SHEET-BULK METAL FORMING: PROCESS DEVELOPMENT AND MECHANICAL CHARACTERIZATION

Paulo A. F. Martins
(Professor of Manufacturing, University of Lisbon)
Sheet-Bulk Metal Forming

Differences in plastic flow resulting from the plane-stress conditions of sheet metal forming and the three-dimensional stress conditions of bulk metal forming have long been utilized to classify metal forming processes into two different groups.

Recent developments in metal forming technology lead to the development of a new group of metal forming processes entitled ‘sheet-bulk metal forming’.

Sheet-Bulk Metal Forming

Sheet-bulk metal forming comprises the production of sheet metal parts with local functional features such as teeth, ribs and solid bosses positioned outside the plane of the sheets from which they are shaped by plastic deformation of sheets and plates with intended three-dimensional plastic flow.
Sheet-Bulk Metal Forming

From a product development and manufacturing design point of view, typical applications of SBMF require application of loading across (S) and/or perpendicular (T and/or L) directions to the sheet thickness.

SBMF introduces new challenges for the development of new manufacturing processes and new mechanical and fracture characterization processes.
Incremental Sheet-Bulk Forming of Gears

Aim and objectives:
Development of an effective, economic alternative to fine-blanking for manufacturing customized low batch production of gears by indentation perpendicular to the sheet thickness that eliminates typical problems related to wear resistance of die materials under extreme shearing loads.

Incremental Sheet-Bulk Forming of Gears

Deformation mechanics:
The analysis of the transient plastic flow associated to the incremental sheet-bulk forming of gears was performed by means of an analytical model built upon the slip-line theory.

Effective strain rate obtained from finite element analysis with simufact.forming12
Incremental Sheet-Bulk Forming of Gears

Deformation mechanics:

\[ p_{2,t} = -2k(1 + \theta) \]

\[ p_{4,t} = -2k \left( 1 + \frac{\pi}{2} \right) \]

\[ p_{4,III} = -2k \left( 1 + \cos(2\theta) \right) \]

\[ F = 2(p_{4,t}lw + (p_{2,t} + p_{4,III})lw\sin\theta) \]
Extent of the plastic deformation region:

The analytical model based on slip-line analysis provides an estimate of the maximum expansion $x$ of the plastic deformation zone undergone by the sheet during indentation by means of a gear tooth punch.

$$x = l + \frac{i}{\cos \theta} \approx 1 + \frac{3.3}{\cos 20^\circ} = 4.5 \text{mm}$$

The measurements were made in accordance to DIN EN ISO 6507-1:2005.
Incremental Sheet-Bulk Forming of Gears

Incipient and repeatable plastic flow:
The underfilling of the punch cavity during the first indentation, which prevents the production of sound disk gears, is explained on the basis of constrained material flow under material strain hardening.
A solution based on the utilization of a tailored disk blank is proposed to overcome this defect.
Incremental Sheet-Bulk Forming of Gears

Incipient and repeatable plastic flow:

The experiments were performed in DC04 steel sheets with 3 mm thickness and numerical simulations were performed in simufact.forming12.

340000 hexahedral elements
6h CPU
Intel Xeon CPU (3.4 GHz) with 12 physical cores
Major differences between incipient (first indentation) and repeatable (second indentation) force-displacement evolutions are found in the second stage and are caused by free sideways spread occurring in the second indentation. This does not happen during the first indentation because the left and right punch wedges are constrained by adjacent non-deforming material.
Overcome underfilling of the first gear tooth by means of tailored disk blanks:

\[ t_b = 1.5 \text{mm}, \ t_t = 1 \text{mm}, \ h = 1 \text{mm}, \ \Theta = 20^\circ \]
Joining Sheets by Sheet-Bulk Metal Forming

Aim and objectives:
Development of a simple, flexible and low-cost solution based on a variant of the traditional ‘mortise-and-tenon’ joint to fix longitudinal in position two sheets perpendicular to one other.

