Forming limit curve based on shear under tension failure criterion

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Abstract: The concept of deriving FLC from the stress state on the failure plane is presented. The quantity referred to as stress flux, defined as an algebraic sum of normal and shear stress acting on a plane inclined at 22.5 degrees to the plane carrying maximum normal stress, allows one to generate a FLC consistent with those obtained using other methods. In this work the strain measurement performed on a single geometry sample provided data sufficient to generate a FLC consistent with a curve obtained using multiple geometries of the samples.
Keywords: FLC, FLSD, stress flux.

1. INTRODUCTION

The assessment of forming severity in sheet metal forming applications for traditional ductile materials is based on the evaluation of principal strains measured on the surface of the formed part, against the forming limit curve, FLC, plotted on the forming limit diagram, FLD. The concept of an experimentally determined FLC was introduced by Lankford (Lankford et al., 1947) and, independently, by Keeler and Backhofen (Keeler and Backhofen, 1964). Over the last several decades the experimental FLC has gained wide acceptance in industry as a tool for evaluating forming severity in sheet metal forming processes, based on the technique outlined by Dinda (Dinda et al., 1981). The experimental procedures of determining the FLC have been legitimatized by ISO and ASTM standards, (ISO 12004-2:2008, ASTM 2218).

Another application of the FLC is in sheet forming process simulation. The conventional FLC pertains to a proportional deformation expressed in terms of the principal strains. The use of principal directions of deformation appears to be natural for determining the FLC as the curve itself is expressed in terms of the principal strains--major and minor. In the case of experimental analysis, using principal strains is the legacy of the work of Keeler and Backhofen (Keeler and Backhofen, 1964) and Goodwin (Goodwin, 1968) who used circle grid analysis, CGA, a technique which ascertains only the apparent principal strain components. The CGA technique cannot detect nor can it measure non-proportional strains and strains in a process in which the principal directions of deformation rotate with respect to the material. This deficiency of CGA is inherited by the FLC and, therefore, the direct application of a FLC in numerical forming process simulation may be flawed as, in general, the deformation evolution may not follow a proportional path. This deficiency of the FLC is eliminated by the concept referred to as the forming limit stress diagram, FLSD, which expresses the deformation state using the major-minor stress space instead of the major-minor strain.

The FLSD employs the constitutive relationship of the material to translate the FLC into the stress forming limit curve, SFLC, (Arrieux et al., 1982, Zhao et al., 1996, and Stoughton, 2000). The forming severity is evaluated assuming that the stress state causing the material failure is the same regardless of whether or not the material arrives at that stress state under a proportional or a non-proportional loading path. Though, for most materials, the FLSD does not provide an informative depiction of forming severity due to the fact that on a FLSD graph the difference between safe and critical stresses often becomes visually indistinguishable when the magnitude of strains approaches the failure level. These shortcomings of the FLSD are rectified by remapping the critical stresses determined for non-proportional deformation from FLSD back into a matching hypothetical proportional strain domain of the FLD, where the safe and critical strains are clearly distinguishable, and by evaluating these hypothetical strains against the conventional FLC. This technique has been applied by Sklad and Yungblud (Sklad and Yungblud, 1992) in the simulation of a multistage sheet forming process.

In actual industrial applications the experimental determination of FLC is time consuming and costly. The standards cited for determining the FLC specify the testing procedure for two widely used test configurations: Nakazima dome (Nakazima et al., 1968) and Marciniak cup with carrier blank (Marciniak and Kuczyński, 1967). Providing a reliable FLC for a specific grade of material requires the preparation of a large number of samples and may take several weeks of testing, as reported by Huang (Huang et al., 2008). On the other hand, if the FLC could be determined quickly and inexpensively, the stamping industry would benefit from a FLC made available for each individual coil as a measure assuring consistency of material formability in production.

Here we present a concept of stress domain based forming limit criterion, which, by employing deformation expressed in non-principal directions simplify the experimental determination of the FLC and can be directly implemented in the simulation of forming processes.

2. FLC BASED ON NON-PRINCIPAL STRESS FAILURE CRITERION

The basic mechanism of plastic deformation in crystalline materials is shear along planes inclined at an angle to the principal directions. The shearing motion of the material is caused by the shear stresses which reach maximum at planes inclined at the angle of 45 degrees to the principal directions. Under the condition of proportional deformation, employed by the FLD, the principal directions and the ratios between principal strains remain constant in the tests determining the FLC. As the principal directions of deformation are stationary so are the directions of the maximum shear stress. Plastic deformation results in a relocation of the material along the shear planes causing rotation of the material with respect to the fixed directions along which the material carries the maximum shear stress as illustrated in figure 1. In a macro-scale the effect of plastic deformation is the change of the material element shape which is captured by the principal plastic strains as those measured using the CGA grid. However, at the atomic level there is no actual equivalent to the principal strains. The dimensions of the unit cell in a crystalline material are constant and the only mechanism for plastic deformation is the rotation of unit cells and a shift of individual atoms along the shear planes, which, by designation are not principal planes.

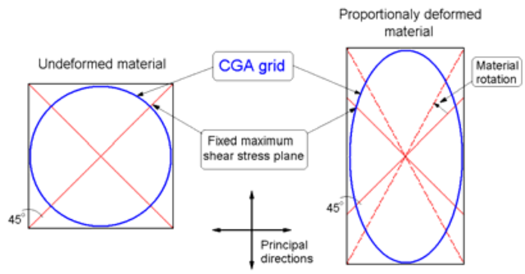


Figure 1; Rotation of the material with respect to the maximum shear stress planes

The FLC pertains to a process in which the failure of ductile material takes the form of a permanent separation of material particles due to the tension acting in a direction normal to the failure plane. In this paper we examine the determination of an FLC based on a failure criterion expressed in terms of critical stresses consisting of a combination of normal stresses - causing separation, and shear stresses - causing plastic deformation. This concept is consistent with the fundamental mechanism of plastic deformation involving the shearing motion of atoms in crystalline materials.

The traditional approach to experimental determination of the FLC and, derived from the FLC, stress domain based SFLC, employs principal directions of deformation. With reference to the principal directions of deformation each specific loading path requires a different geometry of the test sample. Any combination of principal stresses can be resolved into normal and shear stress components acting along non-principal orthogonal planes, with Mohr's circle graphically depicting the transformation. In this paper we examine the hypothesis that the FLC and the FLSC can be determined based on critical shear and normal stresses acting on a failure plane.

In theory any specific combination of normal and shear stresses can be obtained by an infinity of different combinations of principal stresses. This holds true in reverse, i.e. different combinations of principal stresses can be transformed to the same single combination of normal and shear stresses. In spite of this, the actual failure in ductile materials is restricted to three distinct orientations of the failure plane with respect to the direction of maximum stretch. The first is a plane perpendicular to the direction of maximum stretch. This orientation of the failure plane implies fracture under pure normal stress, which primarily pertains to failure in brittle materials as it does not include shear stresses which cause plastic deformation. The second orientation of the failure plane is shown in figure 2 for the case of the failure in the sheet plane. In figure 2 the failure plane is inclined at a 45 degree angle to the direction of maximum stretch and carries a maximum shear stress, $\tau_{\max}$, in addition to the normal stress, σ_n. The third

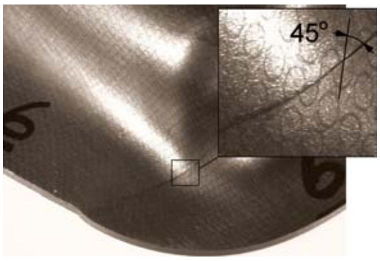


Figure 2; Failure along a plane inclined at a 45 degree angle to the direction of maximum stretch.

orientation of the failure plane is inclined at 22.5 degrees to the maximum normal stress plane. Figure 3 illustrates two examples of uniaxial tension samples exhibiting this type of failure in the sheet plane. The samples in figure 3 are made of different materials which are characterized by different magnitudes of Lakford's coefficient of anisotropy, r = 1.61 and r = 1.04. It is noticeable that the 22.5 degree orientation of the failure planes is the same on both samples and does not conform to the zero extension direction of 35.3 degrees as described by Hill for, r =1.0 (Hill, 1950).

Figure 3; Failure along a plane inclined at a 22.5 degree angle to the maximum normal stress plane.

The failure of the material along planes inclined at 45 or 22.5 degrees to the maximum normal stress plane can take place in the sheet plane as shown in figures 2 and 3 or through the sheet thickness. Figure 4 illustrates a Nakazima test sample with concurrent failures passing through the sheet thickness along planes inclined at 45 and 22.5 degree angles to the maximum normal stress plane.

