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Experimental detection of forming limit strains on samples with multiple local necks

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ABSTRACT

Sheet metal formability is traditionally described by the forming limit curve (FLC). Experimental FLCs are obtained by performing formability tests and determining failure strains. The strains are usually measured either by etching a grid on the sheet surface or by digital image correlation (DIC). Ductile metal sheets fail primarily by local necking which introduces a severe strain gradient in the failure region. This makes accurate detection of the failure strains challenging. An international standard (ISO12004-2:2008) was introduced in 2008 to unify the procedure of FLC detection; prior to this large discrepancies were observed between the results reported by different laboratories. The main limitation of the standard method for detection of forming limits is that its application is limited to cases where a single local neck is formed in the metal sheet prior to fracture. In the case of multiple local necks, the samples are simply discarded. Furthermore, the standard method does not include any guidelines to distinguish the failure by local necking and direct failure by fracture. One of the advantages of DIC over the traditional etched-grid technique is that the former allows us to obtain not only the strain distribution but also its history. This allows for alternative methods for detection of forming limit strains. This paper introduces a DIC-based method which was specially developed to handle the case of multiple local necks and to distinguish failure by local necking from direct fracture automatically. The method is not confined to a single test type and can be used in combination with different formability tests as long as DIC is used to measure strains.

1. Introduction

As stated by Hosford and Caddell (2007), the invention of the forming limit diagram (FLD) by Keeler (1968) and Goodwin (1968) has literally transformed the field of sheet metal forming from art into science. Since then sheet metal formability is commonly described by FLDs that provide a quantitative description. The traditional FLD is a diagram with major and minor strains on its axes with a line dividing safe levels of strains from unsafe ones denoted as the Forming Limit Curve (FLC). The lowest point of the FLC lies near the plane-strain state and is denoted FLD_0.

One of the challenges connected to the use of the FLC for description of formability is the accurate measurement of the failure strains. Since ductile metal sheets typically fail by formation of a local neck, large discrepancies in the measured strains can be observed depending on how far from the neck the measurements have been taken. Liebertz et al. (2004) reported a round robin formability test series on the same material performed by three different laboratories that produced $FLD_0 \approx 0.15$, $FLD_0 \approx 0.21$ and $FLD_0 \approx 0.25$ respectively. In order to prevent such discrepancies Liebertz et al. (2004) developed a set of guidelines for detection of the forming limit strains. In a second round robin the guidelines were implemented and the different laboratories produced similar results. These guidelines served as foundation for the international standard ISO12004-2:2008 and this method for detection of the forming limit strains is referred to as the *standard method* further in the text.

In the standard method, the forming limit strains are detected by fitting an inverse parabola to the strain distribution in the vicinity of the fracture line. Thus, the method relies on the formation of a single local neck prior to fracture to ensure a good fit. The international standard ISO12004-2:2008 explicitly states that samples with multiple local necks shall be discarded.

The experience accumulated of the use of the standard method showed over several years that the method might not be applicable to some types of metallic materials. As reported by Hotz et al.

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(2013), some high-strength steels and aluminium alloys show non-homogeneous deformation behaviour providing no reasonable fit for the inverse parabola. This leads to an invalid mathematical evaluation if the standard method is used. In order to evaluate the formability of such alloys an alternative method is needed.

The development of the digital image correlation (DIC) technique for strain measurements provides new opportunities for the detection of limit strains. DIC is a technique used to determine the displacements of a surface from the analysis of a series of images. Since pictures are taken continuously through the test, the technique produces the displacement history as well. Provided sufficient accuracy, the strain fields can be calculated from the displacement fields. DIC techniques can be classified into 2D-DIC and 3D-DIC. 2D-DIC utilizes a single camera and is limited to in-plane deformations of flat surfaces. 3D-DIC allows for handling surfaces that deform out of their original plane, utilizing two cameras a three-dimensional displacement field is produced, giving the surface topography along with the surface strains.

The onset of local necking corresponds to an increase in the local strain rate. Marron et al. (1997) were the first to suggest using the evolution of strain rate to detect the onset of local necking. They used a combination of a circular grid and cameras to record the strain evolution. Later Merklein et al. (2010) independently implemented a method based on similar principles using DIC. The common feature of the strain-rate based methods is that the plot of strain rate vs. time for a region affected by the local neck is used to determine the onset of local necking. The main difference between the methods used by different authors is the mathematical algorithm adopted. Marron et al. (1997) proposed to use an intersection of two straight lines fitted to the major strain rate evolution: one before the increase in the strain rate and one after. Merklein et al. (2010) used the time derivative of the major strain rate in combination with an original algorithm. Situ et al. (2011) detected the onset of local necking at the maximum value of the time derivative of the major strain rate. Vysochinskiy et al. (2012) used an original algorithm based on the analysis of the major strain rate itself and detected onset of necking at the point of greatest curvature of the strain rate plot. Volk and Hora (2011a) utilized the algorithm similar to Marron et al. (1997) but applied it to the strain rate in the thickness direction $\dot{\epsilon}_3$, instead of the major strain rate $\dot{\epsilon}_1$. A more detailed description of the algorithm is presented in Volk and Hora (2011b). Hotz et al. (2013) presented a comparison of the algorithms proposed by Merklein et al. (2010) and Volk and Hora (2011a) and two new algorithms. Hora et al. (2012) linked the local strain rate to the level of strain localization replacing the traditional FLD with the localisation level FLD (LL-FLD). This approach produces several FLCs that correspond to different levels of localization and is thus similar to the forming limit band approach proposed by Janssens et al. (2001).

The strain-rate based methods for detection of forming limits are not yet standardized and there is no commonly accepted algorithm. Use of different algorithms leads to different results, which can be either more or less conservative than the ones obtained by the standard method. For example, in the comparison presented by Hotz et al. (2013) one of the analyzed methods is more and three are less conservative than the standard. In addition, a drawback of the strain-rate based methods is that calculation of the rate amplifies the noise naturally present in the DIC strain measurements. Thus, these methods require the noise in the measurements to be low, otherwise smoothing of the strain evolution curve may be needed. Smoothing in itself is an additional procedure that may affect the results.

Some DIC-based methods do not utilize the strain rate history. Vacher et al. (1999b) suggested to use the strain velocity map between two subsequent images in the DIC analysis to determine when the strain field is no longer homogeneous. The onset of local necking is detected when a strain gradient above certain tolerance level is observed. This method is limited to the case of homogeneous deformation. Wang et al. (2014) utilized the surface topography produced by the 3D-DIC software to detect the onset of local necking. They compared the surface height of a point inside and a point outside the neck to determine the onset of local necking. This method is limited to the flat surfaces provided by the flat punch in Marciniak–Kuczynski formability tests.

In this paper a new robust and user-independent method for detection of forming limit strains is proposed. The method was developed to enable detection of forming limits in AA6016 aluminium alloy sheets that displayed non-homogeneous deformation in biaxial tension. Thus, the method was designed to handle the case of multiple local necks that is not covered by the international standard ISO12004-2:2008. The method does not require calculation of the strain rate and is thus more robust with respect to noise in comparison with the strain-rate based methods. The detection of the forming limit strains can be fully automated and input parameters and any influence from the user are explicitly specified to ensure that different users would obtain the same result when using the proposed method.

2. Material and experimental program

The investigated material is aluminium alloy AA6016 commonly used in the car-body due to its good forming properties. The investigated sheets have nominal thickness 1.5 mm and are intended for the manufacturing of some inner parts of the car body. Thus, there are no surface quality requirements.

This paper covers the formability tests on as-received AA6016 sheets which are a part of a larger experimental programme intended to characterize the material properties (Vysochinskiy, 2014). The experimentally obtained true stress–strain curve for this material is illustrated in Fig. 1. The formability tests were performed in a BUP600 forming machine.

The intention was to characterize the formability of the material and construct the FLC in biaxial tension through Marciniak–Kuczynski tests (Marciniak and Kuczynski, 1967). In this type of test a sheet of metal is stretched over a flat punch with an underlying blank with a hole that creates a friction-free zone. Rectangular 205 mm long samples were used. To achieve different strain-paths, different widths: 155 mm, 160 mm, 165 mm and 205 mm were used. Since the material is expected to be anisotropic,

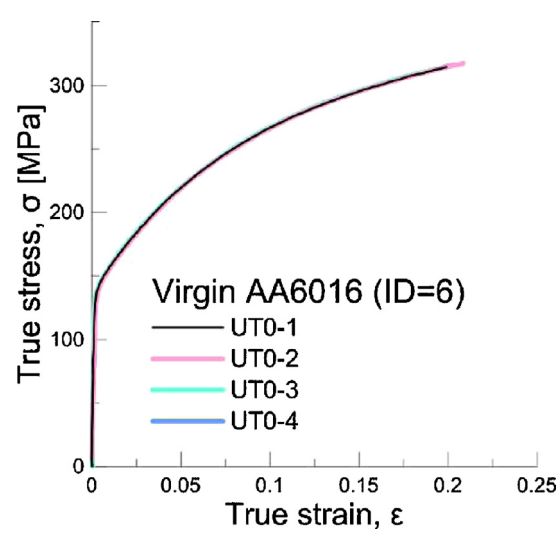

Fig. 1. True stress–strain curves from uniaxial tension tests of virgin AA6016 samples (Vysochinskiy, 2014)