compared to the DP1000 investigated earlier, i.e. the ferrite response is less strong and is able to accumulate more strain compared to the DP1000 continuum material. The damage will therefore develop less quick compared to the single phase representation of DP1000 and the damage integral parameters will be lower compared to the values found in section 5.3.

7.2 Softening

Like the damage integral, the softening of the ferrite phase in the Voronoi diagram will use different parameter compared to the continuum softening values, since the ferrite phase is able to accommodate significantly more strain while maintaining its strength longer compared to the DP1000 continuum sheet. Therefore, the softening will be less severe, especially the second softening parameter \( b_1 \) will be higher in order to accommodate more strain without reaching 100% degradation within the ferrite. For the softening function the formulas which are described by equation (16) are used.

7.3 Nonlocal parameter

Since the strain distribution is imposed on the mesh by the Voronoi diagram, the dependency on the mesh size is less compared to the continuum simulation. However, due to the localization effect which occurs in FE analyses, the nonlocal parameter will also be implemented during the simulation with a Voronoi diagram. The parameter will control the localization by spreading the damage integral among the nodes in the mesh, according to equation (17).

The nonlocal parameter will not change with the implementation of damage in the Voronoi diagram. As addressed in section 5.2.3, where the influence of the nonlocal parameter on the strain distribution was shown, the material will show a necking kind of behaviour with a nonlocal parameter larger than 0.020 mm. This behaviour is not wanted, since the same material will be represented during the simulations with an RVE. Therefore the nonlocal parameter will be equal to the 0.015 mm used in bending simulations with a continuum sheet.
7.4 Strain distribution

Since the strain peaks at the surface and the strain distribution within the Voronoi diagram are controlled by the interaction of the soft ferrite matrix and the hard second phase martensite particles, the implementation of damage should not cause a different strain pattern. This is in contradiction to the damage formation in the continuum simulation which was described in chapter 5, as the shear bands are influenced by the edge length and the nonlocal parameter in the region where the highest deformations take place. However, due to the degradation of the material, it is expected that some of the shear bands will accommodate more strain than others, as a result of the softening of the material by plastic strain. This will cause a higher rate of degradation within the Voronoi diagram, and therefore the material as a whole will also show higher softening.

Since the damage and softening parameters are determined for the continuum DP steel, the parameters are not applicable to the ferrite phase in the Voronoi diagram. Therefore, the parameters are altered to get a first indication of the magnitude of the degradation within the Voronoi diagram and to get an indication of the alteration of the strain pattern with the implementation of damage and softening. The parameters are chosen as follows:

\[
\begin{align*}
    a_0 &= 1.0, \\
    b_0 &= 0.0, \\
    a_1 &= 2.0, \\
    b_1 &= 10.0, \\
    \text{nonlocal parameter} &= 0.015 \text{ mm}.
\end{align*}
\]

The Oyane damage parameter \(a_0\) in this case is lowered to decrease the damage built-up as a result of the strain and stress state during the bending process. The \(b_0\) parameter is similar to that in the continuum simulation and set to zero. However, since the peak strain within the Voronoi diagram is higher, the parameter will have a better behaviour compared to the continuum simulation. This is due to the influence of the parameter which did not work as intended during the continuum bending simulation, as a result of low equivalent plastic strain. The parameter does not react well on strain with a magnitude less than 1.0, as the parameter is used as a powerfactor for the equivalent strain.

The softening parameters are also altered, especially the second softening parameter \((b_1)\) which is double the value used during the continuum simulation. This is in order to increase the strain at which 100% degradation of the material, and therefore numerical problems, occurs. The decrease of the first softening parameter \((a_1)\) will cause the ferrite phase to show softening at similar strains as the continuum simulation, in combination with the \(a_0\) parameter which was lowered to decrease the development of damage.

In Figure 54 the strain distribution within the Voronoi diagram is shown for various Voronoi diagrams ranging from 1000 grains to 20000 grains. For each Voronoi diagram the plastic strain distribution with and without damage is shown, with a similar scale for both distributions. For the simulation with and without damage similar patterns are seen within the strain distributions. Although the peak strain is higher in simulations with damage due to softening of the material, this only occurs in some of the shear bands. In the majority of the shear bands there is no significant change in the plastic strain visible, since the width and colour is similar.
Figure 54 – Plastic strain distribution with and without damage - Former displacement 9.0 mm (except RVE 20000 grains, where: former displacement 8.0 mm) - DP1000 – Embedded Voronoi diagrams – Upper left: 1000 grains - martensite fraction = 0.3910 – without damage, upper right: 1000 grains - martensite fraction = 0.3910 – with damage, middle left: 10000 grains - martensite fraction = 0.3916 – without damage, middle right: 10000 grains - martensite fraction = 0.3916 – with damage, lower left: 20000 grains - martensite fraction = 0.3937 – without damage, lower right: 20000 grains - martensite fraction = 0.3937 – with damage.

