Benchmark 2 – Springback of a Jaguar Land Rover Aluminium Panel

Part A: Benchmark Description

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Abstract. The aim of this benchmark is the numerical prediction of the springback of an aluminium panel used in the production of a Jaguar car. The numerical simulation of springback has been very important for the reduction of die try outs through the design of the tools with die compensation, thereby allowing for the production of dimensionally accurate complex parts at a reduced cost. The forming stage of this benchmark includes one single forming operation followed by a trimming operation. Cross-sectional profiles should be reported at specific (provided) sections in the part before and after springback. Problem description, tool geometries, material properties, and the required simulation reports are summarized in this benchmark briefing.

Keywords: Forming, Trimming, Springback, Plastic Anisotropy

1 INTRODUCTION

Springback is one of the most important problems for the sheet metal forming industry due to the strong geometrical deviations which occurs through elastic recovery after forming. These deviations can lead to many manufacturing difficulties such as joining parts together into a more complex assembly. Springback is influenced by the forming operations and the degree of constraints imposed by the geometry of the part but it is also strongly dependent on the material properties of the blank sheet. For aluminum, springback behaviour is more complex because of its strong plastic anisotropy and low Young’s modulus. Consequently, inaccurate material models can lead to major or unexpected deviations in the prediction of springback.

The main objective of this benchmark is to predict the springback of a single stage formed panel, assess the influence of material models and quantify the influence of different numerical modelling techniques that affect springback prediction. Numerical techniques includes the finite elements used, integration rules, implicit or explicit code analysis, contact and friction models and the use of emerging techniques such as isogeometric analysis and meshless methods.

The kinematic hardening effect of bending and unbending deformation through the different die radius and curvatures of the tools can significantly influence the nature and prediction of panel’s springback. The springback prediction of different loading/unloading forming operations requires the use of appropriate kinematic and/or combined kinematic/isotropic hardening models, together with sophisticated flow rules and yield functions. Cyclical shear tests for different levels of pre-strains were therefore performed for the material characterisation of the kinematic/isotropic hardening (the Bauschinger effect) for this benchmark study and the measured shear strain-stress curves are summarised in the attached excel file “Cyclical_Shear.xls”.

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The blank material to be used in this benchmark is the aluminium alloy (AA6451-T4) with thickness $t = 3.0$ mm. The elastic mechanical properties are given in Table 1.

### Table 1. Elastic mechanical properties

| Sample     | Density, $\rho$ (g.cm$^{-3}$) | Young’s modulus, $E$ (GPa) | Poisson’s ratio, $\nu$ |
|------------|--------------------------------|-----------------------------|------------------------|
| AA6451-T4  | 2.7                            | 70.0 GPa                    | 0.3                    |

The uniaxial tensile yield stress and r-values are given in Table 2.

### Table 2. Uniaxial Tension Test Data

| Test Direction | YS, $\sigma_{yd}$ (MPa) | r-value |
|----------------|--------------------------|---------|
| 0º             | 151.28                   | 0.62    |
| 45º            | 171.2                    | 0.33    |
| 90º            | 163.6                    | 0.8     |

The equal biaxial tensile yield stress and the biaxial r-value are given in Table 3.

### Table 3. Equal Biaxial Tension Test Data

| $\sigma_b$ (MPa) | r-value, $r_b$ |
|------------------|----------------|
| 153.6            | 0.55           |

The material constants for the hardening curve at 0 degrees from the rolling direction (RD) are described in Table 4 for the Voce hardening law.

### Table 4. Hardening curve

| Voce |  |
|------|---|
| $A_0$ (MPa) | $B_0$ (MPa) | $C$ |
| 359.093260 | 196.310139 | 9.374256 |

The Voce hardening curve gives a better fitting to the experimental results at 0 degrees from RD. The material constants for Barlat’s Yld2000-2d yield function are provided in Table 5 with the eight
anisotropy coefficients and the material constants for Barlat’s Yld89 yield function are provided in Table 6.

Table 5. Material Constants for Yield Function Yld2000-2d (a = 8.0)

| Sample   | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\alpha_4$ | $\alpha_5$ | $\alpha_6$ | $\alpha_7$ | $\alpha_8$ |
|----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| AA6451-T4| 1.065173    | 0.841891    | 0.960059    | 0.958652    | 1.034037    | 1.027112    | 0.838988    | 0.877033    |

Table 6. Material Constants for Yield Function Yld89 (m = 8.0)

| Sample   | $a$   | $c$   | $h$   | $p$   |
|----------|-------|-------|-------|-------|
| AA6451-T4| 1.3033| 0.9556| 0.9247| 0.8465|

Cyclical shear mechanical tests were conducted (with the specimen at 0 degrees from RD) for different pre-strains so that a full characterization of the kinematic and/or combined kinematic/isotropic hardening can be conducted effectively for the numerical simulation of the springback of the aluminium panel. The plots for the shear stress vs shear strain for the different pre-strain levels are shown in Figure 2. The excel file “Cyclical_Shear.xls” with the full data for the cyclical shear tests is available on the website of the conference.

