FAILURE BY FRACTURE IN METAL FORMING

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Motivation

• **Left**  The forming limit curve (FLC) in incremental forming is a straight line with a negative slope (close to -1)

• **Center**  Local necking and ductile fracture are competitive modes of failure in sheet metal forming

• **Right**  Fracture strains from DENT tests are aligned along a straight line with negative slope and may be related with fracture toughness
Motivation*

Fracture in metal forming can occur in three different modes:

- Tensile (mode I)
- In-plane shear (mode II)
- Out-of-plane shear (mode III)

The circumstances under which each mode will occur are identified in terms of plastic flow and microstructural ductile damage by means of an analytical framework to characterize fracture loci under plane stress conditions that also takes anisotropy into consideration.

Plastic flow and failure in sheet forming results from competition between modes I and II of fracture mechanics whereas in bulk forming fracture results from competition between modes I and III of fracture mechanics.

Introduction

Under certain conditions tensile fracture can precede necking in traditional sheet metal forming processes, particularly when loading under biaxial tension, in which case the FFLD (fracture forming limit diagram) rather than the FLD (forming limit diagram) determines the deformation achievable.
Marciniak (1984) proposed limiting loci for failure in sheet metal forming always by shear whatever the loading path.

**Drawback:**
Tensile cracks, as found in incremental sheet forming and traditional sheet metal forming processes are not properly considered.

**References:**
- Embury and Duncan, 1981
- Silva et al., 2008
Introduction

FFLD’s for bulk forming are constructed using upset tests performed on cylindrical, ring, tapered and flanged specimens that are able to characterize the locus of the free surface normal strains causing cracking under the combined stress and strain loading conditions found in bulk deformation.

Silva et al., 2014
Introduction

The space of equivalent strain to fracture and stress triaxiality was originally proposed by Vujovic and Shabaik (1986) as a ‘forming limit criterion for bulk metalworking processes, based on the magnitude of the hydrostatic component and the effective stress of the stress state’.

\[ G = 3 \sigma_m / \bar{\sigma} = 3g \]
Bao and Wierzbicki (2004) investigated several well-known ductile fracture criteria in the space of equivalent strain to fracture and stress triaxiality and proposed a different fracture loci from that originally proposed by Vujovic and Shabaik (1986).

**Drawback:**
Unable to reproduce the slope -1/2 that is typical of cracking in opening mode III (bulk forming). Treats sheet and bulk forming simultaneously.
A new vision (mode I)*

Experiments show that, irrespective of the initial loading history before necking in sheet metal forming, tensile fracture occurs approximately at a constant through-thickness true strain.

The fracture locus in **opening mode I (FFL)** is a straight line falling from left to right (slope ‘−1’)


\[ \varepsilon_3 = \text{Const.} \]

\[ R_f = \frac{(t_0 - t_f)}{t_0} \quad \varepsilon_3 = \ln(1 - R_f) \]

\[ \varepsilon_{1f} = -\varepsilon_{2f} - \varepsilon_{3f} \]
A new vision (mode I)

Considering the following modified version of the effective strain fracture criterion

\[ D_{\text{crit}} = \int_{0}^{\varepsilon_f} g \, d\varepsilon \]

\[ g = \sigma_m / \bar{\sigma} \]

where the non-dimensional term \( g \) is a weighting function that corrects the accumulated value of the effective strain until fracture as a function of the strain loading paths, it follows (after considering Hill’s 48 anisotropic plasticity criterion under plane stress conditions and performing significant algebraic manipulation) that,

\[ D_{\text{crit}} = \frac{(1+r)}{3} (\varepsilon_{1f} + \varepsilon_{2f}) \]

\[ D_{\text{crit}} = \frac{(1+r)}{3} \left[ \varepsilon_{1f} + \varepsilon_{2f} - (1 + \beta) \varepsilon_0 \right] \]

\[ \beta = \frac{d\varepsilon_2}{d\varepsilon_1} \]

Remark: Martins et al. showed that the FFL is a material property that is independent from strain loading paths – this result is significantly different from that of the FLC’s.
A new vision (mode I)

A glimpse on the associated algebra:

\[ D_{\text{crit}} = \int_0^{\varepsilon_f} \frac{\sigma_m}{\sigma_1} \frac{d\bar{\varepsilon}}{d\varepsilon} d\varepsilon \]

\[ d\varepsilon_1 = \frac{d\bar{\varepsilon}}{\bar{\sigma}} \left( \frac{1}{1+r} \right) \left( \sigma_1 + r(\sigma_1 - \sigma_2) \right) \]

\[ d\varepsilon_2 = \frac{d\bar{\varepsilon}}{\bar{\sigma}} \left( \frac{1}{1+r} \right) \left( \sigma_2 + r(\sigma_2 - \sigma_1) \right) \]

\[ \bar{\sigma} = \sqrt{\sigma_1^2 + \sigma_2^2 - \frac{2r}{(1+r)} \sigma_1 \sigma_2} \]

\[ \frac{d\bar{\varepsilon}}{d\varepsilon_1} = \sqrt{1+2r} \sqrt{1+\frac{2r}{1+r}} \beta + \beta^2 \]

