Benchmark 1 – Failure Prediction after Cup Drawing, Reverse Redrawing and Expansion

Part A: Benchmark Description

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Abstract. This Benchmark is designed to predict the fracture of a food can after drawing, reverse redrawing and expansion. The aim is to assess different sheet metal forming difficulties such as plastic anisotropic earing and failure models (strain and stress based Forming Limit Diagrams) under complex nonlinear strain paths. To study these effects, two distinct materials, TH330 steel (unstoved) and AA5352 aluminum alloy are considered in this Benchmark. Problem description, material properties, and simulation reports with experimental data are summarized.

Keywords: Fracture, cup drawing, redraw, expansion, FLD, anisotropy

1. INTRODUCTION

The numerical simulation of cupping processes is fundamental for the can making industry. It allows the prediction of many different sheet metal defects and instabilities that significantly affect the efficient production of these parts. These defects include thinning from cup drawing, earing from plastic anisotropy, and damage and fracture from different combinations of strain paths, e.g. drawing and expansion. Due to the earing profile after cup drawing and reverse redrawing, it is usually necessary to perform a trimming operation to bring the cup to a uniform height prior to conducting other challenging sheet forming operations. The numerical simulation will not include this trimming operation.

In sheet metal forming, the Forming Limit Diagram (FLD) is commonly used to predict material failure in forming operations. The sheet material failure or tearing can be triggered by different loading conditions or strain paths ranging from uniaxial tension to plane strain and bi-axial tensile loading. The FLD has been integrated in many different finite element commercial packages for the simulation of sheet metal forming processes, as well as many academic research codes.

More recently there have been intensive studies on the development and use of strain-path independent forming limit diagrams such as the stress-based FLD and the polar FLD. Despite the fact that strain-based FLD has been used with some success in the past, it has been experimentally verified that the material tearing point is strain-path dependent and so the use of strain based forming limit diagrams can lead to erroneous predictions of failure in sheet metal forming analysis. The stress-based FLD can be obtained from a mapping from the strain-based FLD and enables strain-path independence for the prediction of material tearing in sheet metal forming simulations.

In this benchmark study, a strain-based FLD is provided for both the AA5352 and TH330 materials. Other forms of FLD may be used.
Shell elements, solid elements, or solid-shell elements are recommended for this benchmark with careful control of the incremental punch stroke, with sufficient number of elements in the mesh to reproduce the curvature of the dies and capture plastic strain accurately. The analysis in this benchmark is highly nonlinear, including double sided contact with anisotropy. It is recommended that a simple isotropic material model (such as von-Mises yield function) be used before attempting an advanced anisotropic material model.

This benchmark study has the main objective of predicting the failure point after drawing, reverse redrawing and expansion. Different challenging outputs will be required:

i) prediction of earing after the reverse redrawing operation due to the plastic anisotropy of the material;
ii) prediction of the thickness profile after the reverse redrawing operation;
iii) prediction of the failure point after the expansion operation, using either strain-based, stress-based and/or polar FLD.

2. DESCRIPTION OF FORMING OPERATIONS

This section contains a description of the cup-forming and die expansion operations for this benchmark.

Cup forming is a two-stage process of drawing and reverse redrawing which occur sequentially during a single stroke of the drawing operation punch.

2.1 Drawing operation

- Drawing speed: 400.0 mm/sec (15.748 in/sec).
- Blank holder force between pressure pad and die: 21.1 kN or 4743.5 lbf. (For a quarter model, divide by 4.)
- Friction coefficient (recommended): 0.03
Figure 1. Setup for the Drawing operation.
| Parameter | D4    | D5    | R3   | H2   |
|-----------|-------|-------|------|------|
| mm        | 117.445 | 162.911 | 2.54 | 6.35 |
| inch      | 4.6238  | 6.4138 | 0.1  | 0.25 |

Figure 2. Drawing operation – Die.
| Parameter | D7     | D8     |
|-----------|--------|--------|
| mm        | 117.856| 162.839|
| inch      | 4.64   | 6.411  |

Figure 3. Drawing operation – Pressure Pad.
| Parameter | D1  | D2   | D3   | R1  | R2   | H1  |
|-----------|-----|------|------|-----|------|-----|
| mm        | 116.84 | 88.489 | 96.291 | 2.54 | 4.064 | 6.35 |
| inch      | 4.6  | 3.4838 | 3.791 | 0.1 | 0.16 | 0.25 |

Figure 4. Drawing operation – Punch.
2.2 Reverse Redrawing operation

- Reverse redrawing occurs after the cup is fully drawn.
- Figure 5 shows a schematic representation of the tools used in the reverse redrawing stage, with the cup part-formed.
- The geometry and dimensions for the pressure pad and reverse redrawing punch are shown in Figures 6 and 7 respectively.
- The forming speed remains at 400.0 mm/sec (15.748 in/sec).
- Reverse redrawing displacement defined as zero where the reverse redrawing punch contacts the drawn cup.
- Blank holder force: 16.6 kN or 3731.8 lbf. For a quarter model, divide by 4.
- Friction coefficient (recommended): 0.03

Figure 5. Setup for the Reverse Redrawing operation.
| Parameter | D9     | D10    | D13    | R4    | R5    | H3    |
|-----------|--------|--------|--------|-------|-------|-------|
| mm        | 89.408 | 116.713| 108.712| 4.572 | 1.524 | 1.524 |
| inch      | 3.52   | 4.595  | 4.28   | 0.18  | 0.06  | 0.06  |

**Figure 6. Reverse Redrawing operation – Pressure Pad.**
2.3 Die Expansion operation

Practical experiment has shown that the force required to expand the steel cup to fracture will cause metal to flow into the base of the cup. This causes wrinkles in the base and reduces the height of the cup. To prevent this metal flow, the base was clamped using an inner clamp plate bolted through the centre of the cup base as shown in Figure 8.

The benchmark participants shall decide how to define the numerical boundary conditions representing experimental clamping conditions. The same clamp arrangement is used for both materials - steel and aluminium.

- The cup sits in the cup support tool.
- The clamp plate is bolted through the centre of the cup to hold the material securely in the base of the cup to prevent material flow.
- The cup has a 9 mm diameter hole drilled through the centre of the base.
- The expansion punch is driven into the cup until the point of fracture.
- A vent on the punch prevents internal air pressure build up.
- Punch speed is 200 mm per minute (3.33 mm/sec)
- Friction coefficient (recommended): 0.03

| Parameter | D11  | D12  | R6  | H8  |
|-----------|------|------|-----|-----|
| mm        | 65.532 | 87.859 | 4.064 | 3.05 |
| Inch      | 2.58  | 3.459 | 0.16 | 0.12 |

**Figure 7. Reverse Redrawing operation – Punch.**
Figure 8. Practical setup for the die expansion operation.
**Figure 9. Expansion operation – Punch.**

| Parameter | D14  | D15  | H4   | H5   | R7   |
|-----------|------|------|------|------|------|
| mm        | 104.43 | 85.04 | 12.0 | 66.50 | 4.0  |
| inch      | 4.111 | 3.348 | 0.472 | 2.618 | 0.157 |

**Figure 10. Clamp plate**

| Parameter | D16  | R8  | H9  |
|-----------|------|-----|-----|
| mm        | 87.77 | 3.86 | 5.00 |
| inch      | 3.456 | 0.152 | 0.197 |
| Parameter | D17 | D18 | R9  | R10 | H10 | H11 |
|-----------|-----|-----|-----|-----|-----|-----|
| mm        | 100 | 88.43 | 1.00 | 4.28 | 6.50 | 28.50 |
| inch      | 3.947 | 3.481 | 0.039 | 0.169 | 0.256 | 1.122 |

**Figure 11. Cup support tool**
3. BLANK MATERIALS

- AA5352 aluminium and TH330 steel are considered for this benchmark.
- Blank diameter for both materials: 162.9664 mm / 6.416 in
- Thickness: 0.279 mm / 0.0110 in for AA5352; 0.270 mm / 0.0106 in for TH330
- Material properties: see tables in Section 5 of this document.
- The tooling geometry shown in Figures 1 to 11 is used for both materials.

4. BENCHMARK REPORT

All results are expected to be reported using the benchmark report template, which can be downloaded from the conference website, and when completed, uploaded to the website at a later date to submit the entry.

The primary metric of the benchmark will be the degree of correlation with the location, punch depth, and the plane strain tensor components of the onset of failure. The additional data reported will be used to understand the origin and significance of factors contributing to the success or failure of the correlation obtained with respect to the primary metric.