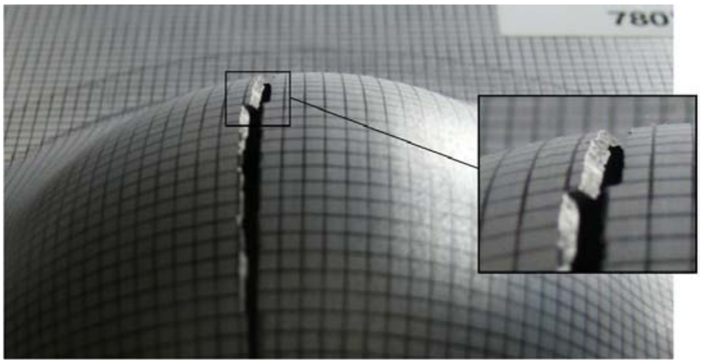


Figure 4; Concurrent failure along planes inclined at 22.5 and 45 degrees passing through sheet thickness.

The experimental evidence presented in figures 2, 3 and 4 indicates the significance in setting the failure criterion based on shear under tension stress state of the planes inclined at 45 and 22.5 degrees to the maximum normal stress plane. Figure 5 provides Mohr's circle depiction of these shear under tension cases for the plane stress condition, $\sigma_3 = 0$.

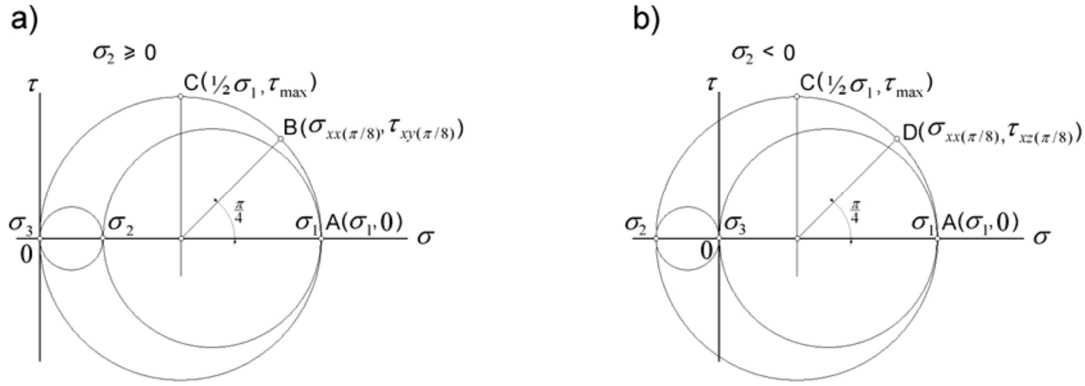


Figure 5; Mohr's circle depiction of stresses acting on planes inclined at 22.5 and 45 degree angles to the maximum normal stress plane.

In this work we have chosen the stress state acting on a plane inclined at 22.5 degrees to the maximum stress plane as an indicator of deformation severity. The chosen plane carries a maximum value of a quantity defined as:

$$R_{22.5} = \sigma_n + |\tau| \qquad (1)$$

which combines the normal stress, σ_n, and the shear stress, τ, and which we refer to as the "stress flux". We assume that the failure of the sheet material occurs when the stress flux, $R_{22.5}$, reaches a critical magnitude. The rationale for this assumption is that if given principal stresses, σ_1 and σ_2 cause failure of the material along the plane carrying the stress flux, $R_{22.5}$, any other combination of principal stress which resolves into the same stress flux will also cause failure. Equation (1) can be applied to define the stress flux on the plane inclined at 45 degrees as, R_{45}. At the present we do not use stress flux, R_{45}. For loading involving, $\sigma_2 \geq 0$, as shown in figure 5a, stress fluxes, $R_{22.5}$ and R_{45}, are different by a constant multiplier, while for loading involving, $\sigma_2 < 0$, as shown in figure 5b, the contribution of normal stress to, R_{45}, diminishes but is retained by the stress flux , $R_{22.5}$.