\[ \beta = \frac{d\varepsilon_2}{d\varepsilon_1} \]

\[ \frac{\sigma_m}{\sigma_1} = \frac{1+\alpha}{3} = \frac{(1+2r)(1+\beta)}{3(1+r)+r\beta} \]

\[ \sigma_1 = \frac{1}{\sqrt{1+2r}} \left[ \frac{(1+r)+r\beta}{1+\frac{2r}{1+r}} \beta + \beta^2 \right] \]

\[ \sigma_1 = \frac{1}{\sqrt{1+2r}} \sqrt{1+\frac{2r}{1+r}} \beta + \beta^2 \]

\[ D_{\text{crit}} = \int_0^{\varepsilon_f} \frac{(1+r)}{3} (\varepsilon_{1f} + \varepsilon_{2f}) \]
A new vision (mode II)

Straight lines with slope ‘+1’ rising from left to right correspond to maximum values of the in-plane distortion and are perpendicular to the FFL.

The in-plane shear fracture limiting locus in opening mode II (SFFL) coincides with the straight line of slope equal to ‘+1’, in which the major and minor in-plane strains and distortions take critical values at fracture.
A new vision (mode II)

Considering the following modified version of the effective strain fracture criterion

\[ D_{crit}^s = \int_{0}^{\bar{\varepsilon}_f} g \, d\bar{\varepsilon} \quad g = \frac{\tau}{\sigma} \]

where the non-dimensional term \( g \) is a weighting function that corrects the accumulated value of the effective strain until fracture by in-plane shear as a function of the strain loading paths, it follows,

\[
D_{crit}^s = \frac{1}{2} \frac{(1+r)}{(1+2r)} (\varepsilon_{1f} - \varepsilon_{2f})
\]

\[
D_{crit}^s = \frac{1}{2} \frac{(1+r)}{(1+2r)} \left[ \varepsilon_{1f} - \varepsilon_{2f} - (1 - \beta) \varepsilon_0 \right]
\]

Remark: The paper by Martins et al. also shows that the SFFL is a material property that is independent from strain loading paths.
A new vision (mode III)

Considering the following modified version of the effective strain fracture criterion

\[ D_{\text{crit}}^{ts} = \int_0^f g \, d\bar{\varepsilon} \]

where the non-dimensional term \( g \) is a weighting function that corrects the accumulated value of the effective strain until fracture by out-of-plane shear (through-thickness shear, opening mode III - OSFFL) as a function of the strain loading paths, it follows,

\[ D_{\text{crit}}^{ts} = \frac{1}{2} \frac{(1+r)^2}{(1+2r)} \left[ \varepsilon_{1f} + \frac{r}{(1+r)} \varepsilon_{2f} \right] \]
A new vision (mode III)

When material is isotropic (r =1) this leads to a straight line with slope ‘-1/2’ similar to what is commonly found in bulk metal forming. The paper by Martins et al. also shows that the OSFFL is coincident to the normalized version of the ductile fracture criterion due to Cockcroft & Latham.

\[ D_{crit}^{ts} = \int_0^{\varepsilon_f} \frac{\tau_{13}}{\sigma} d\bar{\epsilon} = \frac{1}{2} \int_0^{\varepsilon_f} \frac{\sigma_1}{\sigma} d\bar{\epsilon} \]

This means that the normalized version of the Cockcroft-Latham damage criterion is based on a ‘hidden’ out-of-plane shear based condition and, therefore, should not be seen as a principal stress damage based model. This also justifies the reason why the normalized version of the Cockcroft-Latham damage criterion performs well in bulk metal forming applications, such as the bulk formability test specimens that fail by vertical or inclined cracks along the outer surface.
A new vision

The differences in plastic flow resulting from the plane-stress conditions of sheet metal forming and the three-dimensional stress conditions of bulk metal forming that are commonly used as a rationale to classify metal forming processes into two different groups should be employed to distinguish the circumstances under which different processes fail by fracture.

Fracture loci in sheet metal forming (modes I and II)
A new vision

Fracture loci in bulk metal forming (modes I and III)
Fracture toughness and stress-strain curve in SBMF

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MECHANICAL CHARACTERIZATION OF MATERIALS FOR SHEET-BULK METAL FORMING PROCESSES

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Abstract: This paper presents a new experimental methodology for determining the stress-strain curve, the fracture toughness and the critical instability strength of plates and sheets to be used in sheet-bulk metal forming (SBMF) applications. The stress-strain curve and fracture toughness are obtained from double-notched test specimens loaded in shear and the material flow behavior is compared against that obtained from conventional tensile tests. The critical instability strength is obtained from rectangular test specimens loaded in compression by means of a combined experimental and theoretical procedure that makes use of the analytical solution for the elasto-plastic stability of plates subjected to equal uniaxial compression on two opposite edges. The work is performed in aluminium EN AW-6020 and steel DC04 sheets with 3 mm thickness and the proposed experimental methodology reveals appropriate for the mechanical characterization of materials under the high levels of strain that are commonly found in SBMF processes.