Not only do the strain patterns within the Voronoi diagram not significantly change, also the topography of the tensile surfaces does not change substantially. This can be seen when the two surface patterns are shown together in a graph, as is visualized in Figure 55 for various Voronoi diagrams. Although not all the features on the tensile surface are similar, the main outline of the surface is equal for the majority of the undulations at the surface. Some peaks are missing, while some are shifted or increased in height and/or width. The discrepancies of the surface are caused by the fact that some shear bands will accommodate more strain compared to the simulation without degradation. This is due to the implementation of softening in the material, which causes the degraded material to accommodate strain easier due to a lower strength. Therefore the material which did not experience severe degradation will accommodate less strain, since the response of the material is closer to the initial strength.
Figure 55 – Tensile surface outline with and without damage – Former displacement 9.0 mm (except RVE 20000 grains, where: former displacement 8.0 mm) - DP1000 – Embedded Voronoi diagrams.

7.5 Variance

With the usage of a Voronoi diagram to represent the DP structure of the material, large variations arise in the force versus displacement characteristic between the various diagrams, as became clear in section 6.5. The problem is less severe with a higher number of grains within the Voronoi diagram, considering the standard deviation between the force versus displacement curves is less. With the introduction of damage in the material the force displacement curves for Voronoi diagrams with 1000 grains will become as shown in Figure 56. The phenomenon of a high variance is still visible for the different curves. In fact, the standard deviation is even higher compared to the standard deviation for simulations without damage.
Various Voronoi diagrams. Not only does the standard deviation at a former displacement of 8 mm increase, also the trajectory beyond 10 mm former displacement is sometimes changed drastically. Some of the curves are hardly affected by the implementation of damage like the Voronoi diagram with a martensite fraction of 0.3719. The former force is a little lower compared to the simulation without damage, but the strength keeps increasing which is behaviour similar to that of the simulation without damage. The Voronoi diagram which is closest to the experimental structure, that with a martensite fraction of 0.3942, leads to a drastic force decrease above a former displacement of 9 mm. Although the simulations have similar damage and softening parameters, the degradation of most of the other Voronoi diagrams show a large scatter. Also the standard deviation at a former displacement of 8 mm increased to 4.32 N/mm compared to 3.64 N/mm for simulations without damage.

This behaviour is similar to the deviation which is seen in the simulations with Voronoi diagrams without damage. Comparable to the features in the Voronoi diagram, which bring a deviation in the strength of the material, as addressed in section 6.5, the features also differ in reaction to damage. Some of the Voronoi diagrams are prone to develop damage at an increased rate, while other diagrams are hardly affected by the formation of damage. Due to the large grain diameter and the low number of grains with 1000 grain Voronoi diagrams, the grain features with a high sensitivity to damage formation are not counterbalanced by features with a low sensitivity to damage development. Therefore the damage builds up at an increased rate and causes fast degradation of the material.

For a Voronoi diagram with double the number of grains, the damage also has a significant impact on the force versus displacement curves. Similar to the Voronoi diagrams with 1000
grains and damage, the Voronoi diagrams with 2000 grains and damage show an increased standard deviation at a former displacement of 8 mm compared to simulation without damage. The increase is even more significant compared to the Voronoi diagrams with 1000 grains, as the value increases from 1.35 N/mm to 3.44 N/mm. The force versus displacement curves can be seen in Figure 57. The simulations end well before the maximum displacement of 15 mm, where the sheet is bent 180 degrees. However, similar to the simulations with 1000 grains within the Voronoi diagram, the scatter of the force versus displacement curves increases with the introduction of damage and the Voronoi diagrams are not all affected equally.

![Figure 57 - Force vs. displacement - DP1000 - Embedded Voronoi diagram 2000 grains – Various Voronoi diagrams.](image)

The standard deviation decreases for an increase of the number of grains, similar to the simulations without the use of damage within the Voronoi diagram. The grain features are more in balance with a higher number of grains, which lead to a more consistent behaviour between the different Voronoi diagrams. For Voronoi diagrams with 20000 grains this is shown in Figure 58. The force versus displacement curves are similar to each other up till a former displacement of 7.5 mm. Not all simulations reach a displacement of 7.5 mm, which is a result of the introduction of damage. Although the degradation in the ferrite phase has not reached 100%, the simulation is not able to find convergence and numerical problems occur.
Figure 58 - Force vs. displacement - DP1000 - Embedded Voronoi diagram 20000 grains – Various Voronoi diagrams.
8. Calculation time

The finite element (FE) analyses with a smaller grain size give more detailed results with a higher resemblance to the real material. In this section the influence on the calculation time of the smaller grain size is discussed.