Figure 2. Experimental results for the cyclical shear tests on the AA6451-T4 aluminium alloy.

The rolling direction is specified schematically in Figure 3, with the rolling direction making an angle of $87^\circ$ with the global x-axis.
3 SIMULATING THE FORMING OPERATION

The simulation involves three operations: forming, trimming and springback. The drawing occurs continuously in a single action process during which the die moves at 100 mm.s$^{-1}$. The CAD geometries for the blank, the lower punch, the upper die and the binder, as well as a mesh for the punch, die and blank holder are provided. The parts/tools are provided in their corresponding orientation and position in the global axis and the forming direction is aligned to the global $z$-axis, whilst no symmetry plane exists as shown in Figure 4. Participants should not move the tool position in the $x$-$y$ plane.

The indicative values for the coefficient of friction to be used in the forming operations are: i) 0.08 for Pam-Stamp and LS-DYNA; ii) 0.14 for AutoForm.

The lower punch, binder and upper die are illustrated in Figure 4. Only one blank material (3 mm thick) is investigated in this benchmark, properties of which are given in the previous section. The required simulation boundary conditions are given in Table 7.
### FORMING ANALYSIS

4.1 Tool moving directions and force:

4.1.1 Binder Closure

- Lower Punch: stationary
- Upper Die: moving (z-direction), see Table 7
- Binder: stationary

4.1.2 Forming

- Lower Punch: stationary
- Upper Die: moving (z-direction), see Table 7
- Binder: loading (z-direction), see Table 7

4.1.3 Blank holding force

The blank holding force is defined in Table 7. It should be applied after the binder has been moved into position.

4.2 Trimming

The trim line is illustrated in Figure 5 (the red line/edge) and it is provided in the attached IGES file.
Figure 5. Trim line on the formed part.

Figure 6. Springback BC locations.
4.3 Springback Analysis

The locations of the boundary conditions (BCs) to be defined for springback analysis simulation are depicted in Figure 6. A 3-2-1 locating configuration will be used for part measurement. Points 1 and Point 2 correspond to the centre of the holes shown in Figures 5 and 6.

4.3.1.1 **Point 1 – Pin BC (all dimensions in mm)**

The blank is restrained in all global translation directions, $X$, $Y$, $Z$ at Point 1 with the coordinates, (-749.3, 75.5, 206.2).

4.3.1.2 **Point 2 – Slot (all dimensions in mm)**

A local coordinate system is to be defined and restrained in translation directions, $y'$, $z'$. The coordinates of the origin (Point 2) of the local coordinate system is (711.0, 83.8, 220.0) and the vector defining the free $x'$ local axis is (30.0, 10.0, 0.1).

4.3.1.3 **Point 3 – Simply Supported (all dimensions in mm)**

The blank is restrained in global translation direction, $Z$ at Point 3 with the coordinates, (-68.7, -46.5, 193.4).

4.4 Simulation Files

CAD geometry (IGES) files are provided for the die face, binder, blank, punch and the trim line. The trim lines are indicated by lines in the IGES file.

![Figure 7. Sections for springback measurement.](image)
5 BENCHMARK REPORT

The due date for benchmark submission is listed on the website. All results are to be reported using the benchmark report template which can be downloaded from the conference website.

5.1 General Description

- Benchmark participant: name, affiliation, address, email and phone number.
- 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.
- Simulation hardware: CPU type, CPU clock speed, number of cores per CPU, main memory, operating system, a breakdown of CPU time for the three stages and analysis methods adopted (e.g. explicit or implicit) for each operation.
- Material model: Yield function/Plastic potential, Hardening rule and Stress-Strain Relation, strain-based.
- Delegate’s remarks on the results template.

| Plane    | x        | y         | z        |
|----------|----------|-----------|----------|
| Section I| -0.985572| 0.100936  | -0.135870|
| Section II| -0.997984| -0.062806 | 0.009108 |
| Section III| -0.998390| -0.044252 | -0.035492|