4.1 General Description

1) Benchmark participant: name, affiliation, address, email and phone number
2) Simulation software: name of the FEM code, general aspects of the code, basic formulations, element/mesh technology, type of elements, number of elements, contact property model and friction formulation
3) Simulation hardware: CPU type, CPU clock speed, number of cores per CPU, main memory, operating system and total CPU time
4) Material model: Yield function/Plastic potential, Hardening rule and Stress-Strain Relation, strain-based, stress-based or Polar Forming Limit Diagram (FLD) used
5) Remarks

4.2 Simulation results required for AA5352 aluminium and for TH330 steel

1) Cup height “h” (mm) after the reverse redrawing operation, measured from the centre point of the lower surface of the blank around the circumference from the rolling direction (0°) to 360°, reported in 5° increments or less.
2) Plot of punch load (kN) vs punch stroke (mm) for the cup forming operation (both drawing and reverse redrawing). The zero punch stroke is defined at the position when the punch makes initial contact with the blank with no interaction forces.
3) The strain history (Major and Minor principal strains) of the upper surface of the blank as a function of the drawing punch stroke (drawing and reverse redrawing) and the expansion punch stroke. This should be reported for the element at the leading edge of the cup at 0°, 45° and 90° (points 1, 2 and 3 in Figure 12.)
4) Thickness profile at a height of 20mm and 45mm from the base of the cup, after the reverse redrawing operation, measured around the circumference from the rolling direction (0°) to 360°, reported in 5° increments or less.
5) The expansion punch stroke at onset of failure (fracture or necking), and the location of the onset of failure, “Point 4”; reported as angle θ from the rolling direction and the height of the
cup at this location, measured from the base of the cup. Zero expansion punch stroke is defined at the position when the punch makes initial contact with the cup with no interaction forces.

6) The strain history (Major and Minor principal strains) as a function of punch stroke for the predicted onset failure point (point 4).

Figure 12. Schematic view of the location of the required points on the cup.
5. MATERIALS CHARACTERIZATION

5.1 Aluminum AA 5352

### Table 1.1. Elastic mechanical properties

| Sample  | Density g/cm³ | Young's modulus GPa | Poisson’s ratio |
|---------|---------------|---------------------|-----------------|
| AA5352  | 2.72          | 68.5                | 0.33            |

### Table 1.2. Uniaxial Tension Test Data

| Test Direction | YS MPa | UTS MPa | Engineering Strain (%) | r value |
|----------------|--------|---------|-------------------------|---------|
| 0º             | 197.59 | 239.29  | 8.219                   | 11.23   | 0.535 |
| 15º            | 193.39 | 238.45  | 8.964                   | 12.16   | 0.465 |
| 30º            | 196.62 | 236.21  | 9.516                   | 12.62   | 0.655 |
| 45º            | 193.94 | 231.54  | 9.580                   | 13.09   | 1.105 |
| 60º            | 197.03 | 234.19  | 9.772                   | 15.09   | 1.415 |
| 75º            | 196.89 | 235.38  | 11.602                  | 17.96   | 1.595 |
| 90º            | 198.74 | 239.04  | 11.032                  | 16.11   | 2.270 |

### Table 1.3. Uniaxial Tension Test Data

| Test Direction | Swift | Voce | Hollomon | Ludwik |
|----------------|-------|------|----------|--------|
|                | σ = k(ε₀ + εⁿ) | σ = A - B \cdot \exp(-C \cdot εⁿ) | σ = K(εⁿ) | σ = YS + K(εⁿ) |
| k MPa | ε₀ | n | A MPa | B MPa | C | n | K MPa | n | K MPa |
| 0º   | 376.59 | 0.01334 | 0.1594 | 285.41 | 91.88 | 15.5271 | 0.1036 | 333.28 | 0.6433 | 293.01 |
| 15º  | 373.76 | 0.01564 | 0.1640 | 283.34 | 91.05 | 14.5781 | 0.1030 | 326.66 | 0.6426 | 283.76 |
| 30º  | 365.19 | 0.01598 | 0.1552 | 283.55 | 88.44 | 14.0703 | 0.1018 | 326.11 | 0.6372 | 264.13 |
| 45º  | 347.94 | 0.01529 | 0.1439 | 276.53 | 84.11 | 14.2729 | 0.0951 | 313.89 | 0.6341 | 244.62 |
| 60º  | 350.22 | 0.01896 | 0.1448 | 278.71 | 83.53 | 13.7658 | 0.0943 | 315.99 | 0.6153 | 240.19 |
| 75º  | 359.58 | 0.01694 | 0.1535 | 286.96 | 90.77 | 12.0959 | 0.0967 | 321.79 | 0.6457 | 256.66 |
| 90º  | 365.67 | 0.01675 | 0.1537 | 286.88 | 89.46 | 13.7037 | 0.0992 | 328.26 | 0.6448 | 272.27 |

### Table 1.4. Equal Biaxial Tension Test Data

| t, mm | Maximum | Swift | Voce | Hollomon |
|-------|---------|-------|------|----------|
|       | σ MPa  | ε MPa | K | ε₀ | n | A MPa | B MPa | C | n | K MPa |
| 0.279 | 304.24 | 0.1200 | 378.43 | 0.0006 | 0.10120 | 314.53 | 81.74 | 17.1051 | 0.1000 | 377.53 |
### TABLE 1.5. Disk Compression Test Data

| Alloy/Temper | $r_{bx}$ |
|--------------|----------|
| AA 5352      | 0.62     |

### TABLE 1.6a. Material Constants for Yield Function CPB06 ($a=2.0$)

|   | $C_{11}$ | $C_{12}$ | $C_{13}$ | $C_{22}$ | $C_{23}$ | $C_{24}$ | $C_{25}$ | $C_{26}$ | $k$ |
|---|----------|----------|----------|----------|----------|----------|----------|----------|-----|
|   | 0.77037  | -0.32531 | -0.34259 | 1.273241 | 0.13047  | 2.175042 | 1         | 1         | 1.329576 | -0.414982 |

### TABLE 1.6b. Material Constants for Yield Function CPB06ex2 ($a=3.0$)

|   | $C'_{11}$ | $C'_{12}$ | $C'_{13}$ | $C'_{22}$ | $C'_{23}$ | $C'_{24}$ | $C'_{25}$ | $C'_{26}$ | $k'$ |
|---|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----|
|   | 0.212707  | -0.015974 | 0.307484  | 0.924971  | 0.78806   | 1.273241  | 0.13047   | 1         | 0.73172 | -0.283913 |
|   | 1.07512   | 0.207383  | 0.014346  | 1.220567  | 0.086062  | 0.06489   | 1         | 1         | 0.946897 | -0.075132 |

### TABLE 1.7 Material Constants for Yield Function Yld2004-18p ($a=8.0$)

|   | $A_1$     | $A_2$     | $A_3$     | $A_4$     | $A_5$     | $A_6$     | $A_7$     | $A_8$     | $A_9$     | $A_{10}$ | $A_{11}$ | $A_{12}$ | $A_{13}$ | $A_{14}$ | $A_{15}$ | $A_{16}$ | $A_{17}$ | $A_{18}$ |
|---|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|   | 0.6402    | 0.7462    | 0.5014    | 0.0636    | 1.0439    | 0.2379    | 0.9089    | 0.9140    | 0.8654    | 0.6105   | 1.0386   | 1.1726   | 1.3065   | 0.3464   | 1.4753   | 0.9812   | 0.9410   | 1.0763   |

### TABLE 1.8. Material Constants for Yield Function Yld2000-2d ($a=8.0$)

| Sample | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ | $a_6$ | $a_7$ | $a_8$ |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|
| AA5352 | 0.6547| 1.2883| 0.9050| 0.8641| 0.9710| 0.6820| 1.0091| 1.2084|

### TABLE 1.9. Material Constants for Yield Function Yld89  r-value based (m=8.0)

| Sample | $a$     | $c$     | $h$     | $p$     |
|--------|---------|---------|---------|---------|
| AA5352 | 1.0162  | 0.9838  | 0.7086  | 0.8961  |

### TABLE 1.10. Material Constants for Yield Function Yld89  stress value based (m=8.0)

| Sample | $a$     | $c$     | $h$     | $p$     |
|--------|---------|---------|---------|---------|
| AA5352 | 0.3401  | 1.6599  | 1.0052  | 1.0315  |

### TABLE 1.11. Material Constants for Yield Function Hill, r-value based (1948)

| Sample | $F$   | $G$   | $H$   | $L$ | $M$ | $N$ |
|--------|-------|-------|-------|-----|-----|-----|
| AA5352 | 0.3071| 1.3029| 0.6971| 3.0 | 3.0 | 2.5841|
**TABLE 1.12.** Material Constants for Yield Function Hill, stress-based (1948)

| Sample  | F    | G    | H    | L | M  | N    |
|---------|------|------|------|---|----|------|
| AA5352  | 0.7782 | 0.7572 | 1.2428 | 3.0 | 3.0 | 3.4687 |

**TABLE 1.13.** Forming Limit Curve for AA5352

| Major True Strain $\varepsilon_1$ | Minor True strain $\varepsilon_2$ |
|----------------------------------|----------------------------------|
| 0.14                             | -0.038                           |
| 0.109                            | -0.012                           |
| 0.09                             | 0.005                            |
| 0.076                            | 0.012                            |
| 0.078                            | 0.026                            |
| 0.11                             | 0.092                            |
5.2 Steel TH330 unstoved.

| Sample          | Density g/cm³ | Young's modulus GPa | Poisson's ratio |
|-----------------|---------------|---------------------|-----------------|
| TH330 Steel     | 7.8           | 205                 | 0.3             |

| Test Direction | YS     | UTS     | Engineering Strain (%) | r value |
|----------------|--------|---------|------------------------|---------|
| 0º             | 258.87 | 366.87  | 15.881                 | 29.042  | 1.4492 |
| 15º            | 258.25 | 369.08  | 15.835                 | 29.239  | 1.3734 |
| 30º            | 254.36 | 367.66  | 15.357                 | 27.086  | 1.3012 |
| 45º            | 255.25 | 371.02  | 15.665                 | 29.505  | 1.2664 |
| 60º            | 251.47 | 368.25  | 15.126                 | 28.824  | 1.3350 |
| 75º            | 250.33 | 368.49  | 16.104                 | 30.521  | 1.4434 |
| 90º            | 249.42 | 367.08  | 15.771                 | 29.347  | 1.5100 |

| Test Direction | Swift σ = k(ε₀ + εₚ)ⁿ | Voce σ = A − B · exp(−C · εₚ) | Hollomon σ = K(εₚ)ⁿ | Ludwik σ = YS + K(εₚ)ⁿ |
|----------------|------------------------|-------------------------------|----------------------|------------------------|
| 0º             | 575.58 0.00500 0.16200 | 506.63 250.51 7.6342 0.14964 568.01 0.35952 334.14 |                      |                      |
| 15º            | 573.69 0.00484 0.15941 | 505.96 251.22 7.7497 0.14800 566.95 0.35276 334.01 |                      |                      |
| 30º            | 576.85 0.00463 0.15867 | 508.46 254.19 7.8542 0.14786 570.49 0.34961 338.03 |                      |                      |
| 45º            | 577.59 0.00442 0.15561 | 514.28 259.86 7.5711 0.14551 571.63 0.34524 339.66 |                      |                      |
| 60º            | 576.02 0.00424 0.15600 | 512.92 260.80 7.5685 0.14639 570.29 0.34404 340.17 |                      |                      |
| 75º            | 575.59 0.00414 0.15723 | 511.69 263.13 7.6440 0.14792 570.11 0.34006 342.34 |                      |                      |
| 90º            | 575.45 0.00445 0.15567 | 512.98 259.61 7.5040 0.14625 570.02 0.34493 338.23 |                      |                      |

| t, mm | Maximum σ = k(ɛ₀ + εₚ)ⁿ | Swift σ = A − B · exp(−C · εₚ) | Voce σ = YS + K(εₚ)ⁿ |
|-------|------------------------|-------------------------------|----------------------|
| 0.270 | 579.86 0.4642 666.94 0.00775 0.17050 | 575.54 253.87 7.4950 0.1480 650.48 |                      |
**TABLE 2.5.** Disk Compression Test Data

| Alloy/Temper | \( r_{nx} \) |
|--------------|--------------|
| TH330 steel  | 0.984        |

**TABLE 2.6.** Material Constants for Yield Function CPB06 (a=2.0)

| \( C_{11} \) | \( C_{12} \) | \( C_{13} \) | \( C_{22} \) | \( C_{23} \) | \( C_{33} \) | \( C_{44} \) | \( C_{55} \) | \( C_{66} \) | \( k \) |
|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|--------|
| 0.68903     | -0.10408    | -0.16354    | 0.79676     | 0.1931      | -0.60226    | 1.0          | 1.0          | 0.85596    | -0.1693|

**TABLE 2.7.** Material Constants for Yield Function Yld2004-18p (a=6.0)

| \( A_1 \) | \( A_2 \) | \( A_3 \) | \( A_4 \) | \( A_5 \) | \( A_6 \) |
|----------|----------|----------|----------|----------|----------|
| 0.8226   | 0.3634   | 0.9005   | 0.8555   | 0.5851   | 0.6972   |
| 0.9704   | 0.9994   | 0.8117   | 1.1570   | 1.3698   | 1.1071   |
| 0.9483   | 1.1485   | 1.0410   | 1.0426   | 1.0273   | 1.1368   |

**TABLE 2.8.** Material Constants for Yield Function Yld2000-2d (a=6.0)

| Sample   | \( a_1 \) | \( a_2 \) | \( a_3 \) | \( a_4 \) | \( a_5 \) | \( a_6 \) | \( a_7 \) | \( a_8 \) |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| TH 330   | 1.0352   | 0.9875   | 0.8241   | 0.9284   | 0.9345   | 0.8019   | 0.9867   | 1.0585   |

**TABLE 2.9.** Material Constants for Yield Function Yld89, r-value based (m=6.0)

| Sample   | \( a \) | \( c \) | \( h \) | \( p \) |
|----------|--------|--------|--------|--------|
| TH 330   | 0.8068 | 1.1932 | 0.9917 | 0.9570 |

**TABLE 2.10.** Material Constants for Yield Function Yld89, stress-based (m=6.0)

| Sample   | \( a \) | \( c \) | \( h \) | \( p \) |
|----------|--------|--------|--------|--------|
| TH 330   | 0.5275 | 1.4725 | 0.9843 | 0.9793 |

**TABLE 2.11.** Material Constants for Yield Function Hill, r-value based (1948)

| Sample   | \( F \) | \( G \) | \( H \) | \( L \) | \( M \) | \( N \) |
|----------|--------|--------|--------|--------|--------|--------|
| TH 330   | 0.7837 | 0.8167 | 1.1833 | 3.0    | 3.0    | 2.8262 |

**TABLE 2.12.** Material Constants for Yield Function Hill, stress-based (1948)

| Sample   | \( F \) | \( G \) | \( H \) | \( L \) | \( M \) | \( N \) |
|----------|--------|--------|--------|--------|--------|--------|
| TH 330   | 0.7646 | 0.8267 | 1.1733 | 3.0    | 3.0    | 3.0543 |
| Major True Strain £1 | Minor True strain £2 |
|----------------------|----------------------|
| 0.541                | -0.270               |
| 0.205                | 0.000                |
| 0.284                | 0.213                |
| 0.310                | 0.310                |
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Part B: Material Characterisation

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Abstract. This report summarises the material testing on the two metals used in this benchmark study, AA5352 aluminium alloy and TH330 steel (unstoved). In order to characterise the material anisotropic plastic properties and to specify failure criteria, the tests carried out were uniaxial tensile, bulge and disc compression tests, as well as the tests for obtaining forming limit curves. The parameters / material constants required for various material models are also described in this report.

Keywords: material characterisation, uniaxial tensile, bulge, disc compression, anisotropy, r-value, FLC

1. INTRODUCTION

Two metals were selected for Benchmark 1 in Numisheet 2016; AA5352 aluminium alloy supplied by Alcoa USA and TH330 steel (unstoved) obtained from Tata Steel. The thickness is 0.279 mm / 0.0110 inch for AA5352, and 0.270 mm / 0.0106 inch for TH330. This report provides a description of the material testing carried out on both metals for characterising the material properties and for specifying failure criteria. Data fitting to obtain the material constants of various material models is also documented in this report.

2. MATERIAL TESTS

2.1 Uniaxial tensile tests

Uniaxial tensile tests were carried out on both metals at 15 degree increments starting from the rolling direction as zero degrees to 90 degrees to the rolling direction on the plane of a metal sheet, i.e. 7 tests on each metal. For aluminium AA5352, the tests were conducted at University Aveiro, Portugal, based on ASTM norm E8M Standard and at Crown Technology Centre based on ISO 6892-1:2009 Standard. A single tensile test was conducted at the SP Technical Research Institute of Sweden using Digital Image Correlation (DIC) analysis and the results compared well with those obtained from mechanical test. Similarly, the tests on steel TH330 were performed at Tata Steel according to ISO 6892-1:2009 Standard and repeated at University Aveiro and at Crown. The test data were used to obtain the mechanical properties of the material such as yield stress, hardening coefficient, uniform elongation and r-value, etc.

The r-values were determined between 2% and 20% strain or between 2% and uniform elongation when the uniform elongation was lower than 20%. 
2.2 Bulge tests

Thin sheet metal of such small gauge as used in this Benchmark study usually splits at a strain of approximately 10% for Aluminium and 20% for steel in a uniaxial test. In order to obtain the material data at higher strains and to reduce discrepancies on data extrapolation of hardening curves, hydraulic bulge tests are commonly used to extend the tensile test data. The tests were performed at University of Porto, Portugal, and at Alcoa for AA5352. For TH330 the tests were conducted at both Tata Steel and University of Porto.

Figure 1 shows the setup of the bulge test system used in the University of Porto, as well as the measurement and variables used to determine the stress and strain. The full detailed description of the theory for stress and strain measurement can be found in [1], [2] and [3]. The equibiaxial stress is determined by

\[ \sigma_B = \frac{p\rho}{2t} \]  

(1)

where \( p \) is hydraulic pressure and \( t \) is the sheet metal thickness. The radius of curvature \( \rho \) is calculated by

\[ \rho = \frac{(D_{cv}/2)^2 + h^2}{2h} - \frac{t}{2} \]  

(2)

where \( D_{cv} \) is the diameter defined by the spherometer and \( h \) is the difference between the spherometer support and displacement transducer as illustrated in Figure 1. A correction is performed for half thickness of the sheet, since the calculation is done at the external surface of the cap. The current thickness (\( t \)) of the sample can be obtained through Eq. 3, knowing the initial thickness (\( t_0 \)) and the current thickness strain \( \varepsilon_t \).

\[ t = t_0 \cdot \exp(-\varepsilon_t) \]  

(3)

Concerning thickness strain, the following equation is used:

\[ \varepsilon_t = -2 \cdot \ln \left( \frac{D_{st}}{D_{st0}} \right) \]  

(4)

where \( D_{st} \) and \( D_{st0} \) are also defined in

Figure 1.

The bulge test on steel TH330 carried out in Tata Steel followed procedure ISO Standard 16808:2014. Figure 2 shows the results of the bulge test in which 3D digital image correlation (DIC) was applied to determine the in-plane strains and the bulge height. True stress and strain were reported in all the bulge tests.
Figure 1: Hydraulic bulge test system and variables for stress-strain determination
2.3 Disk compression tests

For anisotropic yield models, the biaxial $r$ value ($r_b$) is required and obtained from disk compression tests (Figure 3). For steel TH330, the tests were conducted at CERTETA with Prof. Dorel Banabic and at the University of Porto. For aluminium AA5352, the tests were conducted at the University of Porto and at Alcoa.

Different disk dimensions were used in the various test labs, ranging from 9 mm to 15 mm in diameter. Teflon foil and lubricant were used in both sides of samples to minimise friction effect.

The true total strains along the rolling direction of the metal and the transverse direction were measured and calculated. The biaxial $r$ value ($r_b$) is independent of the amount of thinning of the disk and determined using

$$r_b = \frac{\sum_{i=1}^{N} (\varepsilon^{(p)}_{RD,i} \varepsilon^{(p)}_{TD,i})}{\sum_{i=1}^{N} (\varepsilon^{(p)}_{RD,i} \varepsilon^{(p)}_{RD,i})}.
$$

where $\varepsilon^{(p)}_{RD}$ and $\varepsilon^{(p)}_{TD}$ are the plastic parts of the logarithmic strain of the $i$-th specimen ($i = 1, \ldots, N$) in the rolling and transverse direction, respectively [4].

Figure 2. Bulge test result for TH330
2.4 Forming Limit Curve (FLC)

The Forming Limit Curve for aluminium AA5352 was provided by Alcoa USA based on the concept of the forming limit diagram (FLD) first introduced by [5] and [6]. This diagram is usually plotted on axes representing the major ($\varepsilon_1$) and the minor ($\varepsilon_2$) strains in the plane of a sheet and corresponds to the maximum admissible local strains achievable just prior to the occurrence of visible defects in the sheet metal like necking and fracture.

The experimental technique to determine the FLD involves subjecting specimens of the considered sheet metal to different in-plane strain states, by simple tensile testing or stretching over a hemispherical punch and is known as the Nakajima test (Figure 4). Different deep draw and stretch forming conditions (from biaxial tension to plane strain to uniaxial tension) are achieved in the sheet metal by varying the specimen width. The tests on the AA5352 material followed the ISO 12004-2:2008 standard and used a 101.6 mm ball traveling at 1.5mm/s with strains being measured using an Aramis 5M system.
The Forming Limit Curve for steel TH330 was provided by Tata Steel using the Abspoel & Scholting method [8] in which four points are chosen to define the FLC, i.e., uniaxial tension necking point (TE), plane strain point (PS), intermediate biaxial stretch point (IM) and equi-biaxial stretch point (BI) (see Figure 5). The major and minor strains of these four points can be calculated based on the mechanical properties of an $A_{80}$ tensile bar (total elongation and r-values in transverse direction plus the minimum $A_{80}$ of the three directions, i.e., transverse, diagonal or longitudinal to rolling direction).

The uniaxial tension local necking points were obtained using an MTS 300 test bench with a GOM Aramis optical strain measurement system. The samples were measured transverse to the rolling direction. The other characteristic points were derived from Nakazima tests according to ISO12004-2: 2008, performed on an Erichsen model 145/60 laboratory press. The samples were measured transverse to the rolling direction. All measured strains in the Nakazima tests were corrected to the mid-plane. Figure 5 shows the fracture test data and the derived forming limit curve for TH330.
The three different notched tensile fracture experiments were performed on an MTS 300 test bench with a GOM Aramis optical strain measurement system, where the specimens are “gridded” with a random speckle pattern (Figure 6). The deformation is filmed with two cameras and with the digital image correlation (DIC) method and the 3D coordinates of the speckle pattern are converted into strain components or principal strains contour plots. For every Aramis optical strain measurement, the used facet size is 19 pixels by 19 pixels with a step size of 9 pixels by 9 pixels, which results into an overlap of 53%.

Figure 6. a) Speckle pattern, b) GOM Aramis system

The geometry of the three different notched tensile specimens are shown in Figure 7. The obtained spatial resolution with the GOM Aramis optical measurement system is approximately 0.3 mm for the notched tensile specimens. A remark should be made here regarding the edge of the notched tensile fracture experiments, the edges are milled and polished with a P1000 sand paper. A stack of sheets was magnetically clamped and milled into shape using a die, because a single sheet of the TH330 material is too thin to mill to these geometries.

Figure 7. Geometry of a) Slight Notched- b) Intermediate Notched- c) Plane Strain Notched Tensile Specimen
The Nakajima fracture experiments were performed according to ISO12004-2: 2008, on an Erichsen model 145/60 laboratory press using a GOM Aramis optical strain measuring system (Figure 8). The obtained spatial resolution for the Nakajima experiments with the GOM Aramis optical measurement system is approximately 0.4 mm.

The in-plane fracture experiments were performed on the MTS 300 test bench and the geometry is shown in Figure 9. Normally, the groove is milled at half the thickness of the sheet, but the TH330 material is approximately 0.27 mm thick. Therefore a stack of sheet were glued with DP490 (3M Scotch-weld). The glued strips are placed in a holder and the stacked block is compressed with a PST hydraulic press at a load of 10 kN for 3 hours for the adhesive to cure. The specimen is left at room temperature for 12 hours to acquire the full bonding strength.
Figure 9. Geometry In-Plane Shear Fracture Specimen

For the in-plane shear fracture test the maximum shear angle is measured with a macro scope (Figure 10). The front of the in-plane shear fracture test sample has a groove with a width of 1.5 mm, where 3 scribes are made on the back. One scribe is in the middle of the sample and the two other scribes are made at 5 mm from the edge of the sample, see top right picture in Figure 10. After the macroscope has been calibrated and the in-plane shear fracture test sample is properly aligned, the maximum shear angle can be measured with the Leica measuring software as shown in the pictures on the left side of Figure 10.

The maximum shear angle at fracture is then converted into principal fracture strains. All the fracture experiments were measured transverse to the rolling direction and on the surface of the specimen. Figure 11 shows the fracture test data and the derived Forming Limit Curve (FLC) for TH330.
Figure 10. Maximum Shear Angle Measurements with a macroscope

Figure 11. The FLC of TH330 and the fracture experiment data
3. DATA FITTING

3.1 Stress-strain curves and hardening coefficients
The raw data obtained from the uniaxial tensile tests were mainly load-deformation datasets. The engineering stress and strain data as well as the corresponding true stress-strain data were calculated based on the dimensions of individual specimen depending on different standards used in the tests. The yield stress was determined as proof stress at 0.1% plastic strain from the true stress-strain curve and averaged from all the sample data of each test. Uniaxial tensile tests gave maximum uniform strains of approximately 10% and 16% for aluminium and steel respectively. The bulge test data were scaled such that they overlay the uniaxial test data and plastic work is conserved. This scaled bulge test data was used to extend the uniaxial test data beyond the point of maximum uniform strain to higher levels of strain [9]. The extended true stress-strain curves were used for data fitting and determination of material constants. Parameters for the following hardening functions were calculated using a least square fitting algorithm applied to the data.

Swift law:
\[ \sigma = k(\varepsilon_0 + \bar{\varepsilon}^p)^n \] (6)

Voce law:
\[ \sigma = A - B \cdot \exp(-C \cdot \bar{\varepsilon}^p) \] (7)

Hollomon’s equation:
\[ \sigma = K(\bar{\varepsilon}^p)^n \] (8)

Ludwik’s equation:
\[ \sigma = YS + K(\bar{\varepsilon}^p)^n \] (9)

The obtained material constants for the above four hardening laws are shown in Table 1.3 for aluminium AA5352 and Table 2.3 for steel TH330 in Part A.

Table 1.4 and 2.4 in Part A are the constants obtained from the equal biaxial test data only for AA 5352 and TH330, respectively.

3.2 Yield Functions

Yld2004-18p
The Yld2004-18p model requires an exponent, \( a \), and 18 coefficients to be defined according to the procedure described in [10]. \( a \) is defined based on the crystal system of the alloy. For BCC alloys including steels, 6 is used, and for FCC alloys including Aluminium alloys 8 is used. The 18 coefficients were obtained by an iterative process which matches the material model behaviour to various properties determined from practical tests or assumed. These material properties and their origins are summarised in TABLE 1. The flow stress ratio is a ratio relative to a reference flow stress, in this case that of the 0° uniaxial test.
TABLE 1: Summary of measured and assumed properties used for calibration of the Yld2004-18p model.

| Test                              | Flow stress ratio | r-value |
|-----------------------------------|-------------------|---------|
| Uniaxial (x7 @ 0°, 15°, 30°, 45°, 60°, 75°, 90°) | Y                 | Y       |
| Disk compression                  |                   |         |
| Bulge                             |                   | Y       |

Assumptions

| Flow stress ratio | r-value |
|-------------------|---------|
| 45° tension in TD-ND plane | 1       |
| 45° tension in ND-RD plane | 1       |
| Simple shear in TD-ND plane  | $1/(1 + 2^{a-1})^{1/a}$ |
| Simple shear in ND-RD plane  | $1/(1 + 2^{a-1})^{1/a}$ |

The iterative process to determine the 18 coefficients was driven by an optimisation algorithm. For each iteration, a new set of 18 parameters was generated, and the values of each property in TABLE 1 predicted by the material model with this set of parameters was calculated by a program. The calculated and measured values were then used to calculate an error term for each property:

$$ e_{rr} = (\frac{p_{pr}}{p_{ex}} - 1)^2 , $$

where $p_{pr}$ is the predicted value of a property and $p_{ex}$ is the experimentally determined value of a property. The error term for each property is multiplied by a weighting factor and summed to calculate the objective function:

$$ E = \sum w_{p} e_{rr_{p}} , $$

Where $w_{p}$ are weighting functions. The optimisation algorithm selects a new set of 18 coefficients for the next iteration based on previous coefficient sets and objective functions.

Yld2000-2d

The Yld2000-2d model requires an exponent, $a$, and 8 coefficients to be defined according to the procedure described in [11]. $a$ is defined based on the crystal system of the alloy. For BCC alloys including steels, 6 is used, and for FCC alloys including Aluminium alloys 8 is used. The 8 coefficients for each material given in the benchmark description were obtained by numerical solution of a set of 8 nonlinear simultaneous equations based on the experimental data summarised in TABLE 2.

TABLE 2: Summary of experimental data used in the calibration of the Yld2000-2d model.

| Test                              | Flow stress ratio | r-value |
|-----------------------------------|-------------------|---------|
| Uniaxial (x7 @ 0°, 15°, 30°, 45°, 60°, 75°, 90°) | Y                 | Y       |
| Disk compression                  |                   |         |
| Bulge                             |                   | Y       |

CPB06

The CPB06 model requires an exponent, $a$, a strength differential parameter, $k$, and 7 anisotropy coefficients to be defined. The value of $a$ is taken as 2, and the strength differential and anisotropy parameters are determined according to an optimisation similar to that used for the Yld2004-18p model. The error function in this case also requires terms relating to the error in the predicted
compressive yield stress, but since no experimental data was available in compression, the biaxial
yield stress determined from the bulge test was taken as the uniaxial compressive stress at each angle:

\[
\sigma_0^C = \sigma_0^T, \quad \in [0, 90],
\]

Where superscripts \( C \) and \( T \) denote compression and tension respectively, a subscript \( b \) represents
equibiaxial loading and a subscript \( \theta \) represents the angle of uniaxial loading.

**CPB06ex2**
The CPB06ex model requires an exponent, \( a \), two strength differential parameters, \( k \) and \( k' \), and 14
anisotropy coefficients to be defined. The value of \( a \) is taken as 3, and the strength differential and
anisotropy parameters are determined according to an optimisation similar to that used for the
Yld2004-18p model. The error function in this case also requires terms relating to the error in the
predicted compressive yield stress, but since no experimental data was available in compression, the
biaxial yield stress determined from the bulge test was taken as the uniaxial compressive stress at each
angle, as in Eq. 12.

**Hill**

**Stress based**

Hill’s 1948 yield function [12] may be written in a coordinate system where \( x \) is parallel to the rolling
direction, \( y \) is parallel to the transverse direction and \( z \) is normal to the sheet as:

\[
F \left( \frac{\sigma_{yy}}{\sigma_0} - \frac{\sigma_{xz}}{\sigma_0} \right)^2 + G \left( \frac{\sigma_{xz}}{\sigma_0} - \frac{\sigma_{xx}}{\sigma_0} \right)^2 + H \left( \frac{\sigma_{xx}}{\sigma_0} - \frac{\sigma_{yy}}{\sigma_0} \right)^2 + 2L \left( \frac{\sigma_{yz}}{\sigma_0} \right)^2 + 2M \left( \frac{\sigma_{zx}}{\sigma_0} \right)^2 + 2N \left( \frac{\sigma_{xy}}{\sigma_0} \right)^2 = 2
\]

\( \sigma_0 \) is the reference yield stress, which is taken as the value of yield stress for uniaxial tension in the
rolling direction. Yield stress ratios, \( \frac{\sigma_a}{\sigma_0} \), are calculated using the Swift data for the relevant test given
in the benchmark description, and a plastic strain determined such that the plastic strain energy is the
same in each case. From these yield stress ratios, the components in the material coordinate system,
\( \frac{\sigma_{ij}}{\sigma_0} \), may be derived. By substituting these values of yield stress ratios from the 0°, 45°, 90° and bulge
tests, the following system of equations is obtained:

\[
G + H = 2 \left( \frac{\sigma_0}{\sigma_0} \right)^2
\]

\[
\frac{\sigma_0}{\sigma_45}^2 + N = 4 \left( \frac{\sigma_0}{\sigma_45} \right)^2
\]

\[
F + H = 2 \left( \frac{\sigma_0}{\sigma_0} \right)^2
\]

\[
F + G = 2 \left( \frac{\sigma_0}{\sigma_b} \right)^2
\]

These equations were then solved for \( F, G, H \) and \( N \), while values for \( L \) and \( M \) were fixed at 3.

**r-value based**
The definition of \( \sigma_0 \) as the yield stress for uniaxial tension in the rolling direction means that:
\[ G + H = 2 \]  

\( r \)-values are provided in the benchmark description for uniaxial tests loaded at 0°, 45° and 90° to the rolling direction. These \( r \) values may be expressed in terms of incremental plastic strain components as:

\[ r_0 = \frac{d\varepsilon_{yy}^{pl}}{d\varepsilon_{zz}^{pl}} \]  
\[ r_{90} = \frac{d\varepsilon_{xx}^{pl}}{d\varepsilon_{zz}^{pl}} \]  

The flow rule for Hill’s 1948 yield function is:

\[ d\varepsilon^{pl} = d\lambda \frac{df}{d\sigma} \]  

Substituting this expression into the expression for the \( r \)-values gives:

\[ r_0 = \frac{H}{G} \]  
\[ r_{90} = \frac{H}{F} \]  

There are now 3 equations which may be solved for \( F \), \( G \) and \( H \). The 45° uniaxial test was used to determine \( N \).

\[ r_{45} = \frac{d\varepsilon_{y,135}^{pl}}{d\varepsilon_{zz}^{pl}} \]  

Where a superscript on \( \varepsilon \) denotes the angle from the rolling direction at which the strain is measured, with:

\[ d\varepsilon^{135} = \frac{1}{2}d\varepsilon_{11} + \frac{1}{2}d\varepsilon_{11} - d\gamma_{12} \]  

Leads to:

\[ N = G \left( r_{45} + \frac{1}{2} \right) \left( 1 + \frac{r_x}{r_y} \right) \]  

**Yld89**

*Stress based*

The Yld89 [13] yield function is:

\[ f_{yld89} = a|k_1 + k_2|^M + a|k_1 - k_2|^M + c|2k_2|^M = 2\sigma_0^M \]  

With \( M=8 \) for aluminium alloys, \( M=6 \) for steel and:

\[ k_1 = \frac{\sigma_{11} + h\sigma_{22}}{2} \]  

\[ r_{135} = \frac{d\varepsilon_{y,135}^{pl}}{d\varepsilon_{zz}^{pl}} \]
\[ k_2 = \sqrt{\frac{(\sigma_{11} - h\sigma_{22})^2}{2} + p^2 \sigma_{12}^2} \]  

(29)

Yield stress values are calculated from the Swift data given for uniaxial and bulge tests, with a plastic strain determined such that the plastic strain energy is the same in each case. \( \sigma_0 \) is the reference yield stress, which is taken as the value of yield stress for uniaxial tension in the rolling direction. By substituting the stress components on the LHS of the yield function with values corresponding to the yield stresses in 0°, 45° and 90° uniaxial tests and the bulge test, a system of 4 equations is formed:

\[ a + c = 2 \]  

(30)

\[ \begin{align*}
  a &\left| \frac{(1 + h)\sigma_{45}}{4} + \sqrt{\frac{(1 - h)\sigma_{45}}{4}} \right|^M \\
  &+ a \left| -\frac{(1 + h)\sigma_{45}}{4} - \sqrt{\frac{(1 - h)\sigma_{45}}{4}} \right|^M \\
  &+ c \left| (1 - h)\sigma_{45} + p^2 \sigma_{45}^2 \right|^M = 2\sigma_0^M \\

  h &= \frac{\sigma_0}{\sigma_{90}} \quad \text{(32)} \\

  a &= \frac{2\sigma_0^M}{(1 + h^M)\sigma_b^M} \quad \text{(33)}
\end{align*} \]

This set of equations was solved for \( a, c, h \) and \( p \).

**r-value based**

Based on the flow rule:

\[ de^\text{pl} = d\lambda \frac{df_{\text{yield}}}{d\sigma}, \quad (34) \]

incompressibility during plastic flow:

\[ \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz} = 0 \]  

(35)

and the yield function:

\[ f_{\text{yield}} = a|k_1 + k_2|^M + a|k_1 - k_2|^M + c|2k_2|^M = 2\sigma_0^M. \]  

(36)

the following relationships between Lankford’s coefficients and \( a \) and \( h \) may be derived:

\[ a = 2 - 2\sqrt{\frac{r_0}{1 + r_0} \frac{r_{90}}{1 + r_{90}}} \]  

(37)
The use of the yield stress for uniaxial tension in the rolling direction as the reference stress leads to:

\[ a + c = 2 \]  

The predicted r-value for uniaxial loading at 45° from the rolling direction is given by:

\[ r_{45} = \frac{2m}{\left( \frac{\partial f_{yld89}}{\partial \sigma_0} + \frac{\partial f_{yld89}}{\partial \sigma_{90}} \right)} \sigma_{45} - 1 \]  

This equation was used iteratively to find \( p \) such that predicted and measured values of \( r_{45} \) matched.

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Benchmark 1 – Failure Prediction after Cup Drawing, Reverse Redrawing and Expansion

Part C: Physical Tryout

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Abstract: The practical experiments and measurements of BM1, “Failure Prediction after Cup Drawing, Reverse Redrawing and Expansion” are summarised, including details of the equipment used, process conditions, measurement methods and the results obtained.

Keywords: Cup, cupping, expansion die, ear height, wall thickness.

1. OUTLINE OF EXPERIMENTS AND MEASUREMENTS

A two-stage drawing and reverse redrawing process was used to produce cups in both steel and aluminium.

Cup wall heights were measured at 1\degree \ increments circumferentially to produce an ear profile for the entire circumference of the cups.

Cup wall thicknesses were measured at 10\degree \ increments circumferentially and at 20mm, 45mm and 50mm from the base of each cup to produce a map of wall thickness.

Cups were expanded to fracture using a lubricated, vented conical die tool. The vent holes in the tool ensured that there was no internal air pressure increase as the conical die entered the cup.

Axial displacement and axial load were recorded at approximately 0.01mm increments during the die expansion-to-fracture testing.
2. EXPERIMENTAL FORMING TOOLS & PROCESS CONDITIONS

Details of all tooling are given in Part A: Benchmark report, along with the displacements, blank holding forces, velocities and friction coefficients.

2.1 Draw – Reverse Redraw Cupping Process

Cups were made using Alcoa’s Draw and Reverse Redraw process at the Alcoa Technical Center, Pittsburgh, USA.

![Figure 1: Alcoa Press](image1)

![Figure 2: Draw, Reverse-Redraw tool](image2)

![Figure 3: Typical aluminium cup](image3)

![Figure 4: Typical steel cup](image4)
2.2 Die Expansion to Fracture

The die expansion-to-fracture experiment was conducted at Crown’s Corporate Technology Centre in Wantage, UK. Cups were driven downwards over a lubricated conical tool while both displacement and load were measured. The conical tool had holes drilled to vent the cup during die expansion.

![Cup mounting details](image1)

**Figure 5: Cup mounting details.**

![Die expansion of cup](image2)

**Figure 6: Die expansion of cup**

![Typical aluminium cup fracture](image3)

**Figure 7: Typical aluminium cup fracture**

![Typical steel cup fracture](image4)

**Figure 8: Typical steel cup fracture**
3. MEASUREMENT

3.1 Cup height and ear profile

Cup heights were measured at Crown’s Corporate Technology Centre in Wantage, UK.

Cups were clamped and rotated through 360°.

A sprung-loaded probe measured the vertical position of the edge at 1 degree increments during the rotation, producing an ear profile for the cup.

Steel cups (averaged data)

- 4 ears
- Mean height was 52.61 mm
- Amplitude (max – min) was 1.14 mm.

Figure 9: Ear measurement

Figure 10: Steel cup ear profile
Aluminium cups (averaged data)

- 8 ears.
- Mean height was 52.05mm
- Amplitude (max – min) was 4.13mm.
- The metal in the ears at 0° and 180° was severely thinned due to the blank holder load being concentrated on these last two ears during the forming process.

Comment on aluminium cup ear profile

For the aluminium cups, the upper region of the ears at 0° and 180° were significantly thinner than the rest of the cup, as shown in the images in figure 12 below.

This thinning is believed to be due to the blank holding force exerted on these two ears in the final stages of cup forming.

Figure 11: Aluminium cup ear profile

Figure 12: Aluminium cups – pinched ears
3.2 Cup wall thickness

Figure 13: Sample preparation and measurement of wall thickness

Figure 14: Aluminium cup wall thickness

Figure 15: Steel cup wall thickness
3.3. Die expansion to fracture

Load and displacement data were recorded at approx. 0.01mm travel increments.

Steel cups (averaged data)
- Load at fracture = 8.55 kN
- Travel at fracture = 30.2mm
- Fracture angle = 42°
- Banding observed all around the free edge.

Figure 16: Load to fracture (Steel)

Figure 17: Steel cup after fracture
Aluminium cups (averaged data)

- Load at fracture = 2.76 kN
- Travel to fracture = 16.4mm
- Fracture angle = 96°

Figure 18: Load to fracture (Aluminium)

Figure 19: Aluminium cup after fracture
Benchmark 1 – Failure Prediction After Cup Drawing, Reverse Redrawing and Expansion

Part D: Responses

Martin Watson\textsuperscript{a}, Robert Dick\textsuperscript{b}, Y. Helen Huang\textsuperscript{a}, Andrew Lockley\textsuperscript{a}, Rui Cardoso\textsuperscript{c}, Abel Santos\textsuperscript{d}

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\textsuperscript{d}FEUP, University of Porto, 4200-465, Portugal

| 1. Experimental data: BM1_00 |
|-------------------------------|
| **Name**                      |
| Martin Watson, Robert Dick, Y. Helen Huang, Andrew Lockley, Rui Cardoso, Abel Santos |
| **Prepared by**               |
| Benchmark 1 Committee         |
| **Email**                     |
| NumisheetBenchmark1@uwe.ac.uk  |
### 1. Benchmark Participant : BM1_01

| Name          | Toshiro Amaishi*, Masahi Arai, Yuko Watanabe |
|---------------|--------------------------------------------|
| Affiliation   | 1JSOL Corporation                           |
| Address       | Tosabori Daibiru Building, 2-2-4, Tosabori Nishi-ku, Osaka 550-0001, Japan |
| Email         | * amaishi.toshirou@jsol.co.jp                |
| Phone number  | '+81-6-4803-5820                            |
| Fax number    | '+81-6-6225-3517                            |

### 2. Simulation Software

| Name of the FEM code     | JSTAMP/NV (solver: LS-DYNA) |
|--------------------------|-----------------------------|
| General aspect of the code | Integrated sheet metal forming simulation system |
| Basic formulations       | Dynamic Explicit            |
| Element/Mesh technology  |                             |
| Number of elements       | 29430 (for Blank), Quarter model |
| Type of elements         | Solid element, reduced integration |
| Contact property model   | Penalty Method, Surface to Surface |
| Friction formulation     | Coulomb's friction law      |

### 3. Simulation Hardware

| CPU Type       | Intel Xeon E5-1650 |
|----------------|--------------------|
| CPU clock speed| 3.5GHz             |
| Number of cores per CPU | 6 |
| Main memory    | 16.0G              |
| Operating system | Windows 7 Professional |
Total CPU time

| Material | AA5352: 2 hours 31 min. for drawing, 4 hours 28 min. for reverse redrawing, 2 hours 10 min. for die expansion | TH330: 2 hours 8 min. for drawing, 3 hours 35 min. for reverse redrawing, 2 hours 4 min. for die expansion |

4. Describe the material model used for each material

| Material | AA5352 (aluminium) | TH330 (steel) |
|----------|---------------------|---------------|
| Yield Function/Plastic Potential | Yoshida (sixth order polynomial model) | Yoshida (sixth order polynomial model) |
| Hardening Rule (e.g. Isotropic, kinematic) | Kinematic | Kinematic |
| Stress-Strain Relation (e.g. Swift, Voce) | Yoshida-Uemori Kinematic hardening model | Yoshida-Uemori Kinematic hardening model |
| Failure model | Strain based FLD | |
### 1. Benchmark Participant : BM1_02

| Name          | P.D. Carvalho, P.D. Barros, D.M. Neto, M.C. Oliveira, J.L Alves and L.F. Menezes |
|---------------|----------------------------------------------------------------------------------|
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| Fax number    | +351 239 790 701                                                                 |

### 2. Simulation Software

| Name of the FEM code | DD3IMP                     |
|----------------------|----------------------------|
| General aspect of the code | Static fully implicit          |
| Basic formulations | Updated Lagrangian formulation with associated flow rule |
| Element/Mesh technology |                                |
| Number of elements  | 11552                      |
| Type of elements    | Isoparametric 3D brick elements with selective reduced integration technique |
| Contact property model | Rigid tools modelled by 7550 Nagata patches, Augmented lagrangian method |
| Friction formulation | Coulomb friction law         |

### 3. Simulation Hardware

| CPU Type             | Intel® Core™ i7-2600K        |
|----------------------|-------------------------------|
| CPU clock speed      | 3.4 GHz                       |
| Number of cores per CPU | 4 cores                     |
| Main memory          | 8 GB RAM                      |
| Operating system     | Windows 7 Professional (64-bit) |
4. Describe the material model used for each material

| Material          | AA5352 (aluminium)       | TH330 (steel)         |
|-------------------|--------------------------|----------------------|
| Yield Function/Plastic Potential | Cazacu and Barlat 2001 | Cazacu and Barlat 2001 |
| Hardening Rule (e.g. Isotropic, kinematic) | Isotropic | Isotropic |
| Stress-Strain Relation (e.g. Swift, Voce) | Voce | Swift |
| Failure model     | Maximum element thinning rate | |
1. Benchmark Participant : BM1_03

| Name                        | Kai Oide*, Takaya Kobayashi1, Yasuko Mihara1, Hideo Takizawa2 |
|-----------------------------|---------------------------------------------------------------|
| Affiliation                 | 1Mechanical Design & Analysis Corporation, 2Nippon Institute of Technology |
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| Email                       | *oide@mech-da.co.jp                                           |
| Phone number                | 81(42)482-1539                                               |
| Fax number                  | 81(42)482-5106                                               |

2. Simulation Software

| Name of the FEM code        | Abaqus 3DEXPERIENCE R2016x                                   |
|-----------------------------|--------------------------------------------------------------|
| General aspect of the code  | Dynamic Implicit in Drawing and Reverse redrawing operation  |
|                             | Static Implicit with artificial damping method in Die expansion operation |
| Basic formulations          | Updated Lagrangian formulation with associated flow rule    |
|                            | **Element/Mesh technology**                                   |
| Number of elements          | 16000 elements                                               |
| Type of elements            | 4-node quadrilateral shell element with reduced integration : S4R |
| Contact property model      | Penalty method                                               |
| Friction formulation        | Coulomb friction model                                       |

3. Simulation Hardware

| CPU Type                    | Intel® Xeon® CPU X5650                                      |
|-----------------------------|-------------------------------------------------------------|
| CPU clock speed             | 2.66GHz                                                    |
| Number of cores per CPU     | 6 cores                                                    |
| Main memory                 | 48.0 GB RAMM                                              |
### 4. Describe the material model used for each material

| Material            | AA5352 (aluminium) | TH330 (steel) |
|---------------------|--------------------|---------------|
| Yield Function/Plastic Potential | YLD2004            | YLD2004       |
| Hardening Rule (e.g. Isotropic, kinematic) | Isotropic          | Isotropic     |
| Stress-Strain Relation (e.g. Swift, Voce) | Voce               | Voce          |
| Failure model       | MSFLD              |               |

Operating system: Windows 7 Professional

Total CPU time: average total CPU time is 586868[sec]
1. Benchmark Participant : BM1_04

| Name             | Kai Oide1*, Takaya Kobayashi1, Yasuko Mihara1, Hideo Takizawa2 |
|------------------|---------------------------------------------------------------|
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| Email            | *oide@mech-da.co.jp                                          |
| Phone number     | 81(42)482-1539                                               |
| Fax number       | 81(42)482-5106                                               |

2. Simulation Software

| Name of the FEM code     | Abaqus 3DEXPERIENCE R2016x                                   |
|--------------------------|---------------------------------------------------------------|
| General aspect of the code| Dynamic Implicit in Drawing and Reverse redrawing operation Static Implicit with artificial damping method in Die expansion operation |
| Basic formulations       | Updated Lagrangian formulation with associated flow rule     |
| Element/Mesh technology  |                                                               |

| Number of elements       | 16000 elements                                               |
|--------------------------|---------------------------------------------------------------|
| Type of elements         | 4-node quadrilateral shell element with reduced integration : S4R |
| Contact property model   | Penalty method                                               |
| Friction formulation     | Coulomb friction model                                       |

3. Simulation Hardware

| CPU Type                  | Intel® Xeon® CPU X5650                                     |
|---------------------------|-------------------------------------------------------------|
| CPU clock speed           | 2.66GHz                                                    |
| Number of cores per CPU   | 6 cores                                                    |
| Main memory               | 48.0 GB RAMM                                               |
| Operating system | Windows 7 Professional |
|------------------|------------------------|
| Total CPU time   | average total CPU time is 586868[sec] |

### 4. Describe the material model used for each material

| Material                | AA5352 (aluminium) | TH330 (steel) |
|-------------------------|--------------------|---------------|
| Yield Function/Plastic Potential | YLD2000     | YLD2000      |
| Hardening Rule (e.g. Isotropic, kinematic) | Isotropic   | Isotropic   |
| Stress-Strain Relation (e.g. Swift, Voce) | Voce         | Voce         |
| Failure model           | MSFLD             |               |
1. Benchmark Participant : BM1_05

| Name | Kai Oide*, Takaya Kobayashi, Yasuko Mihara, Hideo Takizawa2 |
|------|---------------------------------------------------------------|
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| Phone number | 81(42)482-1539 |
| Fax number | 81(42)482-5106 |

2. Simulation Software

| Name of the FEM code | Abaqus 3DEXPERIENCE R2016x |
|----------------------|----------------------------|
| General aspect of the code | Dynamic Implicit in Drawing and Reverse redrawing operation Static Implicit with artificial damping method in Die expansion operation |
| Basic formulations | Updated Lagrangian formulation with associated flow rule |

| Element/Mesh technology |
|-------------------------|
| Number of elements | 16000 elements |
| Type of elements | 4-node quadrilateral shell element with reduced integration : S4R |
| Contact property model | Penalty method |
| Friction formulation | Coulomb friction model |

3. Simulation Hardware

| CPU Type | Intel® Xeon® CPU X5650 |
|----------|------------------------|
| CPU clock speed | 2.66GHz |
| Number of cores per CPU | 6 cores |
| Main memory | 48.0 GB RAMM |
| Operating system | Windows 7 Professional |
|------------------|------------------------|
| Total CPU time   | average total CPU time is 586868[sec] |

### 4. Describe the material model used for each material

| Material          | AA5352 (aluminium) | TH330 (steel) |
|-------------------|--------------------|---------------|
| Yield Function/Plastic Potential | YLD89 stress based | YLD89 stress based |
| Hardening Rule (e.g. Isotropic, kinematic) | Isotropic | Isotropic |
| Stress-Strain Relation (e.g. Swift, Voce) | Voce | Voce |
| Failure model     |                    |               |
1. Benchmark Participant : BM1_06

| Name                        | Kai Oide1*, Takaya Kobayashi1, Yasuko Mihara1, Hideo Takizawa2 |
|-----------------------------|------------------------------------------------------------------|
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| Phone number                | 81(42)482-1539                                                   |
| Fax number                  | 81(42)482-5106                                                   |

2. Simulation Software

| Name of the FEM code        | Abaqus 3DEXPERIENCE R2016x                                     |
|-----------------------------|-----------------------------------------------------------------|
| General aspect of the code  | Dynamic Implicit in Drawing and Reverse redrawing operation Static Implicit with artificial damping method in Die expansion operation |
| Basic formulations          | Updated Lagrangian formulation with associated flow rule       |

| Element/Mesh technology     |                                                                 |
|-----------------------------|-----------------------------------------------------------------|
| Number of elements          | 16000 elements                                                  |
| Type of elements            | 4-node quadrilateral shell element with reduced integration : S4R |
| Contact property model      | Penalty method                                                  |
| Friction formulation        | Coulomb friction model                                          |