Alternative joining technologies:
The new proposed joining technology is an alternative to existing joining solutions based on welding, adhesive bonding, mechanical fastening or riveting, and mechanical folding.
Joining Sheets by Sheet-Bulk Metal Forming

The new proposed ‘mortise-and-tenon’ joint is characterized by a rectangular cavity (‘mortise’) cut-out in one sheet and by a tenon cut-out in the edge of the other sheet that passes entirely through the mortise of the first sheet. The tenon is longer than wider and is compressed perpendicular to the thickness direction in order to plastically deform its free length and ensure a mechanical lock between the two sheets to be joined. The laboratory development was focused on a typical ‘unit cell’ of the new proposed ‘mortise-and-tenon’ joint.
Joining Sheets by Sheet-Bulk Metal Forming

The workability limits of the new proposed joining process are limited by two types of defects:

a) Failure by buckling of the slender tenons

A limiting length-to-thickness ratio was determined by experimentation and finite element modelling \( \left( \frac{l_f}{t_0} \right)_{\text{max}} = 2.5 \)
b) Excessive force in the final locking stage

This is due to large volumes of the protrusion of the tenon beyond the mortise and causes the upper sheets to bend.
Joining Sheets by Sheet-Bulk Metal Forming

Force-displacement (joining)

![Graph showing force-displacement relationship for different conditions.](image)

- **Exp. If/w0 = 0.25**
- **Exp. If/w0 = 0.5**
- **Exp. If/w0 = 1**
- **Exp. If/w0 = 1.5**
- **Exp. If/w0 = 2**
- **FEM 2D If/w0 = 0.25**
- **FEM 2D If/w0 = 0.5**
- **FEM 3D If/w0 = 0.5**
- **FEM 2D If/w0 = 1**
- **FEM 3D If/w0 = 1.5**
- **FEM 2D If/w0 = 2**
Joining Sheets by Sheet-Bulk Metal Forming

Force-displacement (detaching the sheets)

\[ F = C\sigma_{UTS}A_c \]

Equation (4)

\[ F = CK \left( \frac{n}{e} \right)^n A_c \]
Joining Sheets by Sheet-Bulk Metal Forming

Applications:
The new proposed ‘mortise-and-tenon’ joint allows connecting two metal sheets (or plates) perpendicular to one other by SBMF, at room temperature, and is a simple, flexible and low-cost alternative to existing joining solutions based on welding, adhesive bonding and fastening.

There is a wide range of industrial applications: from structural applications and crash boxes of vehicles to metallic floors/platforms for passenger trains and boats, among others.
Mechanical Characterization of Materials

Motivation:

Mechanical characterization of materials for sheet-bulk metal forming presents two main challenges derived from the application of three-dimensional stress conditions in metal sheets:

a) Determination of stress-strain curves for high values of strain (far beyond those obtained by conventional tensile tests);

b) Characterization of fracture toughness in new loading conditions perpendicular to sheet thickness.

Mechanical Characterization of Materials

Aim and objectives:
To develop an experimental methodology for determining the stress-strain curve, fracture toughness and the critical instability strength of sheets and plates by means of double-notched test specimens loaded in shear.

Mechanical Characterization of Materials

Stress-strain curve:
The determination is based in two major assumptions.

- Firstly, plastic work is considered to be totally consumed by shear deformation inside the two rectangular patches of the test. The remaining parts of the specimens are assumed to be rigid because the contribution of elastic deformation is negligible.
- Secondly, the shear stresses and strains are considered to be uniformly distributed inside the two shear deformation regions

**Force F**

\[ \gamma \approx \tan \gamma = \frac{\delta}{d} \quad \bar{\varepsilon} = \frac{\gamma}{\sqrt{3}} \quad \tau = \frac{F}{2lt} \quad \bar{\sigma} = \sqrt{3} \tau \]
The poor agreement of the results obtained in the tests that were performed with the largest ligaments \(l=10\text{mm}\) is attributed to plastic work being also consumed outside the two rectangular patches of the test specimens. This causes the stress-state to deviate from pure plastic shearing conditions.
Fracture toughness:
The determination of fracture toughness involves characterization of the evolution of load with displacement for a number of test cases performed with specimens having different ligaments between the two symmetric opposite notches.

\[
W_T = Fd\delta = 2w_p dV_p + 2RdA
\]

\[
W_T = 2\left( \int_{0}^{\bar{\varepsilon}} \bar{\sigma} d\bar{\varepsilon} \right) ld t + 2Rtl
\]

\[ld = \alpha l^2\]

\[
w_T = \left( \int_{0}^{\bar{\varepsilon}} \bar{\sigma} d\bar{\varepsilon} \right) \alpha l + R
\]

\[
w_T = \frac{1}{2} \bar{\sigma}_{mean} \bar{\varepsilon}_\alpha \alpha 2l + R
\]
Mechanical Characterization of Materials

Aluminium EN-AW-1050 and Steel DC04:

The results obtained for the smaller ligaments $2l = 4$ mm were not utilized in the determination of fracture toughness $R$ of DC04 due to the previously mentioned rotational effects of the inner part of the specimens that cause the stress-state to deviate from pure plastic shearing conditions.
Mechanical Characterization of Materials

Alternative test specimens to determine fracture toughness:

- Left – Double-notched tensile test specimen leading to crack opening by tension (mode I)
- Right – Double-notched shear test specimen leading to crack opening by in-plane shear (mode II), but very much influenced by rotation of the plastic shear area during crack propagation.
Critical instability strength:
The critical instability strength to trigger buckling in a sheet is obtained from Timoshenko [9] and is similar to the Euler strength for columns except for the fact that it is a function of the thickness to width ratio $t/w$ because the shorter the width $w$ the larger the resistance to buckling will be.

$$\sigma_{cr} = K \frac{E}{(1 - \nu^2)} \left( \frac{t}{w} \right)^2$$

$$E_t = d\sigma / d\varepsilon$$

$$t = t_0 \exp^{-0.5\varepsilon_h}$$

$$w = w_0 \exp^{-0.5\varepsilon_h}$$

$$\varepsilon_h = \ln(h/h_0)$$
Critical instability strength:
The specimens with smaller heights (e.g. $h = 10$ mm) show a steep increase of the force-displacement evolution without occurrence of plastic instability and subsequent formation of out of plane buckling. In contrast, the remaining test specimens show an initial steep increase of the force with displacement up to the onset of plastic instability followed by a bifurcation into a secondary loading path during which the force increases at a lower rate.
Critical instability strength:
The critical instability strengths are valid for a thickness-to-width $t/w = 0.3$ but the occurrence of plastic instability in the form of buckling out of the sheet plane depends on the slenderness ratio $h/w$ of the specimens. In the tests performed it was observed that safe deformation modes without buckling require $h/w \leq 1$.
Failure by Fracture in Sheet-Bulk Forming

Motivation:
In a recent paper, Martins et al. characterized the circumstances under which the different crack opening modes of fracture mechanics will occur in metal forming (under plane stress conditions) and concluded that failure in sheet metal forming is triggered either (i) by tension or (ii) by in-plane shear (respectively, modes I and II of fracture mechanics) and that failure in bulk metal forming is triggered (i) by tension or (iii) by out-of-plane shear (respectively, modes I and III of fracture mechanics).

Failure by Fracture in Sheet-Bulk Forming

Aim and objectives:
To understand if the formability and the physics of cracking in SBMF are the same of those of sheet metal forming (failure only by tension or in-plane shear) or instead whether fracture by out-of-plane shearing (mode III of fracture mechanics) which is the main separation mode in bulk metal forming can also occur.
The investigation was based on experimental and numerical modelling of the local thickening of aluminium AA1050-H111 sheets by incremental ploughing with a roll tipped tool.

Experimentation:
Experimentation was performed in aluminum AA1050-H111 sheets with 1 mm thickness. The tool was made from a powder metallurgy high-speed steel ASP2023 (WN 1.3344) with a radius $R=10\text{mm}$ and a width $w=10\text{mm}$ and was vacuum hardened in order to ensure a surface hardness of approximately 60 HRc.
Failure by Fracture in Sheet-Bulk Forming

Numerical modelling:
The incremental ploughing of a thin sheet with a roll tipped tool was simulated with the commercial finite element computer program Simufact.forming12. The sheets were modelled as elastic-plastic deformable objects and their geometry was discretized by means of approximately 95500 hexahedral elements.
Failure by Fracture in Sheet-Bulk Forming

Crack opening mode:
The results demonstrate that failure in sheet-bulk metal forming processes may be caused by out-of-plane shearing (crack opening mode III of fracture mechanics) and allow concluding that sheet-bulk metal forming processes have the unique ability of being able to fail by cracking along all the three crack opening modes of fracture mechanics. This justifies its classification into a separate standalone metal forming category placed in between sheet and bulk metal forming.
Conclusions

The first part of the presentation introduced new developments in sheet-bulk metal forming with special emphasis on incremental forming of gears and joining of sheets by forming. Motivation and potential applications of the new proposed processes were addressed along side with major topics in deformation mechanics and experimentation.

The second part of the presentation introduces a methodology to determine the stress-strain curve, the fracture toughness and the critical instability strength of materials supplied in the form of sheets to be used in sheet-bulk metal forming processes. The methodology is based on the utilization of double-notched test specimens loaded in shear and rectangular test specimens loaded in compression.

Results demonstrate the effectiveness of the proposed methodology, namely the capability of the double-notched test specimens to determine the stress-strain curve up to higher strain levels than those commonly attained in tensile tests.

The third part of the presentation discusses fracture in sheet-bulk metal forming and demonstrates that failure can also occur by out-of-plane shearing (crack opening mode III of fracture mechanics), which is known to be typical of bulk metal forming processes.
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