Keywords: Sheet-bulk metal forming, Stress-strain curve, Fracture toughness, Critical instability strength
Fracture toughness and stress-strain curve in SBMF

Development of a new experimental methodology for determining the stress-strain curve and the fracture toughness of plates and sheets to be used in sheet-bulk metal forming (SBMF) applications.
Fracture toughness and stress-strain curve in SBMF

The determination of fracture toughness involved characterization of the evolution of load with displacement for a number of specimens having different ligaments between the two symmetric opposite notches.

\[ W_T = F d \delta = 2 w_p dV_p + 2RdA \]

\[ W_T = 2 \left( \int_0^\infty \bar{\sigma} d\bar{\varepsilon} \right) l d t + 2R t l \]

\[ ld = \alpha l^2 \]

\[ W_T = \left( \int_0^\infty \bar{\sigma} d\bar{\varepsilon} \right) \alpha l + R \]

\[ w_T = \frac{1}{2} \bar{\sigma}_{mean} \bar{\varepsilon}_{av} \alpha 2l + R \]

\[ \bar{\sigma}_{mean} = \left( \frac{1}{\bar{\varepsilon}_{av}} \int_0^\infty \bar{\sigma} d\bar{\varepsilon} \right) \]
Fracture toughness and stress-strain curve in SBMF

Material: EN AW-1050 sheets with 3 mm thickness

Load (kN) vs. Displacement (mm) graph shows different load levels at various displacements for different ligament lengths ($2l$).

Energy per area (kJ/m²) vs. Ligament (mm) graph shows a linear relationship with the equation $R = 173.89$ for ligament lengths $2l = 4, 8, 12, 16$ and $20$ mm.
Fracture toughness and stress-strain curve in SBMF

The methodology for determining the stress-strain curve is based on two major assumptions:

- Plastic work is totally consumed by shear deformation inside the two rectangular patches of the test specimens.
- The shear stresses and strains are considered to be uniformly distributed inside the two shear deformation regions.

\[ \tau = \frac{F}{2lt} \]

\[ \gamma \approx \tan \gamma = \frac{\delta}{d} \]
Fracture locus and fracture toughness in mode II

Kerim Isik M. Sc.
Fracture locus and fracture toughness in mode II

Development of a new experimental test for determining fracture toughness, in plane stress, in crack opening mode II based on the utilization of double-notched circular test specimens loaded in plane torsion.
A brief history of in-plane torsion test

Marciniak (1961)
- First report of the in-plane torsion test
- Investigation of Bauschinger effect for copper sheets

Marciniak et al. (1972, 1973)
- Investigation of forming limit

Tekkaya / Bauer / Pöhlandt (1980-1985)
- Determined flow curves with high strains up to 1.0
- Simplistic manual measurement and evaluation

Yin / Tekkaya et al. (since 2011)
- Introduction of Digital Image Correlation (DIC)
- New types of torsion specimen and evaluation methods
The methodology for determining fracture toughness is based on the evolution of torque with the degree of rotation for a number of tests performed with specimens having different lengths of the ligaments between the circumferential notches.

\[ Td\theta = 2W_p dV_p + 2RdA \]

\[ w_T = \frac{\bar{\sigma}_{\text{mean}} \bar{\varepsilon}_{\text{av}} \pi}{8} 2l + R \]
Fracture locus and fracture toughness in mode II

The open markers correspond to strain pairs that were obtained from in-plane strain measurements with the Aramis system, whereas the solid markers correspond to gauge length strains at fracture that were obtained from thickness measurements along the cracks.

Material: AA1050-H111 sheets with 1 mm thickness
Fracture locus and fracture toughness in mode II

The development of localized necking in double notched torsion test specimens should not be confused with plastic instability, which precedes failure by fracture in conventional sheet formability tests. This is because the proposed mechanism for explaining the formation of necks in double-notched torsion test specimens loaded in shear is not based on the development of unstable plastic deformation during which the deformation continues under falling load or pressure until failure by fracture but rather on a change in the relative ease of plastic flow in width and thickness directions.
Fracture locus in sheet-bulk metal forming

Sebastian Wernicke M. Sc.
Fracture locus in sheet-bulk metal forming

The investigation was focused on the possibility of failure by crack-opening mode III (out-of-plane shearing) in sheet-bulk metal forming processes and was performed in incremental ploughing of thin sheets with a roll-tipped tool.

Material: Aluminium EN AW-1050 sheets with 1 mm thickness
Fracture locus in sheet-bulk metal forming

In case plastic deformation is limited to the upper sheet thickness the overall plastic flow is similar to that obtained during the scratching of permanent grooves in solids by pointed tools with negative attack angles of the leading face.

In case plastic deformation extends across the entire thickness of the sheet due to large indentation depths transverse cracks are triggered at the upper groove surface and propagate downward across thickness along an inclined direction to the sheet surface.
Fracture locus in sheet-bulk metal forming

In contrast to sheet metal forming that only fail by fracture in crack-opening modes I and II, sheet-bulk metal forming present the unique ability of failing in all three possible crack-opening modes, namely, in mode III that is typical of bulk metal forming.
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