Journal of Materials Processing Technology 229 (2016) 758–768

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

An approach to predicting the forming limit stress components from mechanical properties

B.S. Levy[a], C.J. Van Tyne[b,*]

[a] B.S. Levy Consultants, 1700 E. 56th St., Suite 3705, Chicago, IL 60637, USA
[b] Department of Metallurgical and Materials Engineering Colorado School of Mines Golden, CO 80401, USA

ARTICLE INFO

Article history:
Received 31 January 2015
Received in revised form 19 October 2015
Accepted 22 October 2015
Available online 2 November 2015

Keywords:
Forming limit curve
Stress-based forming limit curve
Instability point in a tensile test
Plane-strain forming limit

ABSTRACT

Forming limit curves (FLCs) are used to determine the amount of deformation that can be applied to a sheet metal before the onset of a localized neck. Most FLCs are shown in strain space, and stress-based FLCs have advantages because they are often strain-path independent. The current study develops a method to calculate a stress-based forming limit curve. The necessary data for this calculation can be obtained from a uniaxial tensile test. The calculations depend on the *Z* parameter, which can be considered to be the point of instability during a tensile test. With the use of the Keeler–Brazier equation, the effective stress in plane strain at the forming limit is shown to be a function of the *Z* parameter and thickness. Data from 4 experimental studies are shown to be consistent with this function. With the generally accepted observation that the left side of the strain-based FLC is a line with slope of −1 and an appropriate constitutive model for the stress-strain behavior of the material, the stress-based FLC corresponding to the left side of the strain-based FLC can be calculated. Comparison of the calculated stress-based FLC for three steels with the stress-based FLC determined directly from the strain-based FLC shows good agreement. The calculated stress-based FLC is 15–20 MPa below the data generated directly from the strain-based FLC.

1. Introduction

1.1. Description of a strain-based forming limit diagram

A strain-based forming limit describes the locus of in-plane principal strains at which a critical local neck forms. A critical local neck is the failure criterion for a forming limit diagram (FLD). A typical forming limit diagram shows the major in-plane strain on the vertical axis and the minor in-plane strain on the horizontal axis. The forming limit diagrams typically employed in the press shop use engineering strains, although in most research studies, true strains are used. The forming limit curve (FLC), which is the locus of critical points on the FLD, is the point where necking occurs, which leads to ductile fracture in sheet metal deformation with minimal additional strain.

Limit strains in forming limit curves can be higher than uniform elongation, UE, in a tensile test because during biaxial sheet deformation, geometrical constraints prevent diffuse necking. For an FLC, failure is a critical local neck. The damage process initiates at the point where local necking starts and continues until ductile failure occurs.

Keeler and Backofen (1963) described a local neck as a narrow band of deformation where the incremental principal strain component, $d\epsilon_2$, equals zero along the axis of the local neck, and an angle between the orientation of the local neck and the largest principal stress component, σ_1, can be computed. Levy and Green (2002) showed qualitative agreement between calculated and experimental results.

Marciniak and Kuczynski (1978) described a local neck as a groove where the strain in the groove accelerates along a non-linear strain path where the normal strain component perpendicular to the axis of the groove continues to increase, and the normal strain component along the axis of the groove goes to zero. In order to have a failure criterion, the authors introduced the concept of an incipient notch that initiates failure. Many authors consider the incipient notch to be the result of metallurgical damage.

While there has been considerable additional work on the mechanics associated with the formation and subsequent failure of local necks, further discussion is excluded from the current study, because the emphasis is on failure limits due to a critical local neck.

* Corresponding author. Fax: +1 3032733795.
E-mail addresses: bslevycons@ameritech.net (B.S. Levy), cvantyne@mines.edu (C.J. Van Tyne).

http://dx.doi.org/10.1016/j.jmatprotec.2015.10.027
0924-0136/

1.2. Predicting strain-based FLCs

Keeler and Brazier (1977) developed a relationship between the plane-strain forming limit, FLC_0, and the strain hardening exponent, n, and thickness, t using regression analysis. Keeler (1989) showed that the initial regression analysis is only valid for thickness values of up to 3.1 mm, that between 3.1 and 3.5 mm there is a gradual decrease in the effect of thickness, and above 3.5 mm there is no effect of thickness. The Keeler–Brazier equation is

$$FLC_0 = (23.3 + 14.13t)\left(\frac{n}{0.21}\right) \quad (1)$$

where $n \le 0.21$, $t \le 3.1$ and t is in mm.

With the advent of highly formable interstitial free steels, a study by the North American Deep Drawing Research Group, in which one of the current authors (Levy) participated, showed that higher values of n could be used in Eq. (1).

Hiam and Lee (1978) found a thickness effect on FLCs between 0.86 to 4.32 mm for cold rolled low carbon rimmed and capped steels, hot rolled low carbon steels, and higher carbon HSLA steels. In contrast to Hiam and Lee (1978), Kleemola and Kumpulainen (1980b) studied hot and cold rolled AKDQ steels that were 0.97, 1.95, 3.00, and 4.65 mm in thickness and concluded that the thickness effect on FLCs is due to erroneous measuring techniques and definitions of limit strains.

Cayssails (1998) indicated that the Keeler and Brazier (1977) approach is inadequate for steels that are more than 1.5 mm in thickness. However, two different methods were used to measure FLC limit strains. Cayssails (1998) uses the Bragard (1989) method to measure FLC limit strains, which measures strains on either side of a fracture and interpolates to determine the actual FLC limit strain. More recently, a subgroup of the International Deep Drawing Research Group (Monford, 1999) improved the interpolation method initially used by Bragard. In contrast, the data used to formulate the Keeler and Brazier (1977) equation (i.e., Eq. (1)) is based on a method in which strain is measured over an incipient local neck (i.e., the North American method). An example of this approach is shown in the work of Levy and Green (2002). The difference between the Keeler and Brazier (1977) results and the Cayssails (1998) results may be due to the different methods of measuring FLC strain. Such differences may be more apparent for thicker steels where the FLC strains are larger.

Several research studies have presented evidence supporting Eq. (1), even when FLC_0 was determined by different experimental methods. The work by Shi (1995) used a hemispherical punch; the work by Konieczny (2001) used the Nakazima et al. (1968) method with a spherical punch; and the work by Levy and Green (2002) used the double blank method of Marciniak and Kuczynski (1967), which requires a flat punch. The results from these studies are consistent with Eq. (1).

Cayssails (1998) developed a method for predicting the FLC, based on plastic instability and a damage model which has critical variables of strain hardening, strain rate hardening, and thickness. Cayssails (1998) used a damage model from Schmitt and Jalinier (1982), which is based on the growth of cavities formed during rolling. The volume fraction of cavities and the ratio of sheet thickness to cavity diameter are critical parameters in the Cayssails (1998) model.

Cayssails and LeMoine (2005) extended the initial Cayssails (1998) model to ultra-high strength steels. They indicate that for ultra-high strength steels, the original Cayssails (1998) method must be upgraded to include consideration of a transition from a ductile to a brittle failure mode, a more complex understanding of void growth, and an improved understanding of the effect of thickness.

Raghavan et al. (1992) developed a predictive equation for FLC_0 based on hemispherical punch tests using thickness, t, and total elongation, TE, as independent variables. The equation is

$$FLC_0 = 2.78 + 3.24t + 0.892\text{TE} \quad (2)$$

where the coefficient of determination, R^2, equals 0.93, t is in mm, and TE is transverse total elongation in a 50.8 mm gauge length tensile test using ASTM A646. Their complete FLC curves have a different shape than the standard North American FLC curve.

Total elongation depends on both strain hardening and strain rate hardening. Strain rate hardening has a pronounced effect on post-uniform elongation. Using the North American approach to measuring FLC_0, the use of total elongation with a fixed specimen size can be seen to be a reasonable tensile property for predicting FLC_0. Abspoel et al. (2011a) have shown that necking strain in plane-strain tension has a linear correlation with total elongation.

Abspoel et al. (2012, 2013) used 4 strain paths to describe an FLC using the uniaxial tension necking point, the plane-strain point, the intermediate biaxial stretching point, and the equi-biaxial stretch point. They show that the left side of the FLC is a line of pure shear. Their work also shows a thickness effect, which is consistent with the left side of the North American FLC.

The studies described above show the importance of tensile properties in predicting strain-based FLCs. The tensile properties include strain hardening, strain hardening exponent, n, strain rate, and total elongation. Total elongation is a function of strain hardening, strain rate hardening, and fracture behavior. It can be seen that all the predictive methods use tensile properties that are related to stress-strain behavior, and as a result, stress is implicit in all the predictive methods.

With the exception of Kleemola and Kumpulainen (1980b), all the predictive methods include thickness. In general, thickness and tensile property terms are independent of each other. The Cayssails' method (1998) is not stated in a simple equation form, but the sense from the paper is that thickness is an independent variable. These prior studies show that thickness is an important variable for predicting forming limit curves.

1.3. Explaining the effect of thickness

Abspoel et al. (2012) have shown that once a local neck forms, it grows until failure occurs. Timothy (1989) studied a 1.6 mm aluminum alloy and found that it took 25 s from the initiation of a local neck to failure, though test speed is not given in the paper. Timothy also indicated that the local strain rate increases by two orders of magnitude from just before necking to final failure. It was also found in one alloy that fracture was preceded by initiation and propagation of shear bands.

Korbell and Martin (1988) studied a 0.06% C, 0.75 mm aluminum killed steel with rolling strains from 0.1 to 0.9. They indicated that the macroscopic localization of strain originated from micro-shear banding. They state that micro shear banding is caused by crystallographic cross slip that penetrates several grains and propagates across a sample in the form of thin plates.

Cayssails (1998) indicates the importance of the ratio of thickness to cavity size in his damage model. If it is assumed that cavity size for a given material is independent of final thickness, then the ratio of thickness to cavity size can explain some or all of the thickness effect.

Keeler (1989) suggested that FLC_0 increases with thickness because as thickness increases, a local neck becomes more diffuse and more time would be required for a local neck to reach the critical depth that is defined as failure. Furthermore, in the Keeler (1989) method, which is the North American approach, grids over a critical local neck are used to determine failure. Thus, strain rate hardening is important because strain rate hardening allows