3. EXPERIMENTAL PROCEDURE RESULTS AND DISCUSSION

3.1 Materials, procedure and samples

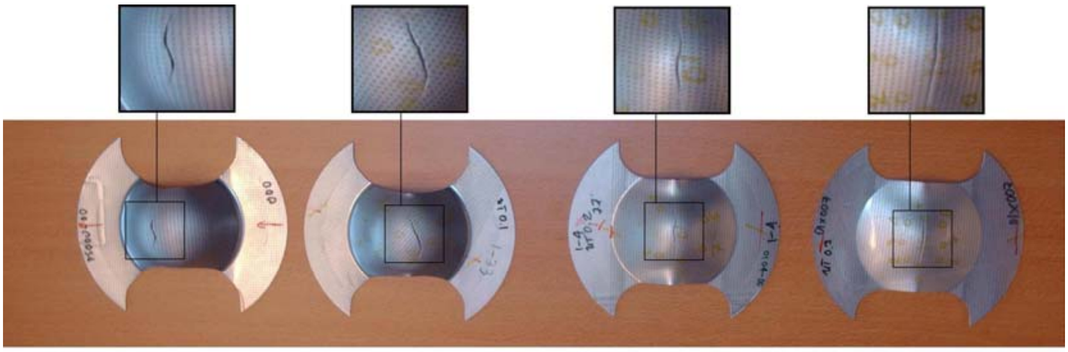
The failure criterion based on stress flux, $R_{22.5}$, has been applied to generate the FLC for two grades of steel, Corus steel DX54D+Z (designation according to EN 10327) and DP 780. The mechanical properties of the steels are listed in table I.

Table I. – Mechanical properties

Steel	Thickness [mm]	Dir. [deg]	Rp [MPa]	Rm [MPa]	A80 [%]	r	n
DX54D+Z	0.815	0	163	297	46.0	2.171	0.226
		45	172	304	43.8	1.849	0.215
		90	169	293	47.4	2.575	0.220
DP 780	1.2	-	519	851	NA	1.0	0.1

The procedure of determining the FLC involved finding the critical stress flux using Nakazima dome samples which failed along a known deformation path. The FMTI grid analyzer, GA100, was used to measure deformation in terms of principal strains and stresses. The measured grid elements were in the proximity of the fracture plane and several readings were taken to determine an average magnitude of critical principal strains. The grid analyzer program provided a calculation of principal stresses from principal strains based on the constitutive law employing yield locus with Hill's normal anisotropy (Hill, 1950) and the stress-strain curve for the material data listed in table I. The principal stresses were transformed to the maximum stress flux plane and the critical value of the stress flux, $R_{22.5}$ was determined using equation (1). Based on the value of critical stress flux, $R_{22.5}$, the FLC was calculated by finding, for each loading path defined on the FLSD by the ratio, $\beta = \sigma_2 / \sigma_1$, two principal stresses, σ_1, σ_2, which yield the critical stress flux and subsequently, corresponding with the principal stresses, proportional principal strains, $\varepsilon_1, \varepsilon_2$.

Figure 6 shows four Corus steel DX54D+Z samples targeting the plane strain used in this and a previous study by Sklad (Sklad et al., 2008). The material of the samples was subject to previous operation of pre-strain under uniaxial tension expressed in terms of effective strain, $\bar{\varepsilon}$, varying between 0.0 and 0.3 as indicated in the figure. The DP 780 Nakazima dome sample, targeting balance biaxial tension, is shown in figure 4.



$\bar{\varepsilon} = \sim 0$ $\bar{\varepsilon} = \sim 0.1$ $\bar{\varepsilon} = \sim 0.2$ $\bar{\varepsilon} = \sim 0.3$

Figure 6; Fractured DX54D+Z steel plane strain Nakazima dome test samples pre-strained using uniaxial tension

3.2 Results

Figure 7 shows the FLD with four series of points constituting the FLCs as calculated for DX54D+Z steel using stress flux, $R_{22.5}$, determined separately from each of the pre-strained samples in figure 6. The darkened points on each series indicate the test points, obtained using the grid analyzer, on which the stress flux calculation is based. For comparison the graph also includes the experimentally measured FLC determined using Corus RD&T procedure AUT-STN-002 which conforms to the previous ISO 12004 standard.

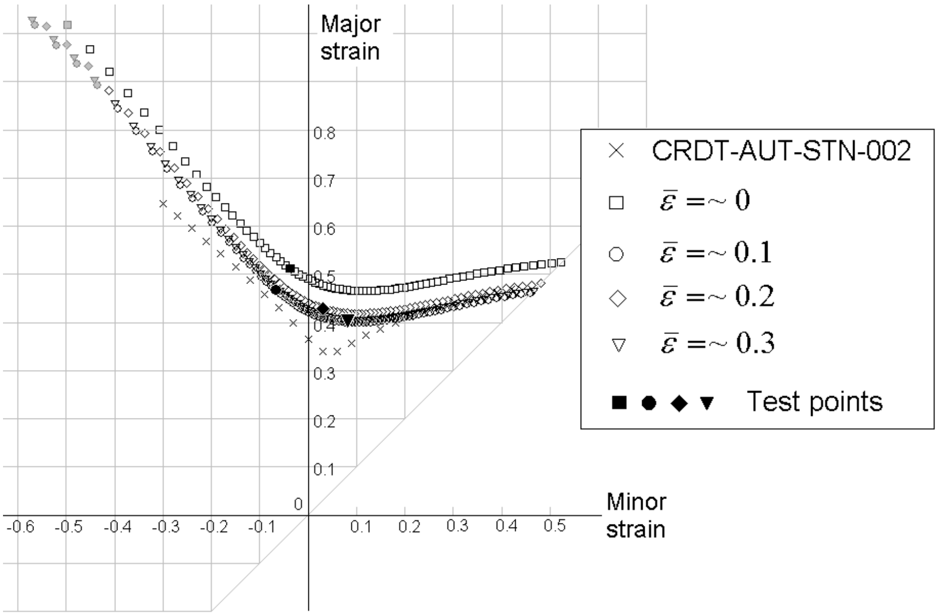


Figure 7; FLCs obtained for Corus steel DX54D+Z

The FLD with FLC calculated for DP 780 using a stress flux determined from the Nakazima dome sample targeting balanced biaxial tension is shown in figure 8.

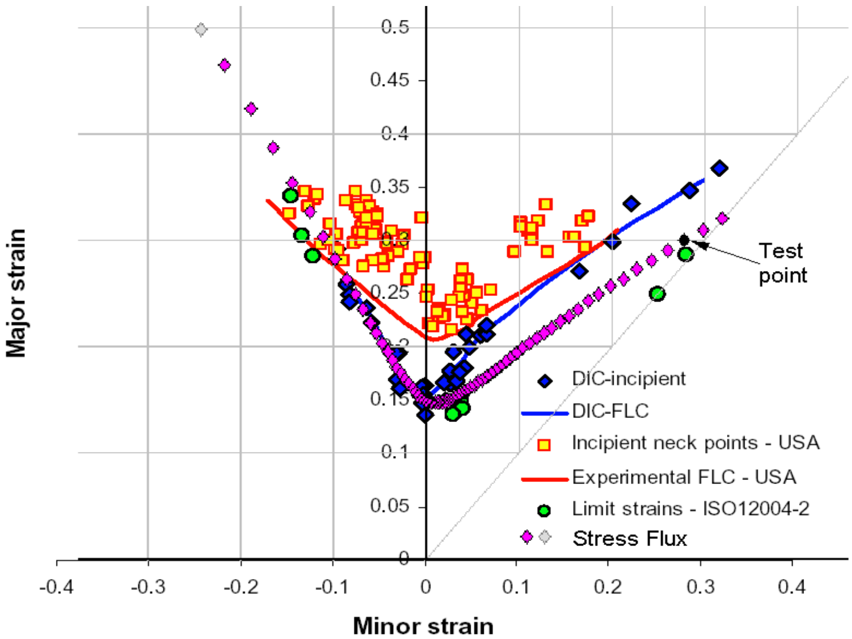


Figure 8; FLCs obtained for steel DP 780

For comparison the graph also includes digitized experimental data obtained for DP 780 steel using several different techniques reported by Huang (Huang, 2008).

3.3 Discussion

For the two materials tested, the FLCs calculated based on the stress flux, $R_{22.5}$, fall between FLCs determined using other traditional methods. The accuracy of the strain measurements and the selection of the test point to be used to determine the stress flux may have significant effect on the final result which has not been addressed in this study. Another issue is the validity of the assumed constant magnitude of the critical stress flux. Use of different loading paths for the same material would provide data regarding this aspect. Also the anisotropy of the material may have an effect on the response of the material to the stress state in terms of principal strains and may subsequently affect the shape of the FLC. These are just a few issues which need to be explored in the future.

4. CONCLUSIONS

1. The concept of deriving the FLC from the stress state at the failure plane is presented.

2. For ductile materials the failure plane carries shear stress associated with plastic deformation and normal stress associated with material separation – fracture.

3. The quantity referred to as stress flux defined as an algebraic sum of normal and shear stress acting on a plane inclined at the 22.5 degree angle to the plane carrying maximum normal stress (major stress) allows one to generate a FLC consistent with a FLC obtained using other methods.

4. In this work the strain measurement performed on a single geometry sample provided data sufficient to generate a FLC consistent with a curve obtained using multiple geometries of the samples.

5. Further research should address the effect of anisotropy and examine whether or not the critical stress flux can be treated as a material constant.

6. The stress flux based failure criterion can be directly implemented in forming process simulation.

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