5.2 Simulation Results Required

The following information are requested from your simulation:

- Die stroke (mm) vs. total punch force (kN) from the simulation during forming, reported for at least every 5 mm of die movement.
- Blank thickness after forming at Sections I, II and III (as shown in Figure 7). The sections are provided as IGES files and the normal vectors of these sections are provided in Table 8, whilst the origin points coincide with the points defined in sections 4.3.1.1, 4.3.1.2 and 4.3.1.3, respectively. Local in-plane axes are defined for each section as described in figures 8, 9 and 10 and Table 9 and, together with the normal vectors from Table 8, they form a right-handed local coordinate system that should be used for the report of the blank thickness after forming.
- Profiles of the formed sheet at Sections I, II and III, taken of the punch-side surface for two different instants: (i) end of the forming operation and (ii) after trimming and springback. The profiles should be plotted in graphs with local coordinate system defined by local axes described schematically in figures 8, 9 and 10 and Table 9 and the normal vectors from Table 8. The origin of these coordinate systems are the BC points defined in section 4.3 – Springback Analysis.
- As an option, the part after springback can be reported in the form of a geometric (*.stl) file. The committee will report the springback results from correlation with the real part after springback. This will be carried out by aligning the springback result to the measured data by using the same three BC points from section 4.3 – Springback Analysis.
Table 9. Local axes for the plot of springback profiles

| Local axis | $x$             | $y$             | $z$             |
|------------|-----------------|-----------------|-----------------|
| $\vec{X}_I$ | $-0.099951436$  | $-0.994896865$  | $-0.013781841$  |
| $\vec{Y}_I$ | $-0.136593212$  | $0.0$           | $0.990627223$   |
| $\vec{X}_{II}$ | $0.062801814$   | $-0.998026018$  | $0.0$           |
| $\vec{Y}_{II}$ | $0.00908191$    | $0.000571486$   | $0.999958595$   |
| $\vec{X}_{III}$ | $0.04432748$    | $-0.999017054$  | $0.0$           |
| $\vec{Y}_{III}$ | $-0.035464739$  | $-0.001573602$  | $0.999369689$   |

Figure 8. Local coordinate system $\vec{X}_I$ - $\vec{Y}_I$ for the report of springback profile at section I.

Figure 9. Local coordinate system $\vec{X}_{II}$ - $\vec{Y}_{II}$ for the report of springback profile at section II.
Figure 10. Local coordinate system $\tilde{X}_{III}$ - $\tilde{Y}_{III}$ for the report of springback profile at section III.
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Aluminium Panel

Part B: Responses

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BM2-00

| 1. Benchmark Participant                |
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| **Prepared by**                        |
| Benchmark-2 Committee                  |
BM2-01

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2. Simulation Software

| Name of the FEM code | Pam-Stamp |
|----------------------|-----------|
| General aspect of the code | Dynamic explicit(forming), Static implicit (gravity, springback) |
| Basic formulations   | Updated Lagrangian formulation with associated flow rule, Barlat2000 yield function, Yoshida kinematic hardening |

| Element/Mesh technology | |
|-------------------------|-----------------|
| Number of elements      | 175,582 (After stamping), 75,084 (after trimming) |
| Type of elements        | explicit solution:Belytschko-Tsay shell , implicit solution: Batoz Q4 gamma shell |
| Contact property model  | explicit solution: non-linear penalty contact, implicit solution: contact 54 |
| Friction formulation    | Standard Coulomb friction |

3. Simulation Hardware

| CPU Type                  | Intel Xeon CPU E5645 approach 1, Xeon e5-2650 approach 2 |
|---------------------------|----------------------------------------------------------|
| CPU clock speed           | 2.40GHz approach 1, 2.6GHz approach 2                    |
| Number of cores per CPU   | 12 approach 1, 8 approach 2                               |
| Main memory               | 48 GB approach 1, 64 GB approach 2                       |
| Operating system          | Linux                                                     |
| Total CPU time            | 17 hours approach 1, 27 hours approach 2                  |

4. Describe the material model used for each material

| Material     | AA6451-T4 |
|--------------|-----------|
| Yield Function/Plastic Potential | Yld2000-2D - the parameters for Yld2000-2D used as provided |
| Hardening Rule (e.g. Isotropic, kinematic) | Kinematic hardening |
| Stress-Strain Relation (e.g. Swift, Voce) | Yoshida-Uemori (Y-U): Cyclic shear data "Cyclical.xls" were transferred into stress-strain curves. And then, Y-U parameters are evaluated from them by |

5. Remarks

There were used 2 approaches of computation:

**Approach 1:**
- Gravity - Holding - Stamping - Trimming & springback using locked nodes of model

**Approach 2:**
- OP20 (Gravity-Holding-Stamping-Springback) - OP30 (Holding-Trimming-Springback)-Fixture(Clamping)
  Since trimming dies and fixtures are not provided by organizer, those shapes are estimated from the specifications and provided CAD data.
  For more please check video: Fixture.avi
There are submitted two result only in STL.
**1. Benchmark Participant**

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**2. Simulation Software**

| Name of the FEM code | PAM-STAMP 2012.2 |
|----------------------|------------------|
| General aspect of the code | Dynamic Explicit (for Holding/Stamping), Static Implicit (springback after trimming) |
| Basic formulations | Updated Lagrangian formulation with associated flow rule, Barlat 2000 (Yld 2000-2D), Isotropic Hardening, Tabulated data for hardening curve following Voce Equation |

| Element/Mesh technology | |
|-------------------------|-------------------------------------------------|
| Number of elements | Number of blank elements = 4856 (initial mesh), 188528 (after mesh refinements at the end of stamping stage) |
| Type of elements | Type of blank elements = 4-node Belytschko-Tsay shell, reduced integration, hour glass control, 5 integration points through thickness. |
| Contact property model | Accurate Contact |
| Friction formulation | Standard Coulomb friction, value is 0.08 which is constant at all blank-tool interface |

**3. Simulation Hardware**

| CPU Type | Intel® Core™ i7-3770 CPU @ 3.40 GHz |
|----------|-----------------------------------|
| CPU clock speed | 3.4 GHz |
| Number of cores per CPU | 1 Core |
| Main memory | 16 GB |
| Operating system | 64-bit Operating System |
| Total CPU time | Total time = 25 hours  [ Binder closure (explicit) = 3.25 hours, Forming (Explicit) = 21.5 hours, Trimming-Springback (Implicit) = 0.25 Hours ] |

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

| Material | AA6451-T4 |
|----------|-----------|
| Yield Function/Plastic Potential | Barlat 2000 or Yld 2000-2D |
| Hardening Rule (e.g. Isotropic, kinematic) | Isotropic Hardening |
| Stress-Strain Relation (e.g. Swift, Voce) | Tabulated data following Voce Equation |

**5. Remarks**

Not Applicable In this Case.
BM2-03

1. Benchmark Participant

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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      | 141476                                                |
| Type of elements        | Isoparametric 3D brick elements with selective reduced integration technique |
| Contact property model  | Rigid tools modelled by 132719 Nagata patches, Augmented lagrangian method |
| Friction formulation    | Coulomb friction law                                     |

3. Simulation Hardware

| CPU Type              | Intel® Core™ i7-5930K                                     |
|-----------------------|---------------------------------------------------------|
| CPU clock speed       | 3.5 GHz                                                 |
| Number of cores per CPU | 6 cores                                           |
| Main memory           | 64 GB RAM                                               |
| Operating system      | Windows 10 Professional (64-bit)                        |
| Total CPU time        | 284 hours (forming) 11 hours (trimming)                |

4. Describe the material model used for each material

| Material         | AA6451-T4                                               |
|------------------|---------------------------------------------------------|
| Yield Function   | Barlat 91                                               |
| Plastic Potential| Armstrong–Frederick kinematic hardening                 |
| Hardening Rule   | (e.g. Isotropic, kinematic)                            |
| Stress-Strain Relation | (e.g. Swift, Voce)                                       |
|                  | Voce law                                                |

5. Remarks
# BM2-04

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## 2. Simulation Software

| Name of the FEM code | LS-DYNA                      |
|----------------------|------------------------------|
| General aspect of the code | Forming: dynamic explicit; springback: static implicit |
| Basic formulations   | Updated Lagrangian formulation with associated flow rule |

### Element/Mesh technology

| Number of elements | 80657                        |
|--------------------|------------------------------|
| Type of elements   | Fully integrated shell element (ELFORM=16) |
| Contact property model | Surface to surface contact |
| Friction formulation | Coulomb friction            |

## 3. Simulation Hardware

| CPU Type            | Intel Xeon64                |
|---------------------|----------------------------|
| CPU clock speed     | 8 SMP double-precision      |
| Number of cores per CPU | 8                        |
| Main memory         | 16GB                        |
| Operating system    | Scientific Linux 6         |
| Total CPU time      | 12 hours 22 minutes        |

