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New approaches to detect the onset of localised necking in sheets under through-thickness strain gradients

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ABSTRACT

The standard ISO 12004-2:2008 provides a position-dependent methodology to estimate the limit strains in Nakazima- and Marciniak-type tests. However, this method is not applicable, at least in its current formulation, when there are significant strain gradients across the sheet thickness, such as when using relatively small punch radii or in stretch-bending operations very commonly in industrial practice. This paper analyses two physically-based methodologies, a time-dependent method and a time-position-dependent method (called here *flat-valley method*), to detect the onset of necking and to evaluate the limit strains under significant strain gradients through the sheet thickness. The digital image correlation (DIC) technique is used to compute the displacement and strain evolutions at the outer surface of the tested specimens using the commercial software ARAMIS®. A detailed analysis and validation of both methodologies, and comparison with other local methods recently published in the literature, are carried out in the light of a series of Nakazima tests and stretch-bending tests for different cylindrical punch radii in AA7075-O.

1. Introduction

The forming limit curve at necking (FLC) is one of the most widely used tools for evaluating sheet metal formability at the industrial level. This curve represents the maximum values of the principal strains (for the major strain ε_1 versus the minor strain ε_2) for the onset of localised necking in a sheet subjected to different "proportional" strain ratios. In this way, a boundary is established between strain states that facilitate sheet forming and those that produce sheet failure.

Both theoretical and experimental methods are being used in practice for the identification of the FLC. Within the theoretical framework, the pioneering work of Hill [1] postulated a criterion for the localised necking under plane stress conditions, in which the neck forms along the zero extension direction. This criterion was suitable for obtaining the left-hand side of the FLC. For the right-hand side, Swift [2] suggested that instability occurs when the principal stresses attain their maximum and predicted the critical strains for diffuse necking. But, perhaps, the most widely used analytical tool is the Marciniak–Kuczynski (M–K) model [3]. This is based on the assumption that necking occurs due to initial imperfections. In biaxial stretching, the onset of necking is associated with the establishment of a localised plane strain state at imperfections perpendicular to the major strain direction. Later, Hutchinson and Neale [4] improved the model to cover the whole range of the FLC. More recently, Eyckens et al. [5,6] have extended the M–K model to include Through-Thickness Shear (TTS) for both isotropic and anisotropic metal sheets. They claimed that formability seems to increase by TTS, this being a parameter to be explored in sheet forming processes in which sliding contact with friction between the punch and the sheet occurs, e.g. in incremental sheet forming.

A number of theoretical modelling based on the continuum plasticity have been reviewed by Zadpoor et al. [7]. They compared four different approaches for necking and fracture to predict the failure of the high strength aluminium alloy 2024-T3. The influence of the through-the-thickness strain gradient in postponing the onset of necking has been discussed by Zadpoor et al. [8] for 2024-T3 and 7075-T6 sheets. Zhang et al. [9] provided an approach to model the localised necking in anisotropic sheet metals to construct the FLC. Based on the plastic instability and uses Swift's diffuse necking and Hill's localised necking concepts, Firat [10] implemented two numerical models into Ls-Dyna to predict the FLC of a high-strength dual-phase steel using in-plane proportional loadings.

Although many efforts have been made to develop theoretical models to predict the FLC, its experimental determination is unavoidable to calibrate or validate these models. Furthermore, in many practical cases, the accurate obtaining of the FLC is mandatory to provide reliable results. The main difficulty is the precise detection of the onset of necking and the measurement of the sheet strain at this point. No standardised methodologies were available until the end of 2008; consequently, different experimental

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techniques have been used historically to determine the limit strains at the onset of necking.

The Bragard method [11,12] is one of the most traditional schemes for determining the strain at the onset of necking. Briefly, the method evaluates the distribution of the major strain along various sections perpendicular to the crack in the fractured specimen. The strain can be evaluated by manually measuring a pre-engraved grid pattern on the sheet or using recent techniques based on three-dimensional digital image correlation (DIC) [13]. The measured major strain distribution (ε_1) is fit, generally with a parabola or an inverse parabola, for each section of the sheet. The limit strain for necking in each section corresponds to the maximum value of the fitting function. Another classic method analyses the principal strain-paths using a ε_1–ε_2 diagram. The experimental observation shows the development of a local plane strain state at the onset of localised necking, independent of the global strain state applied to the sheet. That is, the initiation of necking is associated with an abrupt change in the slope of the ε_1–ε_2 curve because of the local plane strain conditions. Unlike the Bragard method, the strains have to be continuously evaluated during the sheet-forming process in this method. A detailed analysis of these criteria and other representative criteria to estimate the forming limits can be found in the literature [14,15].

Various techniques and principles from the aforementioned methodologies have been appropriated in the ISO standard 12004-2:2008, "Metallic materials – Sheet and strip – Determination of forming limit curves in laboratory" [16]. The standard aims to define specific test conditions and a unified evaluation procedure to reduce the dispersion between the FLC calculations from different laboratories. The current procedure is a position-dependent methodology in which the principal strain distributions are analysed for sections perpendicular to the crack immediately before the appearance of fracture. The procedure is called a position-dependent methodology because the onset of necking is estimated by analysing a single and unique instant in the process. A detailed analysis of the foundations and justification of the ISO 12004-2:2008 methodology has been given by Hotz and Timm [17]. The main steps in the practical application of ISO method have been discussed by Martínez-Donaire et al. [18,19].

Optical techniques and image analysis are being increasingly and extensively used to measure the strains automatically over the entire sample surface for the whole duration of the test. The innate ability to have the strain data continuously throughout the test using these techniques, allowed to explore and to formulate time-dependent methods for the FLC determination, as alternative to the position-dependent methodologies. Some of these methods were developed by Geiger and Merklein [20], Situ et al. [21–23], Eberle et al. [24], Feldmann et al. [25], Volk and Hora [26], Merklein et al. [27], Li et al. [28] and Hotz et al. [29], among others.

In Geiger and Merklein's method [20], the onset of necking is related to the appearance of a load instability in a region where the ε_1 distribution and its spatial gradient differs significantly from the rest of the sheet. The limit strains are estimated at the boundary of this region of instability. More recently, Merklein et al. [27] formulated a criterion involving the major strain rates ($\dot{\varepsilon}_1$) in regions far from and near to the failure region. The onset of necking is identified by applying a regression methodology that the authors previously developed [30].

Situ et al. [21–23] developed a method to analyse the temporal evolution of ε_1 and its first and second time derivatives (referred to as the strain rate and the strain acceleration, respectively) at a point in the fracture region. The onset of localised necking occurs at the instant at which an inflexion point is observed in the first time derivative of ε_1 (the strain rate, $\dot{\varepsilon}_1$), or equivalently, when the second derivative of ε_1 (the strain acceleration, ε_1) reaches a maximum. The authors considered that the reduction in ε_1 from a maximum value to zero represented the strain localisation process.

Feldmann et al. [25] developed an automated algorithm to determine the FLC, which has already implemented in the commercial software Autogrid. This method analyses the time evolution of the difference in the ε_1 strain increments (which are similar to the strain rates) between the most strained point in the failure region and adjacent points. The onset of the plastic instability and the limit strains were identified from the correlation coefficient for the linear fit of the different sections. Based on the previous work by Eberle et al. [24], Volk and Hora [26] proposed a temporal analysis of the thickness strain, ε_3, and of its first derivative (the thickness strain rate, $\dot{\varepsilon}_3$) along a section perpendicular to the failure region. Two straight lines were fitted along the representative thinning rate evolution, one through the stable deformation stages and the other through the last stages just before specimen failure. The authors hypothesised that the intersection of these lines defined the onset of the plastic instability. Li et al. [28] proposed to analyse the strain history and its first derivative with respect to image number from DIC at the most strained point on the specimen surface before fracture. The onset of diffuse necking was associated with the start of a rapid increase in the axial strain rate, which indicates the instability. The localised necking was identified at those points which started to lose information in the DIC postprocessing output. Hotz et al. [29] presented a comparison of four different time-dependent algorithms: a modification of the method by Volk and Hora [26], called here linear best fit; the one by Merklein et al. [27], referred to as correlation coefficient, and two methods proposed by the authors named gliding correlation coefficient and gliding difference of mean to median. Their predicted FLCs were compared with the ISO standard 12004-2:2008 [16]. It was observed that the FLCs obtained using these time-dependent methods showed values slightly greater than the FLC determined according to ISO.

Despite the plethora of existing techniques for determining the FLC, no method is universally accepted. Almost all of these methods were developed and optimised using Marciniak- and/or Nakazima-type tests, for which the curvature of the punches is zero or sufficiently small. In these cases, although slight differences in limit strains between both type of tests are expected, see for instance Leppin et al. [31], the bending effects are almost negligible in comparison with the one induced in stretch-bending tests. For this reason, many of these methods, including the ISO 12004-2:2008 standard [16], should not be applied to practical industrial applications in which strain gradient are relevant, e.g., operations with small-radii punches, corner radii in forming dies, etc.

The effect of bending on sheet formability was first clearly shown by Ghosh and Hecker [32] and later by Charpentier [33]. These studies showed the effect of the punch radius on the FLCs. Thus, the FLCs obtained by using hemispherical or elliptical punches (i.e., for out-of-plane tests), were consistently situated above FLCs that were determined under uniform strain conditions (i.e., Marciniak in-plane tests). Some authors consider the increase in forming limit strains to be a beneficial effect of the strain gradient across the thickness [34–40].

Kitting et al. [41] used a local criterion to estimate the forming limits in stretch-bending tests. In this formulation, the region where necking occurs is estimated using the strain rates in the final stages before failure along a section perpendicular to the fracture line. The limit strain is then defined as the average of the maximum strains at the boundaries of the necking region. The following sections show that this analysis, which can be acceptable when bending is small, can be inaccurate for very small punch radii.

Nowadays, there is no commonly accepted criterion for the assessment of the limit strains when bending effects are important. This paper analyses two physically-based methodologies to detect the onset of necking and to estimate the limit strains under