Study and Characterization of Localization and Failure Behaviour of Ultra High Strength Steel

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Licentiate Thesis
Preface

The work presented in this thesis has been carried out at the Division of Solid Mechanics, Department of Applied Physics and Mechanical Engineering at Luleå University of Technology in Luleå, Sweden. The work has been financially supported by Vinnova, Gestamp R&D (G R&D) in Luleå, Sweden and Ford Forschungszentrum Aachen GmbH (FFA) in Aachen, Germany. I would like to give a grateful acknowledgement for their financial support to this project.

A special thanks to project leader Daniel Berglund, G R&D, for his guidance through the work and for playing an important role in that I even applied for this position. Further, I would like to thank the representatives at FFA, Dr. Horst Lanzerath and Aleksandar Bach for many rewarding discussions.

I would also, of course, like to say thank you to my supervisor Dr. K-G Sundin and to my assistant supervisor Professor Mats Oldenburg for their help and guidance through the project, wouldn’t have made it without you. My gratitude also goes out to all my present and former colleagues at the division of Solid Mechanics.

Finally I would like to thank my family, my friends and, of course, my beautiful girlfriend Cecilia for always being there when I need them.

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Jesper Eman
Abstract

In the vehicle industry there is a constant struggle to develop cars with high passive safety without increasing the fuel consumption. High passive safety requires a very stiff behaviour of the crash protecting components. Accomplishing this often leads to an increase in the weight of the components. An increase in weight results in a higher fuel consumption which is bad for the environment as well as for the economy of the car owner, therefore the manufacturers turn to new materials. One of these new materials is ultra high strength steel which is the material in focus for the present thesis. To be able to utilize all the advantages of ultra high strength steel the material behaviour must be investigated in detail. In this thesis, sheets of ultra high strength steel, which are produced by press-hardening, are investigated using a method called digital speckle photography (DSP). When using the method of digital speckle photography a series of photographs are taken of a deforming specimen. Prior to the experiment a random pattern (speckles) has been applied to the specimen and by studying the deforming speckle pattern on the images, the deformation fields at different time instants can be established. Within the present thesis the deformation fields up to the point of fracture have been investigated on a length scale of the order of $10^{-4}$ meters. With length scales of this magnitude the deformation inside a localized neck can be investigated. This is done, both for a specimen shape that induces a fracture initiation at an inner point of the specimen and a specimen shape where fracture starts from the edge of a hole. These investigations show that there is a strong localization of the strain before fracture is initiated. The local strain values inside a neck are significantly higher than the strain values that can be observed with conventional experimental techniques involving extensometers. It is also noticed that the method used to make holes play an important role for the onset of fracture. Some methods hardly affect the material at all while others can decrease the level of local strain at the onset of fracture down to about a third of the value for unaffected material. Furthermore, a method for characterizing the material based on full-field measurements is presented. The method is a fast and simple alternative to previously used inverse modelling procedures where the material parameters of a finite element simulation is updated iteratively to make the simulation produce the same results as the experiment.
Thesis

This thesis consists of the following papers;

Paper A

J. Eman, K-G. Sundin and M. Oldenburg, “Spatially resolved observations of strain fields at necking and fracture of anisotropic hardened steel sheet material”
To be submitted for publication

Paper B

J. Eman, “Fast method for material characterizations including post-necking behaviour from full-field measurements”
To be submitted for publication

Paper C

J. Eman, K-G. Sundin, “Fracture strains at holes in high-strength steel, a comparison of techniques for hole cutting”
Accepted at International Conference of Experimental Mechanics 13 (ICEM13) in Alexandroupolis, Greece in July 2007
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1 INTRODUCTION
The work conducted in the present thesis has been carried out at the Division of Solid Mechanics, Department of Applied Physics and Mechanical Engineering at Luleå University of Technology (LTU). The studies are part of a collaboration project including representatives from the Division of Solid Mechanics at LTU, Gestamp R&D in Luleå, Sweden and Ford Forschungzentrum Aachen GmbH in Aachen, Germany.

1.1 Background
The public demands on the automotive industry has in recent years focused more and more on high passive safety and low fuel consumption. Lowering the fuel consumption is not only an economical but also an environmental issue. To achieve low fuel consumption the weight of the car must be kept as low as possible. However, a low weight counteracts the demands on high passive safety since this requires a very strong behaviour of the crash protecting structure. To avoid compromising between safety and fuel efficiency, manufacturers have lately been increasing their use of advanced materials such as hardened steel, aluminium and magnesium alloys and in more exotic cases even carbon fibre reinforced composites. Materials like these can increase the stiffness of crash protecting structures as well as increase the energy absorption of deformation zones in a crash situation without affecting the weight of the vehicle in a negative way. In order to achieve the highest output of the materials regarding weight and structural qualities, the components must be designed in a way that utilizes the material properties to their full extent. In short, this means that the components, in a crash situation, should be allowed to deform without fracturing. During deformation, energy is absorbed by the components, reducing the forces experienced by the people inside the car. Fractures, on the other hand, might cause the components to lose their load bearing capability which, for instance, could result in intrusion of objects into the passenger compartment, therefore fractures must be avoided.

Computerized design of crash protecting components is commonly used, because of the cost effectiveness. Simulations have more and more been replacing structural testing which nowadays, more or less, is used only as a validation of the simulations at the end of the development process. The simulation method most widely used to analyze structural behaviour is the finite element method (FEM). An analysis using FEM, often referred to as finite element analysis (FEA), is a numerical solution of a mathematical model of the structural behaviour. This
means that the solution is never more accurate than the model permits. These models describe the material behaviour, the geometry of the component to be investigated, the loads applied to the component and so on. Among these, the most complex problem is how to model the behaviour of the material. The material behaviour, i.e. the relationship between the stresses and the strains, is described with constitutive equations which are non-linear and varying in complexity. Even if complex constitutive equations can predict the structural behaviour with a satisfactory precision, the problem of determining the appropriate model parameters still exists. Determining these parameters requires an intimate knowledge of the material behaviour. By considering detailed experimental investigations such knowledge can be achieved.

1.2 Objective and scope
The present thesis is a part in an ongoing project with work-name “Optimum use of ultra high strength steel”. As the name implies, the objective of the project is to create tools for product developers that allow them to optimally use the material properties of ultra high strength steel. It should also be mentioned that the project is concerning sheet metals used in crash protective structures. The main focus of the project is on predicting the onset of fracture in base material, near edges and at spot welds. In the work, characterisation of the material is performed by observing material behaviour with highly resolved full-field measurement techniques. Furthermore, the dependency of different length scales, both in the measurement and the simulations, are considered.

Within this thesis the work is limited to observing and characterizing the base material and the material near edges.

2 MECHANISMS OF DEFORMATION
In this chapter the mechanisms of metal deformation in general and sheet metal deformation in specific are briefly discussed. The purpose is to give the reader a basic understanding of how metals are built up and how they react when they are loaded.

2.1 Microscopic structure of metals
When observing a metal in its solid state on an atomic level, the atoms are not positioned randomly. Instead they are closely packed in different crystal structures with a very regular atomic arrangement. In a macroscopic piece of metal there is a mixture of different crystals oriented randomly. These crystals develop during the cooling process of the melted metal where the nuclei of the
crystals are first formed. Each crystal then grows from one of those nuclei and the growth is limited by the surrounding crystals. The types of crystals formed and the appearance of the mixture is determined by the cooling process.

When these crystals are grown they enclose certain defects. These could for instance be missing atoms in the crystal lattices, zones of foreign atoms, micro-cracks and edge and screw dislocations. The two latter are illustrated with models in Figure 1. In Porter and Easterling[1], the microstructure of metals is further described.

*Figure 1. Models of edge (a) and screw (b and c) dislocations (Prasad [2]).*

The defects mentioned above may all appear within the material. Due to the cutting procedure used, different defects and irregularities might also emerge at the edges. These could for instance be micro-cracks, rough edges, heat affected zones and residual stresses.
2.2 Macroscopic behaviour of metals

When deformations of metals and most other materials as well, are discussed, one often talks about two types of deformation, elastic and inelastic (plastic). At low stresses the deformations are elastic. During this phase the observed macroscopic effects of loading are results of changes in the inter-atomic distances. As long as the deformations are purely elastic, the original shape of an object is recovered once the loads are removed. Plastic deformation which occurs at higher stresses is a result of changes in the dislocations inside the crystals and crystals moving relative to each other. The dislocations can under certain stress situations start to move through the crystals resulting in macroscopic changes of the geometry. These changes of the geometry are permanent and do not vanish when the load is removed.

To introduce the reader to the rest of the work some terms regarding the deformation of sheet metals are explained. This is done by describing the different stages of a tensile test of a straight specimen, a schematic picture of these stages is found in Figure 2. It should be mentioned that the stages described here are not general for all cases but they are typical for the material in focus in this work. In the first stage the deformation is uniform over the specimen and purely elastic, in the next phase the deformation becomes plastic but it remains uniform over the specimen. After this a neck is formed on the specimen in the direction of the width, this is called diffuse necking. The last stage before fracture is characterized by a neck forming in the thickness direction of the specimen; this process is referred to as localized necking. The diffuse necking has a length in the same order of magnitude as the width of the specimen and the localized necking has a length comparable to the thickness of the specimen.

Once a localized neck has been initialized, all subsequent straining is confined to the region of the neck. This means that the strain in that region will increase rapidly, leading to a fracture of the specimen. Edges play an important role for the instant of fracture. Because of the defects that can be found near the edges the fracture strain can be significantly reduced in these regions. The reduction of the fracture strain is highly dependent of the type of process used to cut the edge. Some processes hardly affect the material at all while others can reduce the fracture strain down to about a third of the one in unaffected material.
In this section, different experimental techniques are briefly discussed and the technique used in this work, digital speckle photography, is explained in more detail.

3.1 Overview of techniques

The most common method to investigate the behaviour of a material is to perform standardized tensile tests. A uniaxial load is applied to the specimens and recorded simultaneously with the extension of an extensometer. The specimens used are normally round bars or thin sheets with a rectangular cross-section. The extension of the extensometer is divided by its initial gauge length to yield the (engineering) strain. This method requires a uniform deformation field, i.e. once a neck is initiated the local strain is underestimated. There are however methods described by for instance Bridgman [3] and Zhang [4] to approximate the real strain.

There are also a number of compression tests where the specimen is exposed to compression instead of tension. These are most commonly used in high strain-rate testing such as the split Hopkinson bar described by Kolsky [5], where a piece of the material to be investigated is positioned between two bars. A projectile is then launched against one of the bars and by observing the wave propagation through the system, the behaviour of the material when subjected to high strain-rates can
be determined. In this work, focus is on the quasi-static behaviour of the material which is why high strain-rate testing is not further discussed.

In recent years a number of full-field measurement techniques have emerged. These techniques do not rely on an assumption of uniform deformation; instead they measure the deformation over the whole or a region of the specimen. Thereby, heterogeneous strain fields can be investigated and the geometry of the specimen can be designed more freely. There are a number of different full-field measurement techniques available, these can be divided into interferometric and non-interferometric techniques. Among the interferometric techniques there are, for instance, Moiré interferometry and electronic speckle pattern interferometry. The non-interferometric methods contain, for example, geometric Moiré techniques and speckle photography which is the type of method used in this work. The full-field experimental techniques mentioned are closer described by Grédiac [6].

3.2 Digital speckle photography

The method used in this work to monitor the deformation fields is called digital speckle photography, often referred to as DSP. DSP is based on a technique called digital image correlation which in this case is used repeatedly to achieve information about the deformation fields throughout an experiment. When applying the technique of digital image correlation, two images of a specimen with a random pattern (speckles) are compared. One of the images is acquired before deformation and the other one after. Within the first image a number of sub-images are defined, which, due to the randomness of the speckles, will have a unique pattern. The pattern of each sub-image is then searched for in the second image by a cross-correlation algorithm. The coordinate where the correlation coefficient is the highest is taken to be the new position of the original sub-image. Since the original coordinates of the sub-images are known the displacements can be achieved, yielding the entire displacement field. By taking a number of images of a speckled specimen during a tensile test, digital image correlation can be carried out several times producing the displacement fields over time. The displacement fields can be differentiated, yielding the in-plane strain fields. Digital image correlation is described in detail in for instance Kajberg and Lindkvist [7], Watrisse [8] and Tong [9]. The accuracy of the method is discussed by Sjödahl [10, 11].

The experimental setup involves a servo-hydraulic testing machine, a cooled CCD (charged coupled device) camera mounted in front of the specimen with the lens
axis perpendicular to the speckled surface and a computer for storing the images and evaluating the deformation fields. A schematic picture is found in Figure 3.

![Experimental Setup](image)

*Figure 3. The experimental setup used in digital speckle photography.*

## 4 PRESENT STUDY

The work carried out within this thesis is presented in this section. The material subject to the study is closer described and issues investigated are discussed.

### 4.1 Material

The material studied in this thesis is boron steel blanks that are treated in a press-hardening process. In this process, which is often referred to as hot-stamping, a hot blank (~900 °C) is simultaneously formed fixed and quenched between cooled tools resulting in a martensitic ultra high strength steel. The definitions for an ultra high strength steel is a tensile strength larger then 700 MPa [12]. The hot-stamping process enables complex shapes of hardened material to be manufactured rationally. In order to produce flat sheet material for the tests, flat tools are used. From these flat sheets of ultra high strength steel, specimens are cut out using water abrasive cutting. This technique is used since it is known not to have a significant influence of the material in the proximity of the edge regarding heat affects, micro-cracks etc.
4.2 Issues considered and work methodology

The main objective with the project is to be able to characterize the behaviour of the material beyond the onset of diffuse and localized necking. By doing this the failure criterion used in simulations can be pushed closer to the true onset of fracture. Currently used criteria are set to be conservative to make sure that no fractures are overlooked in the simulations. The difficulties in predicting the behaviour after necking in general and after localized necking in specific are caused by that these phenomena occur on a length scale much smaller than that of conventional measurements. Further, the simulations of localized necking are very sensitive to the element size of the finite element simulations. The reason for this is that elements commonly used in industrial analyses are too large to resolve the neck. This results in that very different post necking behaviours are obtained for different element sizes depending on how well the neck is resolved by the elements. Large elements are used in product development to decrease the simulation time. Another feature that needs to be investigated is the anisotropy of ultra high strength steel. When conventional measurements are performed, specimens cut out along the rolling direction show up approximately the same behaviour as specimens cut out perpendicular to the rolling direction. However under certain conditions when the deformation is concentrated to a small region, for instance in bending tests, there are large differences between the two directions. The reason for this is believed to be differences in the post necking behaviour.

Conventionally material is characterized by measurements on a large length scale; often extensometers with a gauge length of 50 mm are used. From these measurements the material characteristics to be used in simulations employing elements with a size of a few millimetres are developed. Measurements on these large length scales do not give any information about what is taking place on a small length scale, for instance in a localized neck. By carrying out measurements and studying the behaviour of the material on a length scale smaller than conventional elements (a few millimetres) the post-necking behaviour is observed and the material can be characterized up to the onset of fracture. The problem of predicting the necking behaviour using different element sizes is believed to be best handled by adapting the parameters of the constitutive model for the specific element size. That is, to use different material parameters for different element size. This would require a methodology for extracting material parameters adapted to a specific element size from the small scale measurements.
There are methods available for extracting material parameters from full-field measurements. These are commonly based on updating a finite element analysis until it matches the measurements, this procedure is quite complicated and, above all, it requires a lot of CPU-time [7]. The complexity of this procedure and the time required to carry it out makes it unsuitable to use for running material characterizations in an industrial process. Therefore a new simplified methodology for extracting material parameters from detailed full-field measurements is developed in this work.

4.3 Experimental program

Within this thesis two different specimen geometries have been investigated. The first one has been developed to be able to study the onset of fracture at an inner point of the material and the second one for examining the onset of fracture at the edge of a hole. These two geometries can be observed in Figure 4; (a) shows the specimen geometry where fracture occurs at an inner point while (b) shows the one where fracture takes place at the edge of a hole.

![Figure 4. The geometry of the two specimens used in the investigation, fracture at an inner point is studied in (a) and fracture at the edge of a hole is studied in (b).]
To explore the anisotropy of the material the specimens with the geometry of Figure 4 (a) have been cut out in different directions, 0, 45 and 90 degrees, to the rolling direction of the steel sheets. The specimen in figure Figure 4 (b) is cut out at 90 degrees to the rolling direction since this is the worst case.

In the investigation of fracture that emanates from the edge of a hole, three different hole making procedures are tested. These are pre-punching, post-punching and laser-cutting. A pre-punched hole is punched in the blank before it is heated, post-punching and laser-cutting means that the holes are punched and laser-cut after the material has been hardened.

Two different thicknesses have been studied, 1.2 and 2.4 mm.

4.4 Summary of experimental results

4.4.1 Base material

During the observations of the specimen in Figure 4 (a), the focus has been on studying the plastic localization leading to fracture. The effects of different length scales of the measurement, the growth of the neck and the anisotropic behaviour of the material have been studied. When different grid resolutions are used in the DSP-measurements it is clear that the maximum equivalent plastic strain depends on the chosen resolution. Decreasing the length scale leads to a higher observed maximum equivalent plastic strain until a length scale that can fully resolve the localized neck is reached. Reducing the length scale even more than this is unnecessary. This can be seen in Figure 5 where the normalized equivalent plastic strain along a line in the centre of the specimen is shown for different length scales. The length scale of the experimental grid is monotonically decreasing, yielding an increasing maximum equivalent strain (solid lines). The dashed line is however the result of the smallest length scale. Yielding a lower maximum equivalent strain than the second smallest length scale, it shows that a resolution that is high enough has been achieved. This resolution is about one tenth of the thickness of the sheet material.
Figure 5. Strain profiles with different length scale of the experimental grid.

Studying the growth of a neck throughout a tensile test, Figure 6, it can be observed that the plastic strain is localizing to a smaller and smaller region.

Figure 6. The growth of a strain profile observed through time.

The anisotropic behaviour of the material is clearly visualized by showing the equivalent plastic strain of the point of maximum strain throughout a tensile test. This is done in Figure 7 where it is seen that the specimens cut out perpendicular to the rolling direction show a significantly lower equivalent plastic strain at the onset of fracture than the specimens cut out along and diagonal to the rolling direction.
Figure 7. The equivalent plastic strains observed in the point of maximum strain throughout a tensile test.

### 4.4.2 Edges at holes

The results from the observations of hole-edges are best summarized with a table showing the fracture strains for different types of holes, Table 1. As mentioned, two different thicknesses are investigated, 1.2 and 2.4 mm. In the 1.2 mm specimens, holes with diameters of 4 and 8 mm are machined while only 8 mm holes have been produced in the 2.4 mm specimens. The results have been normalized with the fracture strain of an inner fracture in a 1.2 mm sheet, ($\varepsilon^*$).

<table>
<thead>
<tr>
<th>Specimen description</th>
<th>Normalized local fracture strain $\varepsilon_{\text{max}}/\varepsilon^*$</th>
<th>#1</th>
<th>#2</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>t [mm]</td>
<td>D [mm]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-punched</td>
<td>1.2</td>
<td>4</td>
<td>0.875</td>
<td>0.991</td>
</tr>
<tr>
<td>Laser-cut</td>
<td>1.2</td>
<td>4</td>
<td>0.391</td>
<td>0.525</td>
</tr>
<tr>
<td>Post-punched</td>
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<td>4</td>
<td>0.327</td>
<td>0.286</td>
</tr>
<tr>
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<td>0.939</td>
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</tr>
<tr>
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<td>0.851</td>
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<tr>
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<td>-</td>
<td>0.971</td>
<td>0.729</td>
</tr>
</tbody>
</table>

Table 1. Fracture strain of different types of holes normalized to the fracture strain at an inner fracture in a 1.2 mm sheet material.
In Table 1 it can be observed that there are significant differences between the different hole making procedures. The pre-punched holes show up a fracture strain that is almost as high as the one for unaffected material. Compared to the pre-punched holes, laser-cut and post-punched holes show up a fracture strain that is significantly reduced. The fracture strain of laser-cut holes is approximately half of that of pre-punched holes. Post-punched holes are even worse with a fracture strain of about one third of the fracture strain of pre-punched holes.

4.5 Method for characterizing materials from full-field measurements

4.5.1 Background and theory

As mentioned earlier there are currently available methods for extracting material parameters from full-field measurements. The most commonly used methods rely on updating the material parameters of a simulation until it produces results that within certain tolerances are the same as the ones measured in an experiment. These methods are however too complex and time consuming to use for running material characterizations in an industrial process, especially if several sets of parameters should be extracted for different element sizes. By employing a few simplifications and limitations a faster and simpler method for characterizing material from full-field measurements is suggested.

When a finite element analysis is updated iteratively to match the results of an experiment, the strain field is computed over and over again by the simulations until it corresponds well to the strain field observed in the experiment. This part is actually superfluous since the correct strain field is already known from the measurement. By making use of this fact, the FE-analysis can be replaced with a more simple procedure computing stresses from strains and an assumed stress-strain relationship. This procedure is called the radial return algorithm (described by Belytschko et al [13]) and it is able to compute a full stress tensor if a full strain tensor and a material model is available. From the full-field measurements only the in-plane strain components are available. To be able to compute the stresses from these, some assumptions need to be made, namely that plane stress applies and that the out-of-plane shear is negligible. These assumptions are simplifications, especially after the onset of localized necking when the true stress state is triaxial. The errors that occur because of this simplification should however be relatively small as long as the extracted material parameters are used in a finite element analysis employing shell elements since these also utilize a plane stress assumption. It should be noted that the suggested method does not produce the true material characteristics in a three dimensional sense but the
material parameters that, when used in a shell element model yields a result that predicts reality with a satisfactory precision.

The method uses the fact that every cross-section of a specimen under tension must carry the total load applied to the specimen. Since the strains can be measured over the entire cross-section of a specimen in a tensile test, the stresses can be computed in the same region by using the assumptions mentioned above and an assumed stress-strain relationship. Integrating the stress component in the tensile direction over the cross-sectional area of the specimen yields the load that is experienced by the cross-section. By iteratively varying the stress-strain relationship until a load that matches the one in the experiment is achieved, the correct material parameters for a shell element model can be extracted.

The nature of the radial return algorithm is such that it only allows positive slopes of the stress-strain relationship; this requirement is also found in most finite element codes. If the behaviour of the material is such that a stress-strain relationship with a slope that is almost zero produces a load that is larger than the correct one, a damage function must be used to correctly characterize the material. A damage function is a function of a parameter that reduces the load bearing capability of the material, a damage parameter of, for instance, 0.1 reduces the load bearing capability of the material with 10 percent compared to the undamaged material.

4.5.2 Results

In order to validate the method a synthetic set of experimental data is created by running a finite element analysis with a known set of material parameters. From the analysis, data equivalent to that of an experiment is extracted. By using this data in the method, the material parameters first put into the finite element analysis can be reproduced to a high accuracy. This can be seen in Figure 8 (a) where the circles represent the extracted material characteristics and the lines represent the stress-strain relationship and the damage function first put into the finite element analysis. To investigate the sensitivity of the method to random errors in the measurement, the synthetic set of experimental data is distorted with three different standard deviations, 0.25, 0.50 and 0.75 percent. For each of these standard deviations ten sets of material parameters are extracted by using the method, the scattering of these can be observed in Figure 8 (b), (c) and (d), respectively.
Furthermore, a set of experimental data from a real physical experiment have been used to carry out a material characterization with the method. The material in focus is a press hardened, ultra high strength steel and the full-field measurement technique used is digital speckle photography. In Figure 9 the material parameters extracted by the method are presented as circles. To be able to use these parameters in a finite element analysis, both the stress-strain relationship and the damage function must have a non-negative slope. The slope of the stress-strain relationship is because of reasons explained earlier always positive which is why it can be directly used in an FE-analysis. For the damage function there is however no restrictions when the material parameters are extracted. To make sure that the slope is always positive when using it in the finite element method, a fourth degree polynomial is adapted, using least squares, to the points of the damage function after the onset of damage. The material parameters to use in the finite element simulations are presented with lines in Figure 9.
Figure 9. The material parameters produced by the method when characterizing an ultra high strength steel from a full-field measurement.

These material parameters are used in a finite element analysis of the specimen that the full-field measurement is made upon. The load-extension curves and the instant of fracture of the analysis and the experiment are then compared to validate the method. As fracture criteria in the analysis, the equivalent plastic strain in the last image before fracture is used. The curves can be seen in Figure 10 where the fully drawn line is the experiment and the dash-dotted line is the simulation. There is a discrepancy near the end of the tensile test. The reason for this is believed to be that the simulation is almost perfectly symmetric while this is not the case for the experiment. In the experiment one of the shear bands will dominate after the onset of localized necking while they will develop simultaneously in the simulation. To test this hypothesis a simulation of a slightly distorted (two nodes have been displaced 0.2 mm) is carried out. The load-extension curve of this simulation is presented as a dotted line in Figure 10 and it can be seen that the discrepancies are significantly reduced.
5 SUMMARY OF APPENDED PAPERS

5.1 Paper A
In paper A the plastic strain localization, also referred to as necking, of press-hardened ultra-high strength steel is observed using detailed full-field measurements. The region of the neck is studied during tensile tests of specimens specially designed to yield strain localization at an inner point of the material, thus isolating the deformation and the subsequent fracture from edge effects. By using measurements with a length scale small enough to properly resolve the neck, its growth and shape can be studied. Furthermore, the anisotropy of the material is investigated by examining specimens cut out at different angles to the rolling direction. It is seen that the local fracture strain of specimens cut out along the rolling direction is approximately twice as high as the local fracture strain of specimens cut out perpendicular to the rolling direction.

5.2 Paper B
In paper B a method for characterizing material based on full-field measurements is suggested. The method is developed to be a fast and simple complement to previously used inverse methods. In these methods a finite element simulation of an experiment is carried out repeatedly with different material parameters until the behaviour of the simulation matches the experiment. This process is very time consuming because of the repeated simulation of the complete experiment. In the suggested method the stresses are instead computed directly from the measured...
strains by using the radial return algorithm and an assumed material behaviour. By computing the stresses in a number of points along a line crossing the specimen, the load experienced by the specimen can be calculated and compared to the one recorded in the experiment. The squared difference between the computed and the measured load is used as an objective function to optimize the material behaviour. The full-field measurement technique used, yields in-plane deformation fields. In order to be able to compute the full three dimensional stress and strain tensors, the assumption of plane stress is made. This assumption makes the material characteristics produced by the method most suited for use in finite element simulations employing shell elements since these also assume plane stress.

5.3 Paper C

In paper C different hole making procedures are compared by using detailed full-field measurements. The material is press-hardened ultra-high strength steel. Three different hole-making procedures have been studied; punching before heating, punching after quenching and laser-cutting after quenching. The behavior of the material has been recorded by the method of digital speckle correlation. This method measures highly resolved displacement and strain fields in the specimen until fracture. From these fields, differences in strain at fracture between the hole making procedures can be determined. The main result of the study is that the method with holes punched before heating show a significantly higher resistance to local strain than the other two methods.

6 CONCLUSIONS AND FUTURE WORK

Within this thesis digital speckle photography is used to carry out detailed full-field experiments of press-hardened ultra-high strength steel. From the steel sheets different types of specimens have been machined using water abrasive cutting. These specimens have been loaded in tension while observing the deformation fields.

In the first type of specimen, plastic strain localization at an inner point of the material is investigated in order to isolate the material behaviour from edge effects. The region of localization, also referred to as the neck, is studied during the tensile test. By varying the length scale of the measurement, the length scale needed to properly resolve the neck can be determined. The necessary resolution is established to be approximately 1/10 of the thickness of the sheet material. By using the established length scale both the growth and the shape of the neck can be studied throughout a tensile test. Further the anisotropy of the material is
examined by performing measurements on specimens cut out in different directions to the rolling direction. It is shown that the fracture strain measured locally is about twice as high for specimens cut out along the rolling direction than for specimens cut out perpendicular to the rolling direction.

The second type of specimen includes a hole from where the fracture emanates. This is to investigate the influence of different hole making procedures. Three different procedures are studied, punching the hole before the hardening process (pre-punched), punching the hole after the hardening process (post-punched) and cutting the hole with laser after the hardening process (laser-cut). It can be seen that there are large differences in the fracture strain between the different types of holes. The fracture strain at pre-punched holes is almost as high as the fracture strain of the material unaffected by edges. The laser-cut and post-punched holes however show a significant reduction of the fracture strain. Compared to the pre-punched holes the laser-cut holes have a fracture strain of about half while the post-punched holes show up a fracture strain of about one third.

Furthermore, a method for characterizing material based on full-field measurements is proposed within this thesis. The method is a fast complement to previously used inverse techniques involving a finite element analysis whose material parameters are updated until the results of the simulation match the results of the experiment. The suggested method uses the fact that the strains are already known; hence they do not need to be computed by a finite element analysis. Replacing the simulation with the simpler radial return algorithm requires some simplifications but saves a lot of time. Material parameters can be produced within a few seconds once the results of a full-field measurement are available. Tests of the method show that the resulting material characteristics are reliable and possible to use as in-data in the finite element method.

In an extension to this work investigations could of course be performed on different types of material and in heat affected zones such as spot welds. It could further be imagined that the DSP method is used to observe other loading conditions than the uniaxial one. To be able to fully characterize the material, loading conditions like shearing, biaxial stress and plane strain would be of interest. It would also be interesting to investigate the material at high temperatures and at high strain-rates. Ultimately, combinations of different temperatures, loading conditions and strain-rates are desirable.
7 REFERENCES


Paper A
Abstract

In this work the plastic strain localization, also referred to as necking, of press-hardened ultra-high strength steel is observed using digital speckle correlation. The region of the neck is studied during tensile tests of specimens specially designed to have strain localization at an inner point of the material, thus isolating the deformation and the subsequent fracture from edge effects. By using measurements with a length scale small enough to properly resolve the neck, its growth and shape can be studied. Furthermore, the anisotropy of the material is investigated by examining specimens cut out at different angles to the rolling direction. It is seen that the local fracture strain of specimens cut out along the rolling direction is approximately twice as high as the local fracture strain of specimens cut out perpendicular to the rolling direction.

Introduction

Plastic forming of ductile sheet metal is a very common activity in for example today’s automotive industry as well as in other mechanical applications. Also in unintentional situations such as collisions, sheet material is subjected to plastic deformations. In the beginning of the plastic process at low strain levels the state of strain is generally smooth but after this initial stage the developing strain is often localized to a narrow area. This localization is called necking and it is the prelude of fracture because a crack is ultimately formed in the neck. The most well known example of plastic localization is perhaps the forming of a neck towards the end of a standard tensile test.

The localization of strain to a limited region results in a rapidly increasing strain level within this region. This increase in strain will ultimately lead to the onset of fracture which in all practical situations is an unwanted scenario. The industry however wishes to be able to use the materials to their limits, that is, deform them as much as possible without causing a fracture. Because of this, it is of great
interest and importance to widen the knowledge and understanding of the phenomenon of necking.

Within the automotive industry crash-protecting components such as A- and B-pillars, bumper beams and side impact protections are often made from ultra-high strength steel. The purpose is to save weight and at the same time keep a very strong behaviour of the structures. In order to save even more weight, larger structures of the vehicles could be made from this type of material. However, this requires a very detailed knowledge of the behaviour of the material, also regarding necking and fracture.

The phenomenon of localized necking has been studied for a long time. One goal is to determine the entire true stress-strain relation for a material up to fracture [1-8] which is of importance for accurate simulation of large-strain applications. In sheet forming processes forming limit diagrams (FLD) are often used to predict local necking and subsequent fracture and the establishment of such diagrams includes study of the necking phenomenon under more general conditions than the conventional uniaxial tensile test. Analytical background for FLD theories can be found in e.g. [9-13] and some recent experimental work is reported in [14, 15].

Experimental techniques have developed rapidly during the last decade and the trend towards optical field methods is strong. An example of an older experimental work based on conventional microscopic observations of the metallographic structure during deformation is given in [16]. Examples of modern methods used in observations of plastic deformation and necking behaviour are [14, 15, 17-25]. It seems that digital speckle correlation (DSC) is perhaps the most commonly used full-field experimental method for studies of plasticity. This is explained by the fact that it has come out from the optics lab and it is fairly simple to use also by investigators who are not experts in optics. It is also commercially available nowadays. This method is reviewed and evaluated in [26-28] and some good examples of its application can be found in [15, 22, 29].

DSC is used in the present study with focus on investigation of the nature of necking appearing in ultra-high strength steel under tension. The region of the neck is observed in detail at a number of time instants throughout a tensile test of a specimen. This enables studies of both the growth and the shape of the neck. Strain components in the neck region are followed during the tensile process. Proper measurements of the necking phenomenon require the length scale of the
measurement to be small enough so that the neck is sufficiently resolved. The dependence of different length scales in the measurements is investigated.

In order to investigate the true behaviour of the material itself and not the influence from edges, a non-standard specimen shape is developed. The specimen shape is designed to produce plastic strain localization in the centre of the specimen. This causes the fracture to emanate from an interior point of the specimen, thus eliminating influence from edge effects. Also, the chosen specimen design allows the position of the fracture to be determined prior to the experiment and therefore the measurement can be focused to that region, thus enabling a higher spatial resolution.

Anisotropic behaviour regarding plasticity and fracture is common for rolled sheet material and proper understanding and modelling is essential in simulation of sheet forming processes [30-32]. DSC is a suitable method for experimental investigation of strains in different directions and their development during loading to fracture. Strains at the centre of the neck in specimens taken at 0, 45 and 90 degrees to the rolling direction are studied in this work. The material in the investigation is a press-hardened ultra-high strength steel.

**Experiments**

**Material and specimens**

The material chosen in this investigation is an ultra high strength steel (hardened 22MnB5) which is used in protective structures in cars. Anisotropy is introduced in the rolling process of the base material and simultaneous forming and quenching in water-cooled tools gives the material its strength properties. Components may be loaded in such a way that fracture will not emanate from an edge and therefore it is of interest to examine fracture behaviour at an inner point. Conventional tensile specimens (SS EN 10 002-1) with a straight part are unsuitable because the edge may influence the fracture process to a high degree through irregularities, micro cracks and heat effects from the cutting process. Further, the exact position of the final fracture is unforeseeable in such specimens and since local measurement in the area of plastic instability is the objective of this investigation, straight specimens were not used. Instead a specimen shape with a shallow notch is chosen. A varying cross section of the specimen will cause a non-homogeneous state of strain and stress but the location of the instability and subsequent fracture is possible to predict with high accuracy.
The suitable shape of the specimens was determined through an initial investigation involving FEM-simulations and experimental verification. A plausible stress-strain relation and fracture strain criterion, determined in earlier work, was used in the simulations and different specimen shapes were tested numerically through simulation of tensile loading to fracture. Shapes leading to localisation and fracture initiation in the inner part of the specimen are potential candidates for this research and specimens with shallow notches showed such behaviour. Lower fracture strain at the edges due to influence from cutting was not assumed in the simulation model and therefore the numerical results had to be verified by experiments. The final shape of the specimens that was chosen for the rest of the investigation is presented in Figure 1 a).

For reference, conventional tensile tests using straight specimens and an extensometer are performed. There is a slight modification to the standard straight specimen (SS EN 10 002-1). The sides are not exactly parallel but instead machined with a large radius to ensure that instability and fracture take place within the length of the extensometer. Geometries for both the notched and the straight specimen are presented in Figure 1.

![Figure 1. Specimen shapes a) with shallow notches and b) straight specimen.](image)

The conventional tensile testing of straight specimens according to Figure 1 b) is performed with an extensometer length of 50 mm. Specimens taken parallel,
perpendicular and in a 45° angle to the rolling direction are tested and stress-strain diagrams are presented in Figure 2. Tests are performed on both 1.2 and 2.4 mm thick specimens and each test is repeated two times. All specimens are cut from sheets that are hardened in a press between flat cooled surfaces. Abrasive water cutting is used for manufacturing of all the specimens and testing is performed in the as-delivered condition without further treatment.

**Experimental set-up and procedure**

Local strains are measured with the method of Digital Speckle Correlation (DSC), which is a multi-point or grid method giving strain data in a large number of points over the monitored area. Speckle patterns in the form of randomly distributed black and white dots were applied to the specimens with spray painting. The experimental arrangement, sketched in Figure 3, involves a 250 kN servo-hydraulic testing machine (Dartec M1000/RK, 250 kN) for loading, a CCD camera (PCO Sensicam) with a telecentric lens (Nikon Micro Nikkor 105 mm) mounted in front of the specimen and an ordinary PC for storing images and evaluating the displacement fields. Two ordinary filament lamps were used for illumination. The camera is fixed to one of the grips of the machine and its lens axis is perpendicular to the specimen plane (x-y-plane). Also an extensometer (Epsilon Technology Corp) with a 50 mm gauge length is used to monitor the elongation of the notched area of the specimen.

*Figure 2. Stress-strain curves for specimens taken at 0°, 90° and 45° to rolling direction. True stress versus true strain is displayed and the thickness is 1.2 mm.*
During the test the specimen is loaded in prescribed deformation mode in the x-direction at a constant deformation rate of 0.1 mm/second while the framing rate of the camera is two frames per second. A loading sequence to fracture of the specimen takes about 20 seconds and during that time typically 40 frames are recorded of the translating and deforming speckle pattern at the centre part of the specimen. To acquire an undeformed reference, the framing sequence is started before the tensile deformation starts. The field-of-view is chosen to 5×6 mm in order to get a good representation of the developing plastic localisation in the centre of the specimen. As the specimen is stretched, also out-of-plane displacement will occur, especially towards the end of the test when necking takes place at the centre. However, measurements using white light speckles are only moderately affected by out-of-plane displacements and the depth of focus is verified to be sufficient for the application.

For calibration of the spatial resolution of the images a known rigid body displacement (in millimetres) is imposed on the specimen while images are recorded before and after. The displacement field (in pixels) of the images is evaluated and the mean value over each image is used to compute the calibration factor between physical length and number of pixels.

Figure 3. Experimental setup for tension tests of speckled specimens.
Evaluation of displacement and strain fields

The displacement fields obtained from the DSC-method are determined by performing a cross correlation procedure on images captured before and after a deformation. The first image is divided into a number of small regions, called sub-images. Each of these sub-images has a unique speckle constellation due to the random pattern on the specimen. The cross correlation procedure searches over the second image for the same speckle constellation. The position where the correlation coefficient is the highest is taken as the new location for the sub-image. From the old and the new positions the displacements can be determined [19, 20, 26, 29, 33, 34].

It should be noted that the cross correlation procedure used here does not take into account any strain or rotation of the sub-images when their new positions are determined. Investigation of deformation fields involving large strains and/or rotation may therefore be insecure due to the decorrelation of the sub-images. As large strains are of interest in this investigation a sequence of images is recorded during the process and a stepwise developing displacement field is determined by repeated use of the correlation procedure on images from the sequence. The total displacement is then taken as the sum of the displacements in each step and the output of this procedure is the in-plane displacements $u$ and $v$ of the midpoints of the sub-images.

For the determination of the strain state a procedure based on polar decomposition of the deformation gradient is employed. The method is outlined below and the theoretical background can be found in text books such as [35, 36]. Similar schemes for computation of strains have been used in [19, 20, 29]. Generally in a Lagrangian description of deformation we have $x' = x + u(x)$ where $x'$ is the current position of a particle emanating from the position $x$ and $u(x) = (u(x,y,z) v(x,y,z) w(x,y,z))$ is the displacement vector. The deformation gradient $F$ is defined by

$$F = \frac{\partial x'}{\partial x} = \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} & \frac{\partial u}{\partial z} \\ \frac{\partial v}{\partial x} & 1 + \frac{\partial v}{\partial y} & \frac{\partial v}{\partial z} \\ \frac{\partial w}{\partial x} & \frac{\partial w}{\partial y} & 1 + \frac{\partial w}{\partial z} \end{bmatrix} \quad (1)$$

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In the present case it is a reasonable assumption that the values of $u$ and $v$ that are measured at the surface of the specimen represent the situation also at the midplane of the sheet implying that $u$ and $v$ are constant through the thickness and thus $\frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = 0$. Also $w(x,y) = 0$ in the midplane and therefore $\frac{\partial w}{\partial x} = \frac{\partial w}{\partial y} = 0$.

The upper left $2 \times 2$ matrix of (1) describes the deformation gradient in the x-y-plane and it is denoted $F_{2D}$. Polar decomposition of $F_{2D}$ yields

$$ F_{2D} = R_{2D} U_{2D} $$

where $R_{2D}$ is the proper orthogonal rotation tensor ($R_{2D}^T R_{2D} = I$) and $U_{2D}$ is the symmetric right stretch tensor ($U_{2D}^T = U_{2D}$). Then

$$ F_{2D}^T F_{2D} = (R_{2D} U_{2D})^T R_{2D} U_{2D} = U_{2D}^T U_{2D} $$

which is written

$$ U_{2D}^2 = F_{2D}^T F_{2D} $$

Now, spectral decomposition yields

$$ U_{2D} = \lambda_1 n_1 n_1^T + \lambda_2 n_2 n_2^T $$

where $\lambda_1$ and $\lambda_2$ are the square roots of the eigenvalues of the symmetric matrix $U_{2D}^2 = F_{2D}^T F_{2D}$ and $n_1$ and $n_2$ are the corresponding eigenvectors. The logarithmic (Hencky) in-plane symmetric strain matrix $\varepsilon_{2D}$ with components $\varepsilon_x$, $\varepsilon_y$ and $\varepsilon_{xy}$ is then computed as

$$ \varepsilon_{2D} = \ln(U_{2D}) $$

Assuming conservation of volume during plastic deformation, implies $\det F = 1$ which with equation (1) gives

$$ \left( 1 + \frac{\partial w}{\partial z} \right) \det F_{2D} = 1 $$

and the normal strain in the thickness direction is then computed as
\[ \varepsilon_z = \ln \left( 1 + \frac{\partial w}{\partial z} \right) = \ln( \text{det} \mathbf{F}_{in} )^{-1} \] (7)

So, from the DSP-measurements the displacements \( u \) and \( v \) are known for the experimental nodes corresponding to the midpoints of the subareas. In the next step the in-plane derivatives \( \frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial v}{\partial x}, \text{ and } \frac{\partial v}{\partial y} \) at each node are calculated approximately in a least square sense by applying a so called first order Savitsky-Golay filter [37]. The application of this method is described in [29] and consists of fitting first degree polynomials for \( u(x,y) \) and \( v(x,y) \) respectively to measured displacements of nine \( (3 \times 3) \) neighbouring nodes and assigning data for the polynomials (slopes) to the centre node of the \( 3 \times 3 \) nodes. Thus approximations of the derivatives are assigned to each experimental node. Next the strain components \( \varepsilon_x, \varepsilon_y, \varepsilon_{xy} \) and \( \varepsilon_z \) are calculated according to equations (1-7) and hence the current strains are computed for each experimental node and at each time step. Finally, with the strains known at each time step an equivalent plastic strain can be computed by adding increments according to

\[ (\varepsilon_{ep})_n = \sum_{k=1}^{n} (\Delta \varepsilon_{ep})_k = \sum_{k=1}^{n} \left[ \frac{2}{3} \left( \Delta \varepsilon_x^2 + \Delta \varepsilon_y^2 + \Delta \varepsilon_{xy}^2 + 2 \Delta \varepsilon_z^2 \right) \right]_k \] (8)

where for example \( \Delta \varepsilon_x \) is the change in the strain component \( \varepsilon_x \) between two time steps and \( n \) represents the time step for which the computation is performed. Equation (8) is an approximation in that out-of-plane shear components are assumed to be negligible which has been verified by FE-calculations in a similar situation in [29]. The strains produced by the calculation scheme described above in equations (1-7) represent Lagrangian logarithmic strains obtained in the experiments. Therefore, the equivalent plastic strain evaluated according to equation (8) corresponds to the so called true strain which is a familiar quantity from conventional tensile testing. The accuracy of the evaluated quantities is influenced by the accuracy of the correlation procedure and of the approximations in the strain calculations. An assessment of the uncertainties can be found in [29].
Results
Primary results from the experiments are the time-histories of the tensile force measured by the force transducer, the time-histories of the elongation measured by the extensometer and also the digital records of the speckled specimens taken at known time instants with equal intervals. An example of a plot of force versus elongation with marked instants for the photographic records is shown in Figure 4 a). From the speckle records the evaluation procedure briefly described above produces information of in-plane displacements \( (u, v) \) and of the strains \( (\varepsilon_x, \varepsilon_y, \varepsilon_{xy}, \varepsilon_z \text{ and } \varepsilon_{ep}) \) at different time instants during the plastic process. The experimental grid is defined by the chosen midpoints of the sub-surfaces, and strains are evaluated and presented at those points. A time-sequence of plots of for example equivalent plastic strain is produced and an example of three plots from such a sequence is shown in Figure 4 b) where the spatial distribution of \( \varepsilon_{ep} \) (normalized with the fracture strain for 1.2 mm and 0°) according to equation (8) is presented. These developing strain fields are studied in order to gain knowledge of the evolution of the necking process.

\[ \text{Figure 4. a) Force versus elongation  b) Normalized strain fields (} \varepsilon_{ep} \text{) at three time instants.} \]
First a study was performed with the intention to determine the spatial resolution necessary for observation and measurement of the inhomogeneous plastic strain associated with onset and progress of necking in the sheet material of interest. Different distances between sub-surface midpoints, defining the experimental length scale, were tried in the evaluation algorithm and the equivalent plastic strain $\varepsilon_{np}$ (equation 8) was calculated. Figure 5 shows profiles of $\varepsilon_{np}$ along the centreline of the specimen (x-axis) just before fracture. The profiles are evaluated for different spatial resolutions. Due to experimental uncertainty and the numerical differentiation involved in the evaluation process, noise is introduced in the strain data and the noise level increases with a decreasing experimental length scale. An optimum experimental length scale giving sufficient resolution but limited noise is desired and it is clear from Figure 5 a) and b) that an experimental length scale of about t/10 renders a sufficiently good representation of the main features of the necking. This resolution is used in all subsequent results. In Figure 5 c) the normalised strain profiles for both thicknesses are plotted in the same diagram versus the normalised x-coordinate for the experimental length scale t/10. The profiles are similar which indicates that the sheet thickness is the dominant length scale in the necking process.

The development of local strain with time during a tensile test can now be studied using the suitable spatial resolution t/10. In Figure 6, a time-sequence of strain profiles ($\varepsilon_{np}$) along the x-axis is presented for the 1.2 mm thickness.

![Figure 5. Strain distribution just before fracture for different experimental resolutions. a) 1.2 mm thickness, 25-60 pixels b) 2.4 mm thickness, 50-120 pixels c) both thicknesses, 25 and 50 pixels respectively corresponding to about t/10.](image)
One can observe from the strain profiles in Figure 6 that the localisation has a length scale of about 2t at the early stage but that the subsequent development of strain concentrates to the centre part of the localised area. At the last observation before fracture the strain ($\varepsilon_{ep}$) reaches its largest measured value. This maximum value for the 1.2 mm material in the 0° direction is used for normalisation of strains.

It is important to choose a suitable experimental length scale in order to study the spatial features of the necking process but it is also essential to recognise that the evaluated fracture strain will depend on the chosen experimental length scale. It can also be noted that the necking ultimately ends with the formation of one or more cracks at a very small area and the experimental length scale needed to study details of the actual crack formation is of course very small.

Results such as those presented in Figure 6 are produced for all combinations of the two thicknesses and the three directions. Two repetitions of each experiment were made and normalized values of measured fracture strains are presented in Table 1. Also, in the lower part of Table 1, mean values of the fracture strains for the conventional tensile tests measured with a 50 mm extensometer are presented for comparison. The same normalising value has been used for both the local and the conventional measurements.

Figure 6. Strain profiles through the localising area at different times. 1.2 mm thickness.
The value of the fracture strain is largest in the rolling direction and least in the 90 degree direction. The relations between the results for different directions are more differing for the locally measured strains than for the conventionally measured strains. This is an effect of the much smaller length scale in the case of locally measured strains. The local strains in Table 1 represent an experimental length scale of t/10.

The values in Table 1 reflect the situation just before fracture at the point where the fracture will occur before the next picture is taken. These values represent the fracture strain and are of great interest in for example design work in that they can be used to establish limiting strains in FEM-simulations with larger length-scales (element sizes). However, with this sequential field method in combination with the specimen design giving fracture at a predicted inner point, it is possible to follow the development of certain quantities at the critical point where the fracture originates through the plastic process. In Figure 7 normalised strains $\varepsilon_x$, $\varepsilon_y$, $\varepsilon_{xy}$, $\varepsilon_z$ and $\varepsilon_{ep}$ at the fracture point (for 1.2 mm and 0°) are plotted as functions of the extension of the 50 mm extensometer during a test. Also the applied external force $F$ is plotted.

<table>
<thead>
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<th>0 degrees</th>
<th>45 degrees</th>
<th>90 degrees</th>
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</thead>
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<td>1.026</td>
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<td>0.109</td>
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</tr>
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</table>

Table 1. Normalized maximum effective plastic strains measured on different samples and mean values of the fracture strains for the conventional tensile tests.
It is obvious from the curves in Figure 7 that the strain levels increase slowly in the early stages of the process but accelerate towards the end. This is caused by the localisation of the strain field towards the centre of the specimen, visualised in Figure 4 b). One can also note that the relation between the strains change during the test so that the increase in the shear strain \( \varepsilon_{xy} \) starts late in the process. The strain in the loading direction, \( \varepsilon_x \), is of course the dominating strain component throughout the test. Perpendicular to the loading direction the magnitude of \( \varepsilon_z \) is about three times larger than that of \( \varepsilon_y \) implying a faster decrease in the thickness direction. This is explained by the geometrical constraint that the notch causes in the y-direction. At the very end the magnitude of \( \varepsilon_y \) seems to become almost constant which is interpreted as the onset of the final stage in the localizing process when the thinning and the other in-plane strains accelerate towards fracture in the centre of the specimen.

The strains shown in Figure 7 are, in a sense, the main results of the experiments. However, from these also other quantities can be computed and analysed for the developing plastic process. In general, strain in any direction in the x-y plane can be calculated and in particular the principal strains in the x-y plane and the principal angle may be of interest. Since the strain state is known at different time instants during the plastic deformation it is also possible to evaluate and study rates of all quantities simply by time differentiation.

Some typical results for specimens taken in different angles to the rolling direction are shown in Figure 8. The development of the equivalent plastic strain
in the point of maximum strain for the three directions is shown in Figure 8 a). It is obvious that the strain level at a specific value of the extension is lower for the parallel direction than for the other directions. It is also clear that the fracture strain perpendicular to the rolling direction is much lower than for the other two directions. In Figure 8 b) the development of the principle angle in the sheet plane is presented for the different angles to the rolling direction. The principle angle is almost zero at the beginning of the tensile test but a deviation occurs later. This deviation is synchronous with the development of a preferred shear direction and it occurs earlier for the 90° direction than for the other directions. It is also noted that the principle angle at fracture is smaller for 90° than for 0° and 45°.

![Figure 8. a) Normalised effective plastic strains and b) principle angle versus measured extension for 0, 45 and 90 degrees. Thickness is 1.2 mm.](image)

**Conclusions and discussion**

A tensile specimen for sheet material testing has been designed to have plastic localisation and onset of fracture at an inner point, thus avoiding influence from cut edges on the fracture process. The shape is of dog-bone type but with shallow notches and therefore the strain state is not homogeneous so an optical method is utilized for monitoring of the developing strain state. From a sequence of digital photographs of the speckled surface of the specimen strains are computed at experimental nodes and at times when photographic records are taken. Hence, the measurements allow monitoring of the strain development both in space and in time.

Specimens of ultra high strength steel sheets, 1.2 and 2.4 mm thick, are cut in 0°, 45° and 90° to the rolling direction by abrasive water cutting. The development of necking, or plastic localisation, is studied during deformation. First it is concluded
that a spatial resolution of about t/10 is necessary in order to observe the main features of the neck geometry and that the localisation gets narrower towards the end of the process. At the last time steps before fracture the increase in strain is concentrated to the central part of the neck with an extension of about half the thickness while the peripheral part of the neck that was active in the earlier stage of the plastic process is not active towards the end. Further it is observed that the locally measured fracture strain is significantly higher for specimens cut out at 0 and 45 degrees to the rolling direction compared to the ones cut out perpendicular to this direction.

The method of digital speckle correlation produces displacement measures of high accuracy. This accuracy could however be improved even further by applying smaller speckles and using a camera with higher resolution. By doing this the spatial resolution of the experiment could be increased compared to the one used in this work. Instead of using a camera with a higher resolution one could use a stronger lens, this is however not trivial since the depth of field then is reduced. The out-of-plane displacement of the surface in the region of the neck might then cause the camera to lose its focus. Even in the measurements carried out in this work the definition of the images is reduced in the region of the neck towards the end of the tensile tests.

The material used for the investigations in this work is only studied in room temperature. In hot-forming operations the blanks are heated to about 900°C which completely alters the properties of the material. The phenomena of necking and fracture are of great importance in hot-forming operations which is why a natural extension to this work would be to investigate the plastic strain localisation in material at 900°C.

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Paper B
FAST METHOD FOR MATERIAL CHARACTERIZATIONS INCLUDING POST-NECKING BEHAVIOUR FROM FULL-FIELD MEASUREMENTS

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Abstract
A method for characterizing material based on full-field measurements is presented. The method is intended to be a fast and simple complement to previously used inverse methods. In these methods a finite element simulation of an experiment is carried out repeatedly with different material parameters until the behaviour of the simulation matches the experiment. This process is very time consuming because of the repeated simulation of the complete experiment. In the suggested method the stresses are instead computed directly from the measured strains by using the radial return algorithm and an assumed material behaviour. By computing the stresses in a number of points along a line across the specimen, the load experienced by the specimen can be calculated and compared to the one recorded in the experiment. The squared difference between the computed and the measured load is used as an objective function to optimize the assumed material behaviour. The full-field measurement technique used, yields in-plane deformation fields. In order to be able to compute the full three dimensional stress and strain tensors, the assumption of plane stress is made. This assumption makes the material characteristics produced by the method most suited for use in finite element simulations employing shell elements since these also assume plane stress. The method is tested by using both a synthetic set of experimental data and data from a physical experiment. These tests show that the method is producing material characteristics that are in good agreement with the true ones.

Introduction
In recent years computer simulations of the mechanical behaviour of structures have to an increasing degree been replacing structural testing due to its lower cost and better time effectiveness. These structures can for instance be crash protecting components in cars that must undergo large plastic deformation in a crash situation. Simulations of this kind are most often performed using the finite element method (FEM), which is a very robust and well known method. As long
as the input to a simulation is correct the results will be very close to reality. One of the most important inputs to the FEM is the material model which is the routine that describes how the material responds under different loading conditions. The material model usually consists of a linear relationship between the elastic strains and stresses and a stress-strain curve (often non-linear) describing the relation between yield stress and the equivalent plastic strain. This model works well for many materials, the problem is only how to determine the stress-strain curve. In order to be able to design optimal products regarding weight and performance the materials must be pushed close to their limits, this requires that the stress-strain relationships are known accurately up to the point of fracture.

The simplest way to produce a stress-strain curve is to perform global measurements, using for instance an extensometer or a strain gauge together with a force-transducer, assume homogeneous strain and stress fields and directly produce the relationship between the two. This procedure is often done on standardized straight specimens in tensile tests. The method works fine as long as the stress and strain fields actually are homogeneous but it fails when a neck is formed on the specimen. Determination of the stress-strain relationship after the appearance of a neck can be done with an inverse methodology described by for instance Zhang and Li [1]. These methods imply that the material parameters of a finite element analysis of the experiment are adapted until the global results of the analysis match the corresponding data from the experiment. In this procedure it is assumed that, if the global behaviour of an FE-analysis matches the global behaviour of an experiment, then the local behaviours will also match. This is a simplification and the true local behaviour cannot be known since it is not measured. Other ways to determine the stress-strain behaviour from a global experiment are described by Bridgman [2] and Ling [3] among others.

The experimental methods have lately been refined so that it is possible to get a detailed view of the in-plane displacement field in a region of a specimen throughout a tensile test or some other experiment. These methods include, for instance, digital image correlation, grid methods and interferometric methods. An overview of these and a few others are given by Grédiac [4]. In the present paper the digital image correlation, also referred to as digital speckle photography is used. The basic principle is that a sequence of digital photographs of white-light speckles applied to the surface of the specimen is recorded during loading and the in-plane deformation field is obtained from the changes in speckle pattern by correlation of sub-areas. Recent reviews and evaluations of the method can be found in Tong [5], Schreier and Sutton [6] and Hild and Roux [7] and some
examples of its application in Kajberg and Lindkvist [8], Quinta da Fonseca et al [9], Wattrisse et al [10] and Brunet and Morestin [11].

From a full-field measurement the parameters of a material model can be extracted. The most common method to do this is to use an inverse method where a cost function is minimized by adapting the parameters of an FE-analysis. This cost function can be built up in different ways and generally it includes sums of the squared differences between numerically and experimentally obtained quantities. In Meuwissen et al [12], Faurholdt [13] and Kajberg and Lindkvist [8] different approaches using this method are described.

There is also a more direct theoretical approach for extracting material parameters called the virtual fields method, a procedure that makes use of the principle of virtual work. By applying this principle for a number of different virtual fields (the same number as the number of parameters in the material model) a system of equations is obtained. Solving this system yields the material parameters. The development of the virtual fields method is summarized in a general review by Grédiac et al [14] while examples of its applications are found in Chalal et al [15, 16], Grediac et al [4, 17]. A comparison of the inverse method using an FE-analysis and the virtual fields method is found in Avril and Pierron [18].

In this paper a new method for extracting material parameters is presented. The aim of the method is a fast, robust and simple way to produce material parameters from a full-field measurement. To achieve this, a few simplifications and limitations are made along the way. Since shell elements (assuming plane stress) are used in most large scale simulations of sheet metals the method is focusing on extracting material parameters adapted for shell elements. The stress-strain relationship produced by the method is consequently not the true relation but the relation that yields the correct behaviour of an FE-analysis built up by shell elements. It should be noted that as long as plane stress is a good approximation to the real stress state, the stress-strain relationship produced by the method should be almost the same as the true relationship.

The basic principle of the method resembles the one where the material parameters in an FE-analysis are adapted to make quantities in the simulation match corresponding quantities in the experiment. This new method is using the fact that since the specimen is in equilibrium, every cross section of the specimen must carry the total force applied to the specimen. Instead of running an FE-analysis of the complete experiment, the stresses in a cross section of the
specimen are computed based on the in-plane strain components, a plane stress assumption and an assumed set of material parameters. Then the force can be computed from the stresses and the current cross sectional area. The material parameters are then updated in an iterative process until the force response of the analysis matches the force response of the experiment. It should be noted that the material parameters are determined in several optimizations containing one design variable instead of one optimization containing several design variables.

Method
In this section the suggested method is described both generally and more detailed. Furthermore, the radial return algorithm is briefly presented and the experiments performed to be able to carry out the method are explained.

General
The idea behind the method suggested in this paper is to use the fact that a sequence of full-field measurements yields the deformation field of a specimen throughout a tensile test. Since this deformation field, and hence the strain field, is known it is not necessary to compute it using a finite element analysis. In the inverse procedures mentioned in the introduction the material parameters of an FE-analysis are adapted in an optimizing process to get an agreement between the measurements and the simulation. This agreement is normally measured by a cost function that consists of the differences in the strain field and the force between the measurement and the analysis. In such a procedure the strain field is computed by the FE-analysis over and over again. This is a superfluous part of the procedure since the correct strain field is already known from the measurement. By making direct use of the measured strain field the FE-analysis can be replaced with a more simple procedure called the radial return algorithm which computes stresses from the known strains.

By performing this radial return algorithm for the measured strain at a number of points lying regularly distributed along a line across the specimen, see Figure 1, the stress tensors for these points are produced. Further, the geometry and hence the initial cross sectional area of the specimen is known. Since the sample points across the specimen are distributed regularly, the fractions of the initial cross sectional area associated to each point are also known. Due to lateral contraction the area associated to each point will be reduced during the tensile test. The reduction is directly related to the local strain tensors of the points and since these are known, the current areas associated to the points can be calculated throughout the tensile test. The sum of the products of $\sigma_x$ and the cross sectional areas
associated to the sample points across the specimen yields the total force in the specimen throughout the tensile test. This force, which is linked to an a priori assumed stress-strain relationship, can be compared to the force recorded in the experiment. The stress-strain relationship can then be optimized in an iterative process where the cost function is built up by the differences between the computed force and the force measured in the experiment.

![Figure 1. Schematic picture showing the points where the stresses are calculated.](image)

**The radial return algorithm**

The outline of the radial return algorithm is briefly described in this section, a more detailed description can be found in Belytschko et al. [19]. The algorithm is a procedure for computing the stress tensor related to a certain strain state in a material that follows a certain stress-strain relationship. Assuming that a point in the material is in a known stress and strain state, this could for instance be the unloaded state where both the stresses and the strains are zero. Then the material point is subjected to an increment in strain. By initially assuming that the increment in strain is entirely elastic, an elastic trial stress is computed. From this trial stress the von Mises effective stress can be calculated. The effective stress is then compared to the yield stress related to the equivalent plastic strain of the strain state before the strain increment. If the effective trial stress is larger than the yield stress, the deviatoric stress tensor and hence the effective stress is reduced by increasing the plastic and reducing the elastic part of the strain increment. The ratio between the plastic and the elastic part of the strain increment is modified until the effective stress matches the yield stress related to the current equivalent plastic strain.
Experiments

Tensile tests are considered in this paper. The geometry of the specimens is however non-standard and instead they have been designed to generate a strain localization in an interior point of the specimen and at a position that can be determined before the test. This behaviour of the deformation is desired since the material should be characterized up to fracture for a material point that is not influenced by edge effects. If the strain localizes to an interior point, it is reasonable to believe that the fracture emanates from this point, meaning that the onset of fracture is unaffected by edges. When carrying out full-field measurements the resolution can be increased if the measurement is focused to a region of and not to the whole specimen. If it is possible to determine the region of the strain localization prior to the experiment the measurement can be focused to that region, hence accomplishing a higher resolution. These requirements can be fulfilled by a specimen with a shallow notch. The specimen geometry used in the experiments is shown in Figure 2. This geometry was developed by a series of finite element simulations.

![Figure 2. Geometry of the specimens used in the experiments.](image)

The full-field measurement technique used to monitor the tensile tests is digital speckle photography or DSP. In order to obtain information regarding the deformation between two images the DSP-method utilizes digital image correlation, often referred to as DIC. The basic principle of DIC is to compare two images of a specimen coated with white light speckles (a randomly distributed pattern). Within the image taken before the deformation a number of sub-images are defined. By using a cross-correlation algorithm the position of the unique speckle pattern of each sub-image on the second photograph is identified. The coordinate of the peak of the correlation coefficient is taken to be the new position
of the mid-point of the original sub-image. To avoid problems regarding large
deformations of the speckle pattern between the images, a series of many frames
is recorded and increments of displacements are determined instead of total
displacements. Digital image correlation is able to produce displacement fields
with sub-pixel accuracy. The method is described in detail in, for instance, [8],
[10] and [5] and the accuracy of the method is discussed by Sjödahl [20, 21].

The output of the DSP-method is a number of in-plane displacement fields at
different time instants throughout the tensile test. Each of these fields can be
differentiated to yield the corresponding in-plane strain fields, looking typically
like Figure 3. The out-of-plane strain component could be assessed by assuming
negligible out-of-plane shear and incompressibility. The procedure of obtaining
the out-of-plane strain component is described in [8], [10] and Eman et al [22]. In
this paper the assumption of incompressibility is not made, instead plane stress is
assumed. This choice is made because enforcing incompressibility would result in
erroneous stresses, especially when the deformation is so small that the elastic
fraction of the strain is a significant part of the total strain. It should be noted that
the assumption of plane stress also is a simplification, in particular near the end of
the tensile test when a localized neck has formed and the true stress state within
this neck is triaxial. The errors due to this simplification are however expected to
be relatively small as long as the extracted parameters are used in shell element
models since they also employ a plane stress assumption. It is therefore important
to state that the suggested method does not produce the true stress-strain
relationship in a three dimensional sense but the stress-strain relationship that is
adapted for a shell element model.

Figure 3. Typical strain field in a tensile test.
The full-field measurements produce the quantities $\varepsilon_x^k(t_l)$, $\varepsilon_y^k(t_l)$, $\varepsilon_{xy}^k(t_l)$ and $F_{exp}(t_l)$ where $\varepsilon_x$, $\varepsilon_y$ and $\varepsilon_{xy}$ is the strain in the x-, y- and xy-direction respectively, $F_{exp}$ denotes the experimentally measured force, the superscript $k$ stands for the $k$:th sample point and $t_l$ denotes the $l$:th time instant. Assuming that there are $M$ sample points across the specimen according to Figure 1 and that there are $N$ strain fields produced during the tensile test, the indices $k$ and $l$ goes from 1 to $M$ and 1 to $N$, respectively.

**Evaluation**

The stress-strain relationship that the method establishes is a piecewise linear curve in as many steps as the number of strain fields extracted from the measurement, following the notation above, $N$ steps. In the optimization process the stress-strain relationship is not determined as one optimization of $N$ design variables but as $N$ optimizations of one variable.

Initially a very weak plastic hardening, only slightly above an ideally plastic behaviour, is assumed. During the upcoming optimization the hardening modulus is never allowed to go below the one of the initial guess. It should also be noted that the yield stress at zero equivalent plastic strain is supposed to be known and denoted $\sigma^Y$. This initial guess of the stress-strain relationship is shown in Figure 4.

![Figure 4. The initial assumption of the plastic hardening.](image_url)
With the aid of this hardening curve, the in-plane strain values \( \varepsilon_x^k(t_i), \varepsilon_y^k(t_i), \varepsilon_{xy}^k(t_i) \) and the assumption of negligible out-of-plane shear \( \varepsilon_{xz}^k(t_i) = 0, \varepsilon_{yz}^k(t_i) = 0 \) and out-of-plane stress \( \sigma_z^k(t_i) = 0 \), the complete stress and strain tensors can be computed by using the radial return algorithm. Since the stresses of each sample point now are determined it only remains to calculate the fraction of the cross-sectional area associated to each point to be able to compute the resulting force. The \( M \) sample points are, as mentioned earlier, regularly distributed across the specimen. This yields the fraction of the initial cross-sectional area that is associated to each point as,

\[
A_k(t_i) = \frac{A_{\text{init}}}{M} 
\]  

where \( A_{\text{init}} \) is the known cross-sectional area of the complete specimen. From the fraction of the initial area related to each point and the strain tensor, the area related to the point after deformation can be calculated according to (2).

\[
A_k(t_i) = A_k(t_o) \cdot \exp(\varepsilon_x^k(t_i)) \cdot \exp(\varepsilon_y^k(t_i)) 
\]

When the current cross-sectional area related to each sample point is known, the total force can be computed using (3).

\[
F_{\text{comp}}(t_i) = \int_{A_{\text{init}}(t_i)} \sigma_z(t_i) dA \approx \sum_{k=1}^{M} \sigma_z^k(t_i) \cdot A_k(t_i) 
\]

\( A_k \) and \( dA \) are shown in Figure 5. The computed force \( F_{\text{comp}}(t_i) \) can now be compared to the force measured in the experiment at the same instant \( F_{\text{exp}}(t_i) \).

![Figure 5. Cross section of the specimen with dA and Ak marked.](image)

Generally the hardening modulus will in reality be higher than the initially assumed one shown in Figure 4. This will cause the computed force \( F_{\text{comp}}(t_i) \) to be
lower than the measured force $F_{\text{exp}}(t_i)$. Therefore the slope of the hardening behaviour will have to be modified until the difference between the forces is within a predetermined tolerance. The slope is modified by using a Newton-Raphson optimization algorithm. Once the tolerance is fulfilled the first step of the piecewise linear stress-strain relationship can be finished by fixing the hardening modulus up to the equivalent plastic strain of the sample point showing the largest strain at time step $t_i$. For higher strains than that, the hardening modulus is reset to the lowest allowed value. The procedure is described in Figure 6 where the process of determining the first step of the stress-strain relationship is illustrated.

![Figure 6. Schematic procedure for how the stress-strain relationship is modified in the first step.](image)

This procedure is then repeated $N-1$ additional steps to produce the rest of the stress-strain relationship. In each step, only the part of the curve to the right of the earlier fixed parts is modified.

As mentioned before, the hardening modulus is not allowed to go below a predefined positive value in order to get convergence in the radial return algorithm. Sometimes the material show a softening which could, for instance, be caused by material damage. In this method such a phenomenon is modelled by a damage function. The damage function is expressed as a percentage loss in effective stress as a function of equivalent plastic strain. A value of the damage function of 10 percent means that the material can balance 90 percent of the load that the undamaged material can. The damage function is activated if the computed force at time $t_i$, $F_{\text{comp}}(t_i)$, for the lowest allowed value of the hardening coefficient is higher than the corresponding measured force $F_{\text{exp}}(t_i)$. In order to determine the damage function a procedure very similar to the one for determining the stress-strain relationship is used. That is, the damage function is also a piecewise linear function where the pieces are determined one at a time and
the inclination of each piece is determined with a Newton-Raphson procedure. The procedure for determining one piece of the damage function is schematically shown in Figure 7.

![Figure 7. Schematic procedure for determining the damage function.](image)

Once the optimization has gone through all $N$ steps, two piecewise linear functions have been produced. The first one is the stress-strain relationship and the second one is the damage function. If the material is such that no softening occurs, the damage function is zero for all equivalent plastic strains. Typical functions are shown in Figure 8.

![Figure 8. Typical shapes of the stress-strain relationship and the damage function.](image)
Results

The functionality of the method is tested by producing a stress-strain relationship and a damage function from a synthetic set of experimental data. This dataset is created by carrying out an FE-analysis of a specimen like the one in Figure 2 using shell elements and predefined material parameters, that is, known piecewise linear stress-strain relationship and damage function. The FE-code LS-DYNA 970 is used to carry out the simulation and material model #81 (plasticity with damage) is used. From the FE-analysis, the in-plane strain components ($\varepsilon_x$, $\varepsilon_y$ and $\varepsilon_{xy}$) in a line crossing the specimen (comparable to Figure 1) and the applied force are extracted in a number of time steps throughout the analysis. Using the extracted data, which is of the same type as the data produced by a DSP-experiment, the method should be able to reproduce the stress-strain and the damage curves. The results from such a test are presented in Figure 9 (a) where the predefined curves are shown as solid lines while the points extracted by using the suggested method are shown as circles in the graphs. The correlation between the true material behaviour and the one extracted with the method is very good in this case where the synthetic set of experimental data used in the determination is flawless.

It is of great interest to investigate the robustness of the method, that is, how well it behaves with distorted data. In the case of real physical measurements the strain data will be influenced by noise and measurement errors. To imitate these measurement errors in a systematic way, each value of the synthetic experimental set of data is distorted according to a normal distribution with a standard deviation that is proportional to the magnitude of the strain value. Three different values, 0.0025, 0.0050 and 0.0075, of the proportionality constant are studied to get a view of the sensitivity to measurement errors. For each of these values, ten sets of material parameters are produced. This results in a scattering of points shown in Figure 9 (b), (c) and (d) where the standard deviations are 0.25, 0.50 and 0.75 percent of the current strain values, respectively. In Figure 9, the stress-strain relationship is the upper function and follows the scale on the left hand side while the damage parameter is represented by the lower function and follows the scale on the right hand side.
Figure 9. The extracted stress-strain relationship and damage function for four different variants of the same data. In (a) there is no errors in the synthetic set of experimental data, in (b), a standard deviation of 0.25 percent of each strain value has been applied, in (c) and (d) the standard deviations are 0.50 and 0.75 percent respectively. In (b), (c) and (d) the method has been carried out ten times to produce a scattering of points.

When a stress-strain relationship and a damage function are determined with the suggested method, they are not independent of each other. The onset of damage is defined as the moment when the slope of the stress-strain relationship wants to go under a certain predefined positive value. Instead, the slope is fixed to the preset value and the damage parameter is increased. Hence, the damage function is dependent of the lowest allowed slope of the stress-strain relationship. The pair of curves produced by the suggested method is consequently not unique but dependent of the choice of the lowest allowed slope of the stress-strain relationship. This means that different pairs of curves could produce the same force response. In order to be able to easily compare the material parameters produced from the synthetic set of experimental data with the ones used in the FE-analysis to create the data, the lowest allowed slope of the stress-strain relationship was chosen to be the same as the asymptotic value of the slope of the correct relationship. Not doing this would yield a pair of curves that are not
coincident with the correct curves even though they would produce the correct force response.

Besides these tests of the method where a synthetic set of experimental data is analyzed, a set of real data from a full-field measurement has been examined with the method. The material examined is a press hardened ultra high strength steel with a sheet thickness of 1.2 mm. When applying the method to these data the yield stress at zero equivalent plastic strain is chosen to be 600 MPa. This value is lower than the true value which for the material in question is closer to 900 MPa. A low value of the yield stress has been guessed deliberately since a too low value only will result in a very steep first part of the stress-strain relationship while a too high value instead will overlook the first part of the stress-strain relationship. Further, the lowest allowed value of the hardening coefficient is set to be 100 MPa. The resolution of the experimental grid in the full-field measurement is chosen to be equivalent to square elements with a side of 2.5 mm. With these settings the points shown in Figure 10 are produced. In order to get monotonically increasing functions (for use in an FE-code) the damage parameter is approximated with a fourth degree polynomial while the stress-strain relationship, due to the requirements mentioned earlier, always will have a positive slope. The fourth degree polynomial is adapted to the points of the damage function after the onset of damage using the least squares method. Up to the onset of damage, the function is set to be exactly zero. The onset of damage is in this specific case at $\varepsilon_{ep} \approx 0.074$.

![Figure 10](image_url)

*Figure 10. The stress-strain relationship and the damage function produced by the method are shown as circles. The solid lines show the piecewise linear data used in the FEM validation.*
The stress-strain relationship and the damage function shown in Figure 10 are used input to the material model in a finite element analysis of a tensile test of the specimen in Figure 2. The load-extension curve of this simulation is compared to the corresponding curve of the experiment used to extract the material parameters. It is possible to compare both the appearance of the curve and the point of fracture. The fracture criteria used in the analysis is the equivalent plastic strain of the last point in the extracted stress-strain relationship (or damage function), this value is the same as the maximum equivalent plastic strain of the last image before fracture in the full-field measurement. In this case the critical value of the strain is 0.2725. The load-extension curves of the two cases can be seen in Figure 11 where the experiment is represented with a solid line and the simulation with a dash-dotted line. Near the end of the tensile test it is seen that the simulation slightly overestimates the force. One reason for this could be that the simulation is close to perfectly symmetric, not allowing any of the shear bands to dominate as one of them does in the experiment, see Figure 12 (a) and (b). To test this hypothesis an analysis of a distorted specimen is carried out, where two of the nodes have been displaced 0.2 mm towards the centreline of the specimen. These nodes are marked in red in Figure 12 (c), which also shows a strain field that closer resembles the one of the experiment. The load-extension curve of this analysis is illustrated in Figure 11 as a dotted line and it is evident that the error compared to the non-distorted simulation is significantly reduced.

![Figure 11. Load-extension curves of an experiment and two different simulations, one of the simulations is close to perfectly symmetric while one has been distorted to resemble the behaviour of the experiment.](image)
The strain field of the experiment (a) together with the strain field of the symmetric simulation (b) and the strain field of the distorted specimen (c).

Discussion

In this paper a fast and simple method for characterisation of material is proposed. The method is developed to produce a stress-strain relationship and a damage function adapted for use in an FE-code using plane-stress shell elements.

The functionality of the method is demonstrated by using a synthetic set of experimental data. These data are produced by running an FE-analysis with certain material parameters and extracting the same type of information that is produced by a full-field measurement. By reproducing the material curves (stress-strain and damage) with high accuracy, the functionality of the method, when using flawless experimental data, is illustrated. To systematically investigate the sensitivity to measurement errors the synthetic set of data is distorted with a known standard deviation. Producing the material curves several times with different distorted experimental data reveals a scattering of sample points surrounding the correct curves. Doing this for different standard deviations gives a view of the sensitivity to random errors of different magnitude in the full-field measurement. Furthermore, a set of real data from a full-field measurement is investigated. From this measurement a stress-strain relationship and a damage function are generated. These material curves are then used in an FE-analysis that simulates the experiment. The agreement between the analysis and the experiment is good. There are some discrepancies near the end of the tensile test, these could however, at least partly, be explained by the fact that the simulation is almost perfectly symmetric while the experiment is not. When localized necking occurs in the experiment, one of the shear bands will dominate over the other. In the simulation on the other hand, they will both develop simultaneously. To test this
hypothesis a distorted simulation that closer resembles the behaviour of the experiment is carried out. The results from this analysis significantly reduce the discrepancies from the original simulation.

The suggested method is proved to produce a stress-strain relationship and a damage function that, when used in a finite element analysis with plane-stress shell elements, reproduces the global behaviour of the material with a satisfactory precision.

The main advantage of the suggested method compared to, for instance, a conventional inverse modelling procedure using an updated finite element simulation is that this new method is significantly faster. While a conventional inverse modelling procedure can take up to several hours due to the repeated simulations of the complete experiment, the suggested method produces material parameters from a full-field measurement within a few seconds. Another advantage of the method is that it does not require uniform material characteristics throughout the specimen, only in a cross-section of it. If the material characteristics vary along the tensile direction of the specimen it is not a problem as it would be with a conventional inverse modelling procedure. In the suggested method, the material is characterized only in the chosen cross-section. This property could be valuable, for instance when characterizing different parts of a soft zone in a metal sheet.

One of the drawbacks of the method is that it is depending on a plane-stress assumption. This limits the method to extracting material parameters that are adapted for use in plane-stress shell element models, that is, not the true material characteristics. It should however be mentioned that as long as plane-stress is a good approximation, so is the material parameters extracted by the method. Compared to a conventional inverse modelling procedure the statistical base is smaller since they often use the whole deformation field while the suggested method only use the sample points of the deformation field lying in a line crossing the specimen. The smaller statistical base makes the method more sensitive to random errors in the measurements. This sensitivity could be reduced by producing several sets of material parameters from slightly different cross-sections and taking the mean value of these.

Other specimen shapes than the one suggested in the paper can be used. This shape was chosen because the region of the strain localization could be determined before the actual experiment, making the full-field measurement
easier. It also gives a fracture at an inner point, this results in high values of local strain allowing the stress-strain relationship to be determined up to the highest possible equivalent plastic strain. The only important issue when choosing the specimen shape is that the deformation field in a cross-section that carries a measurable load can be quantified. This means that other loading conditions could be used as well, for instance shear tests. In such a case the shear stress in a cross-section could be used to compute the load applied to the specimen in the same manner as the normal stress is used to compute the load in this paper.

It is a well-known fact that different element sizes yield different global behaviour in an FE-analysis, especially after localized necking since large elements can not resolve the necking zone. This causes large elements to give a stiffer behaviour after necking than small elements. Therefore the material parameters used in an FE-analysis should be tailored to the element size in the model. Due to the flexibility of the measurement technique used in this paper, the suggested method could be used to extract material parameters adapted for different sizes of the elements by just changing the length scale used to evaluate the deformation field. Since the computational cost of extracting one set of material parameters is very small, it is easy to extract a number of sets for different element sizes. This could also be done using a conventional inverse modelling procedure but the computational cost of such a process would be very large.

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Paper C
FRACTURE STRAINS AT HOLES IN HIGH-STRENGTH STEEL,
A COMPARISON OF TECHNIQUES FOR HOLE-CUTTING

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Abstract
In this work fracture strains of ultra-high strength steel in the proximity of holes have been investigated. The material is produced in a press-hardening process where a hot blank of boron steel is formed, fixed and quenched between cooled tools. Three different hole-making procedures have been studied; punching before heating, punching after quenching and laser-cutting after quenching. The behavior of the material has been recorded by the method of digital speckle correlation. This method measures highly resolved displacement and strain fields in the specimen up until fracture. From these fields, differences in strain at fracture between the hole making procedures can be determined. The main result of the study is that the method with holes punched before heating show a significantly higher resistance to local strain than the other two methods.

Introduction
Sheet metal is often used as a raw-material from which more or less complex parts are fabricated through pressing or other forming operations. This is the case for example in the vehicle industry where the entire structure of a car is made from sheet material. In the majority of all modern cars there are crash-protecting parts, like bumper beams, A- and B-pillars and side impact beams, made from ultra-high strength steel. These parts are sometimes produced by press-hardening, a process where a hot blank (~900 ºC) is simultaneously formed and quenched. This results in a strong material with tensile strength of 1500 MPa or more. Knowledge of material characteristics is very important for optimal design of components in terms of their performance and weight. One important issue is to avoid fracture in protective components in a crash situation and instead let such components deform plastically and consume collision energy. Fracture often emanates from geometric irregularities like spot-welds, notches or holes which is explained not only by the stress concentration associated with the geometrical inhomogeneity but also by the fact that the material itself is influenced by the fabrication process.
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That process can for example change the material behavior in the vicinity of the hole by introducing heat effects, micro-cracks, residual stresses and so on. Therefore, the fracture criteria used for homogeneous, non-affected material may be erroneous for the material influenced by for example a hole and the fracture behavior near holes must be investigated separately. This work presents the results of an experimental investigation of the deformation field close to holes in sheet specimens at the onset of fracture.

The method used to monitor the deformation is called digital speckle photography or perhaps more describing; digital speckle correlation. The basic principle is that a sequence of digital photographs of white-light speckles applied to the surface of the specimen is recorded during loading and the in-plane deformation field is obtained from the changes in speckle pattern by correlation of sub-areas. Strains are then calculated from gradients of the displacements. Recent reviews and evaluations of the method can be found in Tong [1], Schreier and Sutton [2] and Hild and Roux [3] and some examples of its application in Kajberg and Lindkvist [4], Quinta da Fonseca et al [5], Wattrisse et al [6] and Brunet and Morestin [7].

The effect of holes has earlier been studied for different materials and situations. Strains near the holes have been monitored using both full field techniques and by attaching a number of strain gages in a carefully chosen configuration. Much of the earlier work is focused on fiber-reinforced composites and other polymer materials. Investigations of different aspects of holes can be found in Bourcier et al [8], Touchard-Lagattu and Lafarie-Frenot [9], Yao et al [10 and 11] and Pandita et al [12]. The present work differs from the reported earlier work in that it highlights the dissimilarities in fracture behavior between different hole making procedures and also in that it focuses on fracture in ultra-high strength steel.
Experimental arrangement and procedure

The material in focus for this investigation is 22MnB5, according to SS-EN 10083-3: 2006, which is a steel with a small content (30 ppm) of boron making the material suitable for press-hardening. In the press-hardening (or hot stamping) process a hot blank (~900 °C) is formed, fixed and quenched between cooled tools. In the production of flat sheet material for the specimens plane tools are used. The specimens are cut from the hardened sheet material into the final shape shown in Figure 1. Abrasive water cutting is used to cut the outer contour in order to avoid heating associated with other cutting methods which may influence the material properties. All specimens are cut so that their loading direction is perpendicular to the rolling direction of the material.

![Figure 1. Geometry of the specimen with a hole of diameter D.](image)

The holes in the specimens are not cut using abrasive water cutting, instead they are produced with the following methods; 1) Punching before heating, 2) Punching after quenching, 3) Laser cutting after quenching. These methods are referred to as pre-punching, post-punching and laser-cutting, respectively. The sheet thicknesses t used in this investigation are 1.2 and 2.4 mm and the hole diameters D are 4 and 8 mm. The extent of the test series is outlined in Table 1.
Table 1. The complete test series; nine combinations of sheet thickness, hole diameter and hole-making procedure.

<table>
<thead>
<tr>
<th>Sheet thickness t [mm]</th>
<th>Diameter D [mm]</th>
<th>Pre-punched</th>
<th>Post-punched</th>
<th>Laser-cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>4</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>1.2</td>
<td>8</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2.4</td>
<td>8</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

The deformation of the material at the edge of the holes is monitored using digital speckle photography or DSP. In the DSP-method digital speckle correlation is used to obtain information regarding the deformation of a specimen between two states of loading. The basic principle of digital speckle correlation is to compare two images of a specimen coated with a randomly distributed pattern (speckles), one image taken before deformation and the other one after. A number of sub-images are defined within the first image and the position of the unique speckle-pattern of each sub-image is then identified in the second image by a cross-correlating algorithm. The coordinate where the correlation coefficient is the highest is taken to be the new position of the midpoint of the original sub-image. Thus the displacement of the midpoint of each sub-image is determined. Deformation or rotation of the sub-images is not taken into account by the cross-correlation algorithm when searching for the new positions and therefore correlation may be low for the case of large deformations rendering uncertain results if high levels of deformation are at hand between the two images. To avoid this problem a series of many frames is recorded during the deformation and new reference images are chosen through the series and increments of displacements rather than total displacements are determined. By differentiation of the displacement field the in-plane components of the strain field can be calculated. Logarithmic strain is used. To determine the out-of-plane strain components some assumptions are made, namely that the in-plane displacements are constant through the thickness, the out-of-plane shear is negligible and that the material is incompressible. Based on measured strains and assumptions the equivalent plastic strain field is computed. A complete description of the procedure can be found in Kajberg and Lindkvist [4].

The experimental setup involves a servo-hydraulic testing machine (Dartec M1000/RK, 250 kN), a digital camera (PCO Sensicam) with a cooled CCD mounted in front of the specimen and a computer for storing the images and evaluating the deformation field. A schematic picture of the setup can be found in
Figure 2. The camera is mounted to one of the grips of the machine and the lens axis is perpendicular to the specimen surface throughout the test.

To calibrate the spatial resolution of the images, a known rigid body displacement is imposed to the specimen and images are taken before and after the displacement. By evaluation of the displacement in number of pixels using the correlation algorithm and relating it to the known displacement in millimeters the number of millimeters per pixel can be computed. This value is $7.2 \times 10^{-3}$ mm/pixel. The camera has $1280 \times 1024$ square pixels which results in a field of view of about $9 \times 7$ mm$^2$. Beside the resolution of the camera, the resolution of the measurement grid also plays an important role for the result of a DSP-measurement. The distance between the centers of the sub-images was chosen to 30 pixels in both x- and y-directions, implying that the resolution of the measurement grid is about 0.2 mm. In this investigation a sub-image size of $64 \times 64$ pixels is used.

The speckles used in the experiments are white-light speckles. Compared to speckles produced by coherent light, white-light speckles have the advantage that they are less sensitive to out-of-plane motions. Since large deformations are investigated there are significant out-of-plane motions due to thinning of the specimens. The speckles are produced by spray-painting each sample with black and white paint.
During the tensile test the specimens are strained in the x-direction with a constant cross-head speed of 0.1 mm/s while the camera is recording images at evenly distributed intervals of 0.7 s. The total time for straining of a specimen until fracture is typically between 15 and 30 seconds and 20 to 40 digital frames of the deforming speckle pattern are recorded during the process. Two specimens of each kind are tested. An extensometer with gauge-length of 50 mm is attached to the specimen symmetrically positioned with respect to the hole. The signals from the extensometer and from the load cell of the test machine were sampled (15 samples per second) and recorded by the computer.

**Results**

The output from the experiments is primarily the photographic records of the deforming speckle patterns and also the time histories of force and elongation of the gauge length. From the records of the speckle patterns the developing strain fields are evaluated by the correlation method briefly described above and a sequence of strain states is obtained for each test. The last strain field in each sequence represents the strain state just before fracture and is therefore of highest interest in this study of fracture behavior for different hole-making procedures. In Figure 3 - 7 contour plots of the normalized equivalent strain $\varepsilon_e/\varepsilon^*$ in the last frame before fracture is shown for different specimen types. The normalizing strain $\varepsilon^*$ is the local equivalent fracture strain at an inner point of a 1.2 mm thick, specimen, which is specially designed not to fracture from an edge. Consequently the value $\varepsilon^*$ reflects fracture that is not influenced by edge effects. DSP is used also for measurement of $\varepsilon^*$ but these experiments are not reported here.

Levels as well as differences in the normalized strain fields depending on thicknesses, hole making procedures and hole diameters can be assessed from the plots in Figure 3 - 7. Note that the scales are different in the plots.
Figure 3. Pre-punched, $t=1.2$ mm, $D=8$ mm.

Figure 4. Laser-cut, $t=1.2$ mm, $D=8$ mm.

Figure 5. Post-punched, $t=1.2$ mm, $D=8$ mm.

Figure 6. Laser-cut, $t=2.4$ mm, $D=8$ mm.

Figure 7. Pre-punched, $t=1.2$ mm, $D=4$ mm.
Figure 3 - 5 show the strain fields of tensile tests under the same conditions regarding sheet thickness and hole diameter but with different procedures for making the hole. Most significant with these strain fields is the difference in strain levels. Figure 4 and Figure 6 show results for sheet thickness, 1.2 and 2.4 mm respectively for the same hole-making procedure (laser-cut). The strain levels in this case is approximately the same, however the region of the concentrated plastic strain is considerably larger for the thicker material. This phenomenon is also observed when studying the localization of strain in sheet metals. According to for example Kokkula [13] the localized neck is a narrow band with a width approximately equal to the thickness of the sheet. Figure 3 and Figure 7 show results for the same conditions except for the hole diameter. Here, as well as between Figure 4 and Figure 6, the strain levels are about the same but the spatial extension of the concentrated plastic strain is different between the images. The 4 mm hole gives, as expected, a more concentrated region of plastic strain.

Alternatively the strain state at fracture near the hole can be investigated by plotting the normalized strain as a function of the distance from the edge of the hole. Figure 8 - 10 show the normalized strain component in the loading direction ($\varepsilon_x/e^*$) as a function of the lateral distance (in y-direction) from the edge of the hole for different cases. In Figure 8 the difference between the hole making procedures is evident. It is clear that the strain at fracture is significantly higher for the pre-punched specimen, which also implies a larger area with high strain level. Figure 9 displays results for the two different hole diameters 4 and 8 mm and it shows that the slope of the strain is higher for the 4 mm hole than for the 8 mm hole.
Figure 8. Strain in x-direction versus the y-distance from the edge of the hole for a pre-punched, a laser-cut and a post-punched hole.

Figure 9. Strain in x-direction versus the y-distance from the edge of the hole for an 8 and a 4 mm hole.

Results for the two different thicknesses are compared in Figure 10. The slopes seem to be quite similar; the difference is at least not as significant as in Figure 9. When comparing Figure 4 and Figure 6 it is clear that the largest difference is in the extension of the strain fields. This difference in width can be seen in Figure 11
where the normalized x-component of the strain is plotted as a function of the x-coordinate along a line close to the edge of the hole.

Figure 10. Strain in x-direction versus the y-distance from the edge of the hole for an 8 mm hole in a 1.2 and a 2.4 mm thick specimen.

Figure 11. Strain in x-direction versus the x-coordinate along a line close to the hole.
From the strain fields in Figures 3 - 7 and strain profiles in Figures 8 - 11, quantitative as well as qualitative information regarding the influence on fracture strain from different procedures, thicknesses and diameters can be derived. Such information is important in situations when strength of components is estimated from tests on specimens. The maximum value of the local normalized equivalent strain is perhaps the most straightforward way of characterizing the condition for fracture and these values are presented in Table 2 as $\varepsilon_{\max}/\varepsilon^*$. For comparison, also normalized strains at fracture measured in the conventional way by extensometer are presented in Table 2 as $\varepsilon_{\text{conv}}/\varepsilon^0$. Here, the normalizing value $\varepsilon^0$ is the fracture strain measured by the same extensometer in a conventional tensile test of a specimen with thickness 1.2 mm. In the last two rows of Table 2 the results for homogeneous specimens without holes are presented and from those, the average fracture strains for the 1.2 mm thickness are chosen for normalizing.

The two normalizing strains $\varepsilon^*$ and $\varepsilon^0$ reflect different physical processes and length scales and are therefore of different magnitudes. The local equivalent fracture strain $\varepsilon^*$ is measured by DSP on a small length scale at an inner point in a specimen where plastic localization and fracture develops and is therefore not influenced by edge conditions. On the other hand, the conventional fracture strain $\varepsilon^0$ measured with an extensometer represents a mean value of the strain over a length of 50 mm in this case. A conventional tensile fracture strain value is also influenced by the conditions of the edges of the specimen which in this case were produced by abrasive water cutting. Due to these differences the two normalizing strains differ and the ratio $\varepsilon^*/\varepsilon^0$ is 6.1 for the tested material.

<table>
<thead>
<tr>
<th>Specimen description</th>
<th>Normalized local fracture strain $\varepsilon_{\max}/\varepsilon^*$</th>
<th>Normalized conventional fracture strain $\varepsilon_{\text{conv}}/\varepsilon^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># 1</td>
<td># 2</td>
</tr>
<tr>
<td>Pre-punched</td>
<td>1.2</td>
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<tr>
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<tr>
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<tr>
<td>Homogeneous</td>
<td>2.4</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2. Normalized values of the maximum local strain and of the conventionally measured strain at fracture.
Table 2 clearly shows that there are significant differences in fracture strain between the different hole making procedures especially for the case of normalized local fracture strains. The pre-punched specimens show a considerably higher level of strain at fracture than both the laser-cut and the post-punched samples. The difference between laser-cut and post-punched samples is not as noticeable but the laser-cut samples seem to have a slightly higher maximum local strain. The differences are less pronounced for the normalized conventional fracture strain.

For the case of normalized local fracture strains it is noted that the values for pre-punched specimens are about 90% of the value for 1.2 mm homogeneous specimen. This implies that the pre-punching procedure does not significantly affect the fracture behavior of the material. On the other hand post-punching has a detrimental effect in that the local fracture strain is only about 20-30% of the local fracture strain \( \varepsilon^* \) for the 1.2 mm homogeneous material without edge effects.

Comparing results for normalized conventional fracture strains reveals that pre-punching lowers the observed fracture strain to less than half of the fracture strain of homogeneous 1.2 mm specimen. Thus, the result for conventional fracture strains is in contradiction to the results for local fracture strains; the latter being of similar magnitude for pre-punched holes and homogeneous material.

**Discussion and conclusions**

Measurement of local strain at edges of holes is facilitated with optical field methods like digital speckle correlation and the small length scale associated with the speckle method makes monitoring of local conditions possible. The detailed information of the strain field just before fracture that can be derived from the speckle measurements makes results from field methods more useful than results from conventional test methods based on extensometer measurements when assessing fracture behavior. Fracture criteria should be based on local conditions at the edge of a hole rather than on mean strains over the gauge length of an extensometer.

The detailed measurements of the deformation in the proximity of holes show that there are significant differences between different hole making procedures. The local fracture strain at the edge of the hole is for instance approximately three times higher for pre-punched holes than for post-punched holes. This knowledge is important when designing products that should withstand as large deformations as possible. The large differences are probably due to a number of phenomena.
like; micro-cracks, heat effects and residual stresses. In the case of post-punching of a hardened material it is likely that micro-cracks appear, partly because hardened materials are more brittle than non-hardened materials and partly because large forces are required to punch the hole. Large forces give rise to large stresses which in turn could produce the micro-cracks. The pre-punched hole requires less force since the punching is performed on a non-hardened material, the material itself is also less brittle and therefore less sensitive to crack formation than the hardened material. Since the local failure strain is approximately the same for fracture at a pre-punched hole as for a fracture that emanates from an interior point it can be assumed that the material is almost unaffected. For the laser-cut holes the thermal effects are believed to reduce the materials fracture strain at the edge of the hole but this effect is less than the effect from post-punching.

In this study two specimens of every type have been tested. For such small populations the results can not be considered reliable from a statistical point of view but they can serve as an indication of trends.

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