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

| Material | AA6451-T4 |
|----------|-----------|
| Yield Function/Plastic Potential | Hill1948-3R, associated flow rule |
| Hardening Rule (e.g. Isotropic, kinematic) | Yoshida-Uemori model (isotropic + nonlinear kinematic hardening rule)
| Stress-Strain Relation (e.g. Swift, Voce) | Voce |

## 5. Remarks


BM2-05

1. Benchmark Participant

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2. Simulation Software

| General aspect of the code | AutoForm R6 |
|---------------------------|-------------|
| Basic formulations       |             |

| Element/Mesh technology   |             |
|---------------------------|-------------|
| Number of elements        | 117081      |
| Type of elements          | Shell element |
| Contact property model    | N/A         |
| Friction formulation      | constant (0.14 as instructed) |

3. Simulation Hardware

| CPU Type                  | Working Station with 8 Cpus |
|---------------------------|-----------------------------|
| CPU clock speed           | N/A                         |
| Number of cores per CPU   | 48                          |
| Main memory               | 32 GB                       |
| Operating system          | LINUX                       |
| Total CPU time            | Forming: 2 hours & Springback: 1min |

4. Describe the material model used for each material

| Material | AA6451-T4 |
|----------|-----------|
| Yield Function | Barlat |
| Plastic Potential | Isotropic |
| Hardening Rule | (e.g. Isotropic, kinematic) |
| Stress-Strain Relation | Combined Swift/Hockett-Sherby |

5. Remarks
**BM2-06**

### 1. Benchmark Participant

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### 2. Simulation Software

- **Name of the FEM code**: LS-DYNA
- **General aspect of the code**: Basic formulations

| Element/Mesh technology |
|-------------------------|
| Number of elements      | 560000 |
| Type of elements        | Fully integrated shell element |
| Contact property model  | FORMING_ONE WAY_SURFACE_TO_SURFACE + Penalty |
| Friction formulation    | constant (0.08 as instructed) |

### 3. Simulation Hardware

- **CPU Type**: HPC
- **CPU clock speed**: N/A
- **Number of cores per CPU**: 48
- **Main memory**: N/A
- **Operating system**: LINUX
- **Total CPU time**: Forming: 23 hours & Springback: 17 mins

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

| Material   | AA6451-T4 |
|------------|-----------|
| Yield Function/Plastic Potential | M36: Barlat89 |
| Hardening Rule (e.g. Isotropic, kinematic) | Isotropic |
| Stress-Strain Relation (e.g. Swift, Voce) | Swift |

### 5. Remarks
**BM2-08**

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| 2. Simulation Software |
|------------------------|
| **Name of the FEM code** | JSTAMP/NV |
| **General aspect of the code** | Integrated sheet metal forming simulation system |
| **Basic formulations** | Forming: Dynamic Explicit(LS-DYNA); Spriningback : Static implicit(LS-DYNA) |

### Element/Mesh technology

| Number of elements | Solid Blank: 1398855 / Die shell: 150884 / Holder shell: 87704 / Punch shell: 97480 |
|--------------------|----------------------------------------------------------------------------------|
| Type of elements   | Constant stress solid element with 8 nodes                                       |
| Contact property model | Penalty Method, Node to Surface                                                   |
| Friction formulation | Coulomb’s friction law, friction coefficient m=0.08                             |

| 3. Simulation Hardware |
|------------------------|
| **CPU Type**           | Xeon E5-2670 |
| **CPU clock speed**    | 2.60GHz |
| **Number of cores per CPU** | 16 Core |
| **Main memory**        | 64G |
| **Operating system**   | CentOS5.8 |
| **Total CPU time**     | 37533 seconds (10 hours 25 min. 33 sec.) for 1420998 cycles |

| 4. Describe the material model used for each material |
|------------------------------------------------------|
| **Material**                                         | AA6451-T4 |
| **Yield Function/Plastic Potential**                 | Hill48 |
| **Hardening Rule (e.g. Isotropic, kinematic)**       | Yoshida-Uemori Kinematic hardening model |
| **Stress-Strain Relation (e.g. Swift, Voce)**        | Swift |
# BM2-09

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## 2. Simulation Software

| Name of the FEM code | Pam-Stam |
|----------------------|----------|
| General aspect of the code | Dynamic explicit(forming), Static implicit (gravity, springback) |
| Basic formulation    | Updated Lagrangian formulation with associated flow rule, Barlat2000 yield function, Yoshida kinematic hardening |

### Element/Mesh technology

| Number of elements   | 175,582 (After stamping), 75,084 (after trimming) |
| Type of elements     | explicