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THE EXPERIMENTAL STUDY OF THE EDGE FORMABILITY OF HIGH STRENGTH STEEL SHEETS

Booklet of PhD Theses

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1. INTRODUCTION

1.1 PRELUDE

In the past decades, the researches in the automotive industry have been influenced by two factors: the environmental-, and the safety regulations. Due to the growing number of vehicles on the roads, their emissions need to be reduced in order to protect the environment. Several ways to reduce the environmental impact are known, such as the use of start-stop engines or electric cars, but a significant portion of cars – currently running on the roads – are still equipped with conventional internal combustion engine. One of the most effective way to reduce emissions in terms of mass production is, to reduce the total weight of components used in car construction, with it reducing the total weight of vehicles. For some of the originally steel and other metal parts, weight reduction was achieved using other groups of materials (polymers or ceramics). Due to the degree and complexity of the mechanical stress on the car body parts, these materials could not be considered, so a different solution was needed.

In case of car body parts, a reduction in the amount of material used will also reduce the compliance of these components with the safety requirements, set out in the safety regulations. The reduction in weight can therefore only be compensated by increasing the strength of the used steel sheets. Due to this, although vehicles have been based on cold-rolled steel sheets for decades, there have been dynamic progresses in material development over the last 20-30 years [1]. As a result of these developments, a wide range of high-strength sheets are now available to the automotive industry.

In addition to the advantages of using high-strength steel sheets, mention should also be made of their limitations. The most important disadvantage of high-strength steels (and aluminiums) is the inverse proportionality between strength and formability. To overcome the lack of formability, multi-step – typically hot forming – technologies have been developed. However, their use involves significant cost overruns compared to traditional procedures.

Achieving cost-effectiveness has thus induced new developments, as a result, a wide variety of software systems are available novadays. These software helps engineers from the geometric design of a given component, through to manufacturability analysis to its in-service testing. The most common software in the field of sheet metal forming are finite element modelling (FEM) software. Although there are differences between these software, the structure of the simulations are always based on an accurate description of the material behavior. The steel sheets with the increasing load first undergo elastic, then plastic deformation, so for the simulations the elastic and the plastic behavior need to be described. Charaterizing the behavior of the material in these two stages of deformation is not a challenge, as standards are available in both ranges that accurately describe the tests required.

The limit of deformation is the failure of the material according to a given aspect, but this aspect may differ depending on the application of the part.

By conventional interpretation, failure is the breaking of a part. The research of the fracture prediction, so the limit state of the formability has a significant history [2]. The aim of the research in the beginning was to describe the fracture limit using mechanical-mathematical models, that define the edge formability according to the stress states that occur during each deformation. To accurately define models describing the full stress field – which can be applied to complex deformations –, a series of test (involving different specimens and methods) have been developed. The models defined this way, however, were not unconditionally applicable to sheet metal parts [3] – as they tipically used bulk test to investigate different individual stress states –, and their import into industrial software was questionable.

In the case of automotive sheet metal parts, not only the failure, but usually even 30% thinning is not acceptable. Therefore there was a need for a method that – in addition to predicting damage – would provide a good visualisation of the deformation states throughout the forming process. The most common way of describing the current state of the deformation was therefore to use the Forming Limit Diagram (FLD), which gives the limit states of the deformation as a function of the major and minor strains. Its main component is the Forming Limit Curve (FLC), which describes the major and minor strains, corresponding to the onset of necking. The widespread use of FLD and FLC can be explained by the ease of definition according to the standard [4] and their applicability in industrial software.

The forming limit curve is therefore defined by local thinning due to structural instability during deformation. However, this instability may differ [3] for global deformation (e.g. stretching), which affects a large volume, and local deformation (e.g. flanging), which affects a small volume of material. Although the former is adequately approximated by the forming limit curve, nowadays more and more emphasis is put on operations generating local deformation, where fracture may occur in the region below the limit curve (for example due to surface cracking on the drawn side [5]). This explains the increasing focus in industrial applications on the consideration the true limit of forming, i.e. the occurrence of fracture, which is characterised by the Fracture Forming Limit Curve (FFLC) in the context of major and minor strains [6].

In the case of plastic deformation of sheets, it is important to distinguish between the range of deformation due to tensile and shear loading. Deformation in the tensile stress range is delimited by the FLC and FFLC. However, in automotive applications, cases where no or negligible thinning precedes fracture are becoming more common. This is typical for parts (small radius, straight-walled deep drawn parts) where the strains fall outside of the space limited by the FLC. In these cases, in the absence of necking, neither the forming nor the fracture limit curve define the limit of formability.

As a result, ongoing research is being directed towards an increasingly precise definition of the fracture limit over the entire deformation space. Research on forming limit diagrams has shown that in the tensile stress range the fracture limit can be easily determined by conventional standard tests, but in the shear stress field the fracture limit and the damage process itself are significantly different. Newer and newer versions of these specimens are being developed.

The study of pure shear strain to fracture is a crucial part of today's research. New test methods have been developed, such as the experimental cup drawing test [7], or improved, such as the in-plane torsion test [8]. However, the most widely used testing method remains the use of tensile loaded specimens. The complexity of the test methods is demonstrated by the fact that the shear strain to fracture values for a given material can vary significantly in some literature [9].

1.2 THE PURPOSE OF THE DISSERTATION

The actual limit of the formability of a given material is therefore determined by its strain to fracture. Accordingly, today's research is focused on the determination of the fracture limit diagram, i.e. the FFLC, and its possible applications. The validity of my research is underlined by the fact that there are significant differences between the global – i.e. the entire material – and the local – i.e. the small part of the material – strain to fracture of the DP (Dual Phase) steels I investigate in this thesis. Although the FFLC is a good characterisation of the strain to fracture of a given sheet material, there is currently no standardised method for its determination.

For the preparation of parts for manufacturing, the proper definition of the limit deformation in finite element software has become essential. This requires the determination of the fracture strain corresponding to a given strain (or stress) condition, which is interpreted without standards, using specimens of different designs under varying considerations [10]. However, differences between measurements may lead to different results and the comparability of materials may be questionable.

The aim of my thesis is to determine the strain to fracture in the range relevant for automotive sheet metal parts. The subject of my research is the high strength DP steels which are commonly used in the automotive industry. My investigations on 1 mm thick DP600, DP800 and DP1000 sheets can be divided into two major parts in the space of principal shape changes, thus I have defined two objectives.

One of my objectives is to determine the fracture strain in the range between uniaxial and biaxial tensile. There is a commonly used, although not standardized, method for determining the fracture behavior of sheet metal components in the range above the forming limit diagram. Thus, to determine the fracture limit diagram in the range between uniaxial and biaxial tensile, I will perform the conventional Nakazima test on the above mentioned DP steels and then derive the fracture strain points based on the fracture thickness of the specimens.

My second objective is to determine the fracture strain for pure shear and the range between shear and uniaxial tensile. For shear loading, a number of test specimens and test methods have been developed to determine the fracture strain. Studying the specimens and test methods, it was found that the suitability of simple specimens is questionable, and that the production of specimens with complex geometries leads to significant cost overruns. Based on the literature review, the objective was therefore to create a test specimen that could be produced cost-effectively using commonly available equipment, yet still meet the requirements of the latest test specimens. Using the new shear specimen geometry, other specimens are being developed to extend the shear limit into the shear-tensile range.

At the end of my dissertation, I will obtain a fracture forming limit diagram by combining the fracture points determined in the two domains (shear versus uniaxial tensile and uniaxial versus biaxial tensile stresses). By transforming the fracture strain points defined in the strain space to the fracture points in the stress space, the mathematical relationship between the fracture strain and stress triaxiality for the DP steels investigated, will be determined.

In summary, I set the following objectives for my research:

- I will investigate the feasibility of replacing the technology typically used for the manufacture of pure shear specimen (wire-EDM) with a more economical, more achievable technology.
- The contour geometry of the shear specimens used nowadays is complex. My objective is to create a test specimen which follows a pure shear strain path using simple geometric elements.
- Optimizing the contours of the currently used test specimens for different material grades, is a time consuming process due to their complex geometry. For the new simple geometry test specimen, my purpose is to investigate the relationship between strength and geometry, thus allowing simple optimization
- Furthermore, my research goal is to use the geometry of the new shear specimen to create shear-tensile test specimens, so that the range between uniaxial tensile and pure shear deformation paths can be covered by a simple modification of the geometry.
- Mathematical approximation curves were fitted to the fracture strain points determined by the Nakazima test and using the new test specimens.

2. METHODOLOGY

After a review of the relevant literature, physical measurements were carried out using modern shear specimens as stated in the objectives. The results of these tests confirmed the literature, that changing the shear zone contour geometry of the specimen results in a deviation in the strain path and the strain to fracture [12]. An investigation of the effects of different manufacturing technologies has shown that the application of each technology has an impact on the fracture strain. Based on the tests carried out on specimens made by the three chosen technologies (wire EDM, laser cutting, milling), it can be stated that the manufacturing technology strongly influences the interpretation of the strain to fracture of shear specimens subjected to tensile loading. The microstructure images of each contour and the measured hardness distributions suggested that, the greater the change in the microstructure of the material near the contour (hardening), the less it can withstand the tensile stresses occurring there, and that crack initiation from the contour leads to an underestimation of the fracture strain.

One objectives of my research was to create a new test specimen – based on finite element modeling – that can be manufactured using commonly available techniques, has a simple geometry and is also suitable for state-of-the-art test specimens. The geometry was designed and optimised in the MSC Marc Mentat 2018 finite element modelling software. Three main requirements were defined for the new specimen namely: that the strain distribution in the shear zone should have one local maximum, the strain path (at the local maximum) should correspond to pure shear, and that the values of the metrics introduced to characterise the stress state during deformation should also correspond to the pure shear stress state.

Using finite element modelling, a test specimen was created by modifying the current standard specimen. By changing the geometry of the shear zone of the new shear test specimen, the relationship between the geometry and the strain and stress states was investigated. The new design of the specimen was optimized for the three steel grades that were tested in my dissertation, by rotating the shear zone relative to the load axis. To develop test specimens to determine the fracture strain in the range between pure shear and uniaxial tensile, also the angle of the shear zone with the load axis was modified. In summary, by numerical modelling, a specimen geometry built up from easily manufacturable geometric elements has been created, which, by varying a single parameter, is suitable for determining the fracture strain of the three tested steel grades under pure shear and shear-tensile loading.

The objective was to determine, by physical measurements, the strain to fracture in the strain range relevant for automotive sheet metal parts for the three investigated DP steels. The determination of the fracture limit curve was performed in two steps. First, the Nakazima test was carried out on the tested DP steels, then the fracture region was cut out from the specimens, and using a specially developed specimen preparation tool, the fracture thickness was measured. In the range between uniaxial and biaxial strain paths, the fracture strain was determined using the maximum principal strain changes in the last image recorded by DIC (Digital Image Correlation) and the fracture thickness. The fracture limit curve was then extended to the range between the strain paths corresponding to uniaxial tensile and pure shear, with the two-bridge test specimen that was created. For the shear-tensile specimens, the points corresponding to fracture were determined using the fracture thickness, as in the Nakazima test. The specimens were loaded to failure by uniaxial tensile loading, while the deformations were measured using DIC technology. Using the maximum strain - measured in the last image before fracture - and the corresponding sheet thickness on the surface of the fracture, the fracture limit was extended to the shear-tensile range.

Although automotive software typically uses the principal strain space to define damage, scientific software specifies damage, typically using a mechanical-mathematical model of comparative strains to failure based on a stress space. Therefore, it was important to investigate the fracture strain by converting it from strain space to stress space. Since the double parabola showed the best fit of the approximation relations investigated for the equivalent strain points recorded in the stress field, the fracture points of the three materials were approximated by this relation.

3. NEW SCIENTIFIC RESULTS – THESES

T1. In the case of shear specimnes cut from high strength DP steel sheets to determine the fracture strain of the material, conventional chipping or wire EDM cutting processes should be preferred to laser cutting, as the laser cutting causes a change in the microstructure of the material along the cut contour, which results a significant underestimation of the actual fracture strain of the material. (1.)

T2. For high-strength steel grades DP600, DP800 and DP1000, the newly developed so-called two-bridge specimens with a shear zone rotated with respect to the load direction, which easy to manufacture and can be constructed from simple geometric elements, are suitable for maintaining the strain and stress state of pure shear loading. (1.)(2.)

T3. For high-strength steel grades DP600, DP800 and DP1000, there is an inverse proportional relationship between the tensile strength (R_m) of the materials and the angle of rotation ($\delta^{DP600} = -13°$; $\delta^{DP800} = -11°$; $\delta^{DP1000} = -9°$) to the shear zone, measured with respect to the axis of the tensile load on the so-called two bridge shear test specimen, whtich maintains the shear zone in the pure shear strain and stress state for the longest time during the measurement. (2.)

T4. Based on the results of my physical measurements, the range of strain paths that can be captured by the Nakazima test can be extended from tuniaxial tensile to pure shear, thaks to the new two bridge specimen. By converting the defined fracture points from the strain field to the stress field, the stress- dependent fracture behaviour of the investigated materials was described, and the following conclusions were drawn: (3.):

a. The fracture points show the best correlation with the double parabola, i.e. with two adjacent intersecting polynomials of degree two, of the approximate relationships that have been tested.

b. Altough the fracture strain values of the double parabolas applied to the fracture points of the high strength DP600, DP800 and DP1000 steels show an inverse proportionality with strength, the intersection points of the parabolas are always at a stress triaxiality value of 0.54.

4. INDUSTRIAL UTILIZATION AND FURTHER DEVELOPMENT

By using the fracture strains determined as a result of my research, it is now possible to extend the fracture limit curve (FLC) - used in numerical modelling software focusing on the field of sheet metal forming - to regions between pure shear and uniaxial tensile, where the values of the fracture strain were not defined for the investigated materials. This will address the discrepancies in the physical and numerical analysis of the modelling problems (small radius drawn cylindrical pot) described in the introduction to my thesis.

The conversion of the fracture points from principal strain space to stress space can provide the possibility to determine the parameters of fracture theories commonly used in general finite element software, based on the extended test results. The mathematical approximation of the measurement points with a double parabola provides the possibility to determine the fracture strain changes over a relatively wide range of stress triaxiality.

The developed test specimen design procedure, based on numerical testing, anticipates the testing of additional material qualities by modifying the basic geometric elements. Comparison of the double parabola fracture strain - stress triaxiality diagrams of the investigated material grades can serve as a basis for more general statements about fracture strains.

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