8.1 Edge length

In the continuum simulations an edge length of 10 µm is used in the region where the highest strains are expected. Additionally, due to the symmetry of the bending process, only half of the sheet needs to be modelled. This is beneficial for the number of nodes and elements within the sheet, since just half is necessary to run the simulation. This brings the number of nodes around 75000 and the number of elements for the sheets is approximately 37000, which is roughly half the number of nodes.

For the Voronoi diagrams with 1000 and 2000 grains, the edge length of the elements is similar to that for the continuum simulations. However, due to the representation of the dual-phase material by a Voronoi diagram, the sheet is modelled over the entire width of 60 mm, due to the asymmetry in the Voronoi diagram. This increases the number of elements within the sheet and brings the value approximately \( \frac{3}{4} \) higher compared to the continuum simulation, to respectively 135000 nodes and 67000 elements. So while the edge length has not changed for the region where the highest strains take place, the number of elements increased significantly.

![Figure 59 - Number of nodes and elements in the simulation vs. edge length](image)

In order to accommodate the features within the Voronoi diagram with even higher number of grains, the edge length of the mesh needs to be decreased. The elements need to be small enough to follow the contours of the grains, and at the same time keep a shape close to that of an equilateral triangle. As can be seen in Figure 59, the number of nodes and elements...
increase with the decrease in edge length of the mesh for both the continuum simulation, as well as the simulation with a Voronoi diagram. For a Voronoi diagram with 5000 grains the edge length within the Voronoi diagram is decreased to 8 µm, which brings the number of nodes to 180000 and the number of elements to 90000. 10000 grains within the Voronoi diagram lead to a smallest edge length of 5 µm, with a corresponding number of nodes and elements of respectively 381000 and 190000. The increase to 20000 grains brings even higher number as a result of the need to decrease the edge length to 2 µm. The number of nodes and number of elements therefore increase significantly to 2.1 and 1.1 million respectively.

8.2 Calculation time

The decrease in the edge length of the mesh, to accommodate the features within the Voronoi diagram, is a drawback during the simulations. This is because the calculation time for the simulation will increase as a result of the number of elements which are used during a particular simulation. This is due to the stress and strain state which acts in a node that needs to be calculated for every displacement step. The number of nodes and elements has a quadratic dependency on the edge length of the elements, since the area of the Voronoi diagram is equal for the different diagrams. Therefore a significant impact on the calculation time is visible for the Voronoi diagrams with a higher number of grains and the concurrent need to decrease the edge length.

![Figure 60 - Calculation time till step 2510 vs. number of nodes in the simulation - Embedded Voronoi diagram with 1000 grains.](image)

The calculation time for the simulation has a quadratic dependency on the number of nodes in the mesh of the sheet, as the majority of the nodes are situated in the sheet and the tools do not change. This can be seen in Figure 60, where the calculation time is shown for the
Voronoi diagram with 1000 grains and a martensite fraction of 0.3719 for various edge lengths. The calculation time is for simulations up till displacement step 2510; this in order to acquire consistent calculation periods for the different simulations. Since the simulations which are run with smaller edge length tend to experience convergence problems, the simulations terminate well before a displacement of 10 mm is reached. The edge length of the mesh in the Voronoi is varied between 10 µm and 1.5 µm, and as a result the number of elements for the simulations varies between 67000 and 2.5 million, and correspondingly the number of nodes varies between 135000 and 5.0 million.

Figure 60 clearly indicates the increased calculation time for the simulations run with a smaller edge length and a higher number of nodes, even though an attempt is made to decrease the calculation time by using multiple cores for a simulation. For the simulations with a number of nodes higher than 200000 and a correspondingly long calculation time, more calculation units are used for the calculation steps. In this manner the calculation step of a former displacement increment is divided among multiple calculation units. Although the calculation time is not cut in half when double the number of calculation units are used, the calculation time for a simulation is decreased significantly.

For the Voronoi diagrams with a higher number of grains and various edge lengths, a similar tendency is seen compared to the Voronoi diagram with 1000 grains and various edge lengths, see Figure 61. The calculation time increases with an increased number of nodes, although the quadratic increase does not show during the simulations with an increased number of grains, a more linear development is seen. The maximum calculation time of the simulation with various number of grains is also lower to the maximum calculation time of the simulations with various edge lengths. This is due to a lower number of nodes and a lower number of elements compared to the various edge length simulations. Due to the minimum edge length which is used within the various Voronoi diagrams is 2 µm compared to the minimum of 1.5 µm in the simulation with 1000 grains and various edge length.