3. Simulation Hardware

| CPU Type                    | Intel® Xeon® CPU X5650                                         |
|-----------------------------|-----------------------------------------------------------------|
| CPU clock speed             | 2.66GHz                                                         |
| Number of cores per CPU     | 6 cores                                                         |
| Main memory                 | 48.0 GB RAMM                                                    |
| Operating system | Windows 7 Professional |
|------------------|------------------------|
| Total CPU time   | average total CPU time is 586868[sec] |

4. Describe the material model used for each material

| Material | AA5352 (aluminium) | TH330 (steel) |
|----------|---------------------|---------------|
| Yield Function/Plastic Potential | Hill stress based | Hill stress based |
| Hardening Rule (e.g. Isotropic, kinematic) | Isotropic | Isotropic |
| Stress-Strain Relation (e.g. Swift, Voce) | Voce | Voce |
| Failure model | MSFLD | |
1. Benchmark Participant : BM1_07

| Name          | Hariharasudhan Palaniswamy, Subir Roy |
|---------------|---------------------------------------|
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| Phone number  | 248-614-2400                          |
| Fax number    | 248-614-2411                          |

2. Simulation Software

| Name of the FEM code        | HyperForm - RADIOSS |
|------------------------------|---------------------|
| General aspect of the code   | Commercial nonlinear finite element software |
| Basic formulations           | Forming (Explicit), Springback(Implicit) |
| Element/Mesh technology      |                      |
| Number of elements           | 810934               |
| Type of elements             | Shell element - QEPH formulation |
| Contact property model       | Penaltly based contact formulations |
| Friction formulation         | Coulomb's Law       |

3. Simulation Hardware

| CPU Type                       | Laptop with Inter Core I7 processor |
|--------------------------------|-------------------------------------|
| CPU clock speed                | 2.5Ghz                              |
| Number of cores per CPU        | 4 cores with 2 threads each, 3 cores with 2 threads used for calculation |
| Main memory                    | 16GB                                |
| Operating system               | Windows 7                           |
Total CPU time

| Material          | AA5352 (aluminium) | TH330 (steel)  |
|-------------------|--------------------|----------------|
| Yield Function/Plastic Potential | Barlat 3 parameter model | HILL 1948 Material model |
| Hardening Rule (e.g. Isotropic, kinematic) | Combined hardening rule | Combined hardening rule |
| Stress-Strain Relation (e.g. Swift, Voce) | Hollmon hardening law | Hollmon hardening law |
| Failure model     |                    |                |

4. Describe the material model used for each material
1. Benchmark Participant : BM1_08

| Name              | Jan SLOTA, Marek, SISER |
|-------------------|--------------------------|
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| Phone number      | +421556023545 |
| Fax number        |                          |

2. Simulation Software

| Name of the FEM code | PamStamp 2G, v2015.1 |
|----------------------|----------------------|
| General aspect of the code | Dynamic explicit code |
| Basic formulations |
| Element/Mesh technology |
| Number of elements | blank: 5472 elements |
| Type of elements | shell/membrane |
| Contact property model | accuracy |
| Friction formulation | Coulomb friction model, u=0.03 |

3. Simulation Hardware

| CPU Type           | Intel XEON E5 |
|--------------------|---------------|
| CPU clock speed    | 2.60GHz       |
| Number of cores per CPU | 8           |
| Main memory        | 16 GB         |
| Operating system   | Win 8.1 Pro 64-bit |
4. Describe the material model used for each material

| Material          | AA5352 (aluminium) | TH330 (steel)   |
|-------------------|--------------------|-----------------|
| Yield Function/Plastic Potential | Barlat2000          | Orthotropic Hill48 |
| Hardening Rule (e.g. Isotropic, kinematic) | Isotropic       | Isotropic         |
| Stress-Strain Relation (e.g. Swift, Voce) | Swift/Krupkowski | Swift/Krupkowski  |
| Failure model     |                    |                 |
Table of figures
Figure 1: (AA5352) Cup height vs angle from rolling direction after the reverse redraw operation.
Figure 2: (AA5352) Cup height vs angle from rolling direction after the reverse redraw operation.
Figure 3: (AA5352) Cup height vs angle from rolling direction after the reverse redraw operation.
Figure 4: (TH330) Cup height vs angle from rolling direction after the reverse redraw operation.
Figure 5: (TH330) Cup height vs angle from rolling direction after the reverse redraw operation.
Figure 6: (TH330) Cup height vs angle from rolling direction after the reverse redraw operation.
Figure 7: (AA5352) Wall thickness vs angle from rolling direction 25mm above cup base.
Figure 8: (AA5352) Wall thickness vs angle from rolling direction 25mm above cup base.
Figure 9: (AA5352) Wall thickness vs angle from rolling direction 25mm above cup base.
Figure 10: (AA5352) Wall thickness vs angle from rolling direction 45mm above cup base.
Figure 11: (AA5352) Wall thickness vs angle from rolling direction 45mm above cup base.
Figure 12: (AA5352) Wall thickness vs angle from rolling direction 45mm above cup base.
Figure 13: (TH330) Wall thickness vs angle from rolling direction 25mm above cup base.
Figure 14: (TH330) Wall thickness vs angle from rolling direction 25mm above cup base.
Figure 15: (TH330) Wall thickness vs angle from rolling direction 25mm above cup base.
Figure 16: (TH330) Wall thickness vs angle from rolling direction 45mm above cup base.
Figure 17: (TH330) Wall thickness vs angle from rolling direction 45mm above cup base.
Figure 18: (TH330) Wall thickness vs angle from rolling direction 45mm above cup base.
Figure 19: (AA5352) Load vs expansion punch stroke.
Figure 20: (AA5352) Load vs expansion punch stroke.
Figure 21: (AA5352) Load vs expansion punch stroke.
Figure 22: (TH330) Load vs expansion punch stroke.
Figure 23: (TH330) Load vs expansion punch stroke.
Figure 24: (TH330) Load vs expansion punch stroke.
Figure 25: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.
Figure 26: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.
Figure 27: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.
Figure 28: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 29: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 30: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 31: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 32: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 33: (TH330) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 34: (TH330) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 35: (TH330) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 36: (TH330) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 37: (TH330) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 38: (AA5352) Position of point of first failure during expansion test.

Figure 39: (AA5352) Stroke of expansion punch at first failure.

Figure 40: (TH330) Position of point of first failure during expansion test.

Figure 41: (TH330) Stroke of expansion punch at first failure.
Figure 1: (AA5352) Cup height vs angle from rolling direction after the reverse redraw operation.

Figure 2: (AA5352) Cup height vs angle from rolling direction after the reverse redraw operation.
Figure 3: (AA5352) Cup height vs angle from rolling direction after the reverse redraw operation.

Figure 4: (TH330) Cup height vs angle from rolling direction after the reverse redraw operation.
Figure 5: (TH330) Cup height vs angle from rolling direction after the reverse redraw operation.

Figure 6: (TH330) Cup height vs angle from rolling direction after the reverse redraw operation.
Figure 7: (AA5352) Wall thickness vs angle from rolling direction 25mm above cup base.

Figure 8: (AA5352) Wall thickness vs angle from rolling direction 25mm above cup base.
Figure 9: (AA5352) Wall thickness vs angle from rolling direction 25mm above cup base.

Figure 10: (AA5352) Wall thickness vs angle from rolling direction 45mm above cup base.
Figure 11: (AA5352) Wall thickness vs angle from rolling direction 45mm above cup base.

Figure 12: (AA5352) Wall thickness vs angle from rolling direction 45mm above cup base.
Figure 13: (TH330) Wall thickness vs angle from rolling direction 25mm above cup base.

Figure 14: (TH330) Wall thickness vs angle from rolling direction 25mm above cup base.
Figure 15: (TH330) Wall thickness vs angle from rolling direction 25mm above cup base.

Figure 16: (TH330) Wall thickness vs angle from rolling direction 45mm above cup base.
Figure 17: (TH330) Wall thickness vs angle from rolling direction 45mm above cup base.

Figure 18: (TH330) Wall thickness vs angle from rolling direction 45mm above cup base.
Figure 19: (AA5352) Load vs expansion punch stroke.

Figure 20: (AA5352) Load vs expansion punch stroke.
Figure 21: (AA5352) Load vs expansion punch stroke.

Figure 22: (TH330) Load vs expansion punch stroke.
Figure 23: (TH330) Load vs expansion punch stroke.

Figure 24: (TH330) Load vs expansion punch stroke.
Figure 25: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 26: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.
Figure 27: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 28: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.
Figure 29: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 30: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.
Figure 31: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 32: (AA5352) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.
Figure 33: (TH330) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 34: (TH330) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.
Figure 35: (TH330) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.

Figure 36: (TH330) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.
Figure 37: (TH330) Forming limit diagram and principal strain plot at point of first failure for cup draw, redraw and expansion operations.
Figure 38: (AA5352) Position of point of first failure during expansion test.

Figure 39: (AA5352) Stroke of expansion punch at first failure.
Figure 40: (TH330) Position of point of first failure during expansion test.

Figure 41: (TH330) Stroke of expansion punch at first failure.