Compared to the continuum simulation, the simulations with a Voronoi diagram are more time consuming. The calculation time for a typical continuum simulation with damage implemented and a step size of 0.002 mm is approximately 5 hours. This is for a simulation with an edge length of 10 µm and up till a former displacement of 10 mm which amounts to 5010 displacement steps, which is twice the displacement which is shown in Figure 60 and Figure 61. So the effectivity of the FE analysis is a lot less for the simulations with a Voronoi diagram, as a result of the long calculation time for a simulation.

8.3 Optimization of damage parameters

The long calculation time has a major drawback on the ability to optimize the damage variables. In order to run an optimization for the damage parameters a large number of simulations with varying parameters is needed. For the continuum simulation with a mesh size of 10 µm more than 200 simulations are done to obtain the best fitting parameters to match the experimental curve. With a calculation time of approximately five hours per simulation, this leads to a total calculation time of approximately a 1000 hours.

For the simulations with a Voronoi diagram, the simulations with 20000 grains acquire the most consistent data between the various Voronoi diagrams. Compared to the continuum simulation the mesh size is decreased significantly with an increase of number of nodes and elements as already mentioned in the previous section. As a result, the calculation time for
one set of parameters increases to six or seven days, with the use of four calculation units per simulation. An optimization of the damage and softening parameters for the ferrite phase within the Voronoi diagram will lead to an approximate calculation time of 30000 hours if a similar number of simulations is needed for the optimization, which corresponds to approximately four years of calculation with four calculation units.

![Graph showing calculation time till step 2510 vs. number of nodes in the simulation – Voronoi diagrams with 1000 to 20000 grains.](image)

Simulations can be done simultaneously, as long as there are calculation units available. In this manner, an optimization can be done significantly quicker. However, the usage of multiple calculation units per simulation leads to a higher virtual time. Since the number of calculation units is limited, the number of simulations which can be done simultaneously is lower if more calculation units are used for one simulation. Therefore, the total time for running the optimization is governed by the number of available calculation units and not by the number of calculation units used for a single simulation.
9. Discussion

In this section the results are analysed and discussed.

9.1 Material model

9.1.1 Continuum simulation

For the continuum simulation of dual-phase (DP) steel the material characteristics of the two phases, which are present in the material, are combined to form a uniform material model. The parameters for the Nadai hardening characteristic where obtained by using an analysis based on the least squares method. The force versus displacement curves for the simulations are compared to the experimentally obtained curve. The height and the slope of the curve are altered by changing the K and n parameters of the Nadai hardening characteristic. The resemblance of the force versus displacement curves is good for almost the entire displacement range.

However, due to a different response in the elastic region, which is up till a former displacement of 0.5 mm, the force versus displacement curve of the simulation differs from that of the experiment during the first few millimetres of bending. Beyond a former displacement of 3 mm the influence of the elastic material parameter on the force versus displacement curve decreases, due to the fact that most of the material is deformed plastically. The material which endures the highest deformation, situated directly beneath the former, behaves according to the Nadai hardening model.

Since the material is loaded during the simulation, and no unloading takes place, springback does not occur and is not considered. The elasticity of the material is therefore only used during the initial loading up till a former displacement of 3 mm in the region of the highest deformation. The region of the sheet with lower deformation, which is situated past 1 mm from the symmetry axis in the x direction, does remain elastic for the majority of the simulation. The deformation in the sheet in this part is very small, and the influence on the force versus displacement curve is therefore also small.

9.1.2 RVE simulation

For the ferrite phase which is used in the simulations with an embedded Voronoi diagram, a different Nadai hardening curve is used compared to the Nadai hardening curve for the continuum simulation. This is due to the fact that two material properties are needed within the Voronoi diagram. The ferrite phase is softer compared to the continuum phase, since the ferrite phase combined with the much harder martensite phase forms the DP properties. However, what can be seen in section 6.3, the material characteristic of 100% ferrite measured by a tensile test has a response which is not appropriate to match the force versus displacement curve which was obtained experimentally.

The parameters for the ferrite phase are adjusted, since the ferrite accumulates the highest strains, while the martensite phase hardly deforms and has less influence on the response of the sheet (Shen et al., 1986; Al-Abbasi & Nemes, 2007). The ferrite in this case is adjusted to have a stronger response compared to the tensile test and this can be justified by the fact that the material response of ferrite is tougher as a result of the martensite formation during production. The martensite grains create geometrically necessary dislocations (GNDs) in the
ferrite close to the phase boundaries, and this causes the ferrite phase to have a stronger behaviour (Liedl et al., 2002; Tsipouridis et al., 2011; Sodjit & Uthaisangsuk, 2012; Paul, 2013). The material parameters which are found lie between the tensile experiment of the ferrite phase and the continuum material parameters for the DP1000 continuum phase.

In section 2.2.9 a direct method to measure the material behaviour within a DP steel by Sun et al. (2009) was described. The method used an in-situ measurement of the strain by using a high energy X-ray diffraction (HEXRD) technique to obtain the flow data for the ferrite phase of a DP980 steel. The sample was subjected to a uniaxial tensile test to provide for the necessary deformation during the experiment. Here, the actual microscopic behaviour for the ferrite phase is captured. Although the material which was tested (DP980) by Sun et al. (2009) has very similar properties on paper compared to the material provided by Tata Steel (DP1000), the properties of both ferrite phases and both martensite phases differ from each other. Figure 62 shows the stress versus strain curves for the experimentally and numerically obtained characteristics for ferrite. A peculiar observation can be made, since the strength of the ferrite phase obtained by Sun et al. (2009) shows a stronger response compared to the response obtained by the continuum analysis of the bend test, i.e. the ferrite phase found by Sun et al. (2009) is stronger than the DP1000.

![Stress vs. strain – Ferrite phase and DP1000 – Experimentally and numerically obtained.](image)

The support structure, which extends up to one third of the height of the sheet, has material properties similar to the parameters of the continuum simulation. The influence of the support structure on the behaviour of the representative volume element (RVE) is the highest at the boundaries of the Voronoi diagram. As a result of the stronger material parameters compared to the ferrite matrix, the Voronoi diagram has less deformation at the boundaries with the support structure. However, the deformation at the boundaries with the support structure is low. Since the maximum plastic deformation is seen at the outer surface, directly underneath the punch. The top boundary of the Voronoi diagram is close to the neutral line of the sheet, which leads to low deformations at the boundary with the support structure.

An enlargement of the Voronoi diagram to cover 1500 µm of the height of the sheet does lead to similar results as for the smaller Voronoi diagrams. This can be seen in Figure 63, where the force versus displacement characteristics are shown for Voronoi diagrams with a
height of 1500 µm and a width of 2000 µm. The response of the materials is in a similar range as the curves obtained with a Voronoi diagram with a height of 1000 µm. The differences are similar to the deviation which is seen between the various Voronoi diagrams used in section 6.5. Thus, the height of the Voronoi diagram does not significantly change the behaviour of the sheet.

Figure 63 - Force vs. displacement - DP1000 - Various Voronoi diagrams – Various martensite fraction.

9.2 Strain distribution

9.2.1 Continuum simulation

The strain distribution within the sheet during the bending process is an important parameter in the deterioration of the material, since the damage which builds up during bending is controlled by the magnitude of the plastic strain. A simulation without damage is seen in Figure 64, where the plastic strain is shown in a continuum sheet. The plastic strain at the outer surface of the sheet increases gradually closer to the symmetry axis, where the punch is situated. The inner surface shows an even higher plastic strain, as a result of contact with the punch. However, the strain distribution does not show irregularities as seen in the actual material. Localization effects, which are seen in DP steels, are not present since there are no initiation points for localization due to the continuum representation of the material and smooth surface.
9.2.2 RVE simulation

For the simulation with the Voronoi diagram at the outer surface of the sheet a completely different strain pattern comes to light, as can be seen in section 6.4. This strain pattern shows similarities to the strain distribution which is seen in the real material. The internal differences of the strain lead to an irregular surface, similar to the roughened surface of the real material after being bent. The maximum equivalent plastic strain is located close to the outer surface of the modelled sheet in the ferrite phase.
Compared to the continuum simulation the strain distribution within the Voronoi diagram has a more consistent behaviour. The mesh size does not influence the characteristic of the strain distribution within the Voronoi diagram. However, the magnitude of the peak plastic strain increases concurrent with the decrease in mesh size. Nevertheless, the macroscopic strain does not change, as the outer surface of the sheet is not changed at equal former displacement. In Figure 65 the strain distributions at a former displacement of 5.0 mm can be seen. The scale of the plastic strain is equal in each image, where the maximum plastic strain is set to the maximum reached with a simulation with a mesh size of 10 µm. This causes the plastic strains with a higher magnitude in the images with finer mesh sizes to be greyed out, as they are out of the range.

A smaller mesh size leads to more regions with a plastic strain higher than the peak strain reached with a mesh size of 10 µm. The widths of the shear bands within the Voronoi diagram are less wide compared to the simulation with a mesh size of 10 µm. This is due to the higher peak strains within the shear bands and therefore a more concentrated shear band, as a result of which the directly surrounding elements experience less deformation. The nonlocal parameter does not interfere with the strain distribution, since the parameter can only be used in combination with damage and softening. Therefore, the strain shows localization effects with the usage of a smaller mesh size.

Another drawback of the simulations with an RVE in the sheet, are the discrepancies in the former force versus former displacement curves which arise between the Voronoi diagrams with equal number of grains and similar martensite fraction. The features which are caused by the morphology of the grains cause the Voronoi diagram with similar properties to show a different former force versus former displacement behaviour. Some differences are expected due to the inhomogeneous nature of the Voronoi diagram and the random distribution of grains within the diagram. However, the magnitude of the discrepancies is much higher compared to the differences seen in the former force versus former displacement curves acquired by the experiment.

This phenomenon is less pronounced if the number of grains is increased, the Voronoi diagrams with equal number of grains and martensite fraction show a behaviour which is closer to one another. The standard deviation of the former force at a former displacement of 8 mm has decreased significantly from 3.64 N/mm to 0.77 N/mm for Voronoi diagrams with respectively 1000 and 20000 grains. This value is closer to the value found during the experiment, which is 0.34 N/mm at a former displacement of 8 mm. Therefore, in order to acquire consistent data Voronoi diagrams with a number of grains higher than 15000 need to be used.

Another advantage of the simulations with a high number of grains is the surface pattern which comes to light during the bending process. With an increase of the number of grains within the Voronoi diagram the number of undulations at the surface also increases. The peaks and valleys in the surface roughness of the Voronoi diagram with a higher number of grains show a closer resemblance to the actual surface after bending. The height difference of the peaks and valleys which form at a higher number of grains in the Voronoi diagram are less high and greater in number compared to simulations with fewer grains. This is a better approximation, since the surface roughness which appears on the surface of the actual material, which can be seen in Figure 66, is not as severe as the surface of the simulations.
The Voronoi diagrams with a number of grains lower than 15000 show a surface roughness which is too irregular to represent the bent sheet.

![Image of optical microscopy image - DP600 - After bending.](image)

**Figure 66** - Optical microscopy image - DP600 - After bending.

### 9.3 Damage

#### 9.3.1 Continuum simulation

The implementation of the damage and softening model during the FE analysis can lead to a good representation of the degradation behaviour of a DP1000 sheet during bending. The former force versus former displacement of the simulation can approximate the course of the former force versus former displacement curve of the experiment very well. However, the strain patterns which arise in the sheet during the bending process are dependent on the mesh size and the nonlocal parameter. This is a major drawback of the FE analysis as already described by several other studies (Triantafyllidis et al., 1982; Tvergaard, 1987; Tvergaard & Needleman, 1997; Reusch et al., 2003; Sun et al., 2009; Bettaieb et al., 2010; D’hers & Dvorkin, 2011; Uthaisangsuk et al., 2011).

Simulations with a continuum sheet and a damage model implemented show a different strain distribution as can be seen in section 5.2.3. The gradual increase of the plastic strain closer to the symmetry axis is changed to an irregular strain pattern. The pattern is dependent on the nonlocal parameter in combination with the mesh size of the area next to the symmetry axis. This leads to an unpredictable strain behaviour, which results in a different shear band pattern when different mesh size and nonlocal parameters are used. And although the shear pattern also differs in the actual material due to the random...
distribution of ferrite and martensite grains within the material, this is not the behaviour that is
strived for. This is because the degradation behaviour of the material is also altered by using
a different mesh size in combination with the nonlocal parameter.

The width of the shear bands can be controlled by the nonlocal parameter, rather than being
depended on the size of the mesh in the region with high plastic strains. However, the strain
patterns which come to light are still dependent on the mesh size, despite the introduction of
the nonlocal parameter. Simulations with an equal nonlocal parameter but a different mesh
size lead to different patterns within the sheet and on the surface, as can be seen in Figure
67. The former displacement is different for some of the simulations, since convergence
problems due to small elements or high damage formation make some of the simulations
stop before reaching a former displacement of 10 mm.

![Figure 67 - Tensile surface outline with damage – Former displacement between 9.7 and 10.0
mm - DP1000.](image)

Not only a difference is seen in the surface pattern, but also the former force versus former
displacement is affected by a different mesh size. The initial response up till a former
displacement of 9 mm is equal for the simulations. The degradation behaviour of the
simulations is different in the final stage, where degradation starts to occur. The different
mesh sizes lead to a deviation of the former force versus former displacement
characteristics, as can be seen in Figure 68. It is therefore possible to obtain a
representation of the degradation behaviour of DP1000 in a bending process. However, the
parameters which are obtained are only valid for the mesh which is used in combination with
the nonlocal parameter when a continuum representation is used.
Figure 68 - Force vs. displacement - Simulation and experiment – Damage parameters, $a_0 = 3.15$, $a_1 = 1.5$, $b_1 = 4.5$ nonlocal parameter = 0.015 mm - Various mesh sizes.

The optimum parameters for different combinations of the mesh size and the nonlocal parameter do not deviate from each other much, as could be seen in Table 3. The parameters which are found are all within 10% of the optimum parameters found during the analysis of a mesh size of 0.010 mm and a nonlocal parameter of 0.015 mm. This can also be seen in the former force versus former displacement curves in Figure 68. Although there is a difference, the degradation of the several simulations takes place in the same range of the former displacement between 9 mm and 10 mm. It can be possible that these optimum parameters are part of a local optimum and other optimums with very different parameters are present. However, the chances are slim due to the nature of the parameters and the dependency on the equivalent strain.

The differences which occur due to the different meshes in combination with damage and softening are a major drawback of the FE analysis. The nonlocal parameter is not able to overcome this phenomenon during the continuum simulation. Therefore, the simulations are only valid for the particular experiment, which acted as the basis for the simulations. An accurate prediction based on simulations for other deformation processes or other material thicknesses cannot be guaranteed to give a good representation.

9.3.2 RVE simulation

Since the influence of the mesh on the outcome of an FE analysis should be as low as possible, an RVE with a dual-phase grain structure was implemented within the sheet. The strain distribution, in the region of high plastic strains, is imposed on the sheet by the distribution of hard and soft grains within the RVE and with it the points of localization. The
behaviour of the sheet with damage implemented should therefore behave in a more predictable way, since the localization pattern is not dependent on the mesh size.

The damage is only implemented in the soft ferrite matrix, since the hard martensite particles scarcely deform (Shen et al., 1986; Al-Abbasi & Nemes, 2007). It is therefore assumed that the martensite particles do not show degradation nor softening due to the lower plastic strains in the martensite grains compared to the ferrite matrix. This also reduces the number of parameters which are needed for the simulations run with an RVE. The number of parameters is already increased, due to the fact that three material characteristics are used and the addition of damage and softening parameters in one of the phases.

The strain distributions which are found in the RVE during the bending process with the use of damage are very similar to the strain distributions found during the simulations without damage and softening. The shear bands which arise during the bending process appear in the same locations within the RVE. Also the pattern in the roughness of the surface is similar to the patterns which are found during the simulations without damage and softening. Therefore, the simulations including damage and softening within the sheet are less dependent on the mesh size compared to the continuum simulation, where the location of localization is affected by the mesh size and the nonlocal parameter.

Although the strain distribution within the RVE does not significantly change with the addition of the damage and softening model, the problem with the discrepancies which arise due to the usage of different grain morphologies within the Voronoi diagram is still present. In fact the discrepancies have increased with the addition of the damage and softening model. The standard deviation of the former force at a former displacement of 8 mm has increased from 3.64 N/mm to 4.32 N/mm for Voronoi diagrams with 1000 grains. The morphology of the grains has an influence on the effect which the damage and softening have on the ferrite matrix.

Similar to the RVE simulation without damage, the discrepancy between the former force versus former displacement decreases when the number of grains within the RVE is increased. Due to the larger number of grains within the Voronoi diagram, the behaviour under the influence of damage and softening leads to a more consistent response. The susceptibility of the Voronoi diagram to be affected by one grain morphology is less. This corresponds to a lower standard deviation of the former force at a given former displacement. The simulations run with a total number of grains of 20000 show the lowest deviation of the former force at a force displacement of 7 mm with a value of 0.39 N/mm. This value is close to that found in the experiment, which had a standard deviation of the former force of 0.33 N/mm.

However, the degradation which is seen during the experiment could not be simulated easily with the use of a Voronoi diagram. The damage and softening are able to acquire a decreasing former force with increasing former displacement. The effect, which damage and softening causes, is similar to that caused during the continuum simulation. However, since the Voronoi diagrams with a low number of grains show variance between the different diagrams, the number of grains needs to be increased. The increase of the number of grains requires the mesh size to decrease in order to accommodate all the features of the grain boundaries. Therefore, the number of nodes and elements within the sheet increases, which
leads to longer calculation times needed for one simulation. As a result an optimization of the damage and softening parameters for the simulations with the use of an RVE is within reach.

9.4 Calculation time

The calculation time which is needed has a great influence on the optimization which can be done. When a simulation consumes a large amount of time, the optimization process for the bending experiment will utilize an even larger time to complete. This will significantly decrease the efficiency of the FE analysis. The number of nodes and elements has a big influence on the final time which is needed for a simulation to complete. The number of nodes and elements should therefore be as low as possible, to ensure an acceptable time for optimization of the damage and softening parameters.

The former displacement per step is an important factor on the calculation time, since the displacement increment is directly linked to the number of increment steps which is needed to complete a simulation. This is due to the total former displacement which is prescribed by the former displacement of the experiment, since the former should reach a total displacement of 10 mm for DP1000. The displacement increment also influences the outcome of the damage and softening model. The differences, of the damage development and former force versus former displacement, with different stepsize used during the simulations are caused by the fact that the degradation (ω) is kept constant during an increment step (Wisselink & Huëtink, 2008). The former increment which leads to an acceptable limit for the simulations with damage and softening is from an increment of 0.002 mm and smaller, this results in a simulation with 5000 increments or more.

The results of the continuum analysis for the optimization of the damage and softening parameters for a mesh size of 10 µm are obtainable in an acceptable timeframe. The optimization with over 200 different combinations of the damage and softening parameters takes approximately a 1000 hours to calculate. With the use of ten calculation units, the optimization takes less than five days to complete. This is within a timeframe which can be described as acceptable. However, due to the mesh dependency of the simulations, the results of the simulations show discrepancies when damage is used.

The simulations with a Voronoi diagram implemented in the sheet show a more consistent behaviour concerning the dependency of the strain distribution on the mesh size. However, it is seen that the Voronoi diagram itself causes differences in the material behaviour between different Voronoi diagrams during the bending process. The standard deviation of the former force versus the former displacement decreases for an increased number of grains in the Voronoi diagram. The impact on the time which is needed for a simulation to be calculated is significant, due to the increase of the nodes and elements to represent the features of the smaller grains. The optimization of the damage and softening parameters will therefore take approximately 30000 hours of calculation when four calculation units are used per simulation. Due to the use of more calculation units per simulation, the number of simulations which can run simultaneously is decreased by a factor four. This makes the use of a Voronoi diagram to represent the dual-phase material for the bending process not feasible with the calculation power currently available, due to the long calculation time which is needed.
10. Conclusions

Problems with the prediction of the bendability of dual-phase (DP) steels come to light with the use of forming limit diagrams for the bending process. A bending analysis with the use of a finite element (FE) analysis combined with a damage and softening model introduces possibilities to simulate the degradation of the DP steel. For the continuum FE analysis using a damage and softening model it was found that:

- The former force versus former displacement characteristic can be simulated well.
- The strain patterns which appear within the sheet show similarities to the patterns which are visible on the scanning electron microscopy (SEM) images.
- Damage and softening parameters can be found within a reasonable timeframe using an optimization process.
- The former displacement increment has an influence on the damage development in the sheet.
- The nonlocal parameter controls the extent of localization and with it the damage mode of the sheet.
- Damage and shear band formation are sensitive to differences in the mesh size where the highest plastic deformation takes place.

Bending analyses using FE software with an embedded Voronoi introduces new possibilities to simulate local mechanisms which are involved in degradation and crack formation during the bending process. For the FE analysis using an embedded Voronoi diagram it was found that:

- The embedded Voronoi diagram leads to similar strain patterns and strain localization compared to those found in SEM images.
- Addition of a second phase in a material changes the strain distribution and increases the maximum peak strain during bending.
- The strain pattern is imposed on the sheet by the Voronoi diagram and is not influenced by the mesh size.
- The maximum strain in the sheet accumulates in the softer ferrite phase near the martensite grains.
- The ferrite phase should show a stronger response in DP steel compared to an undeformed single phase ferrite, due to the geometrically necessary dislocations (GNDs).
- The highest strains in the Voronoi diagram do not have to be situated at the surface of the sheet contrary to the highest strains in the continuum simulation without damage and softening.
- Differences for different Voronoi diagrams in the former force versus former displacement response are more significant for a lower number of grains.

For the FE analysis using an embedded Voronoi diagram with a damage and softening model implemented it was found that:

- Localization of strains is seen in the same locations in a Voronoi diagram independent of the mesh size.
- Different Voronoi diagrams with a low number of grains show a high discrepancy in the former force versus former displacement, even more severe as simulations with an embedded Voronoi diagram without damage and softening implemented.
• Voronoi diagrams with a small mesh size due to a large number of grains can be susceptible to numerical problems and an early ending of the simulation.
• The time which is needed to complete an optimization of the damage and softening parameters will be too long to be effective, with the calculation power which is currently available.

11. **Recommendations**
• Better understanding of the geometrically necessary dislocations which make the ferrite phase stronger near phase boundaries and implementation in the finite element (FE) analysis.
• Increase the computation power by making use of graphics processing units (GPUs) instead of central processing units (CPUs) for faster optimization.
• Introduction of more phases in the representative volume element (RVE) so complex phase steels can also be represented.
• 3D Voronoi diagrams which will enable the simulation of more complex bending geometries.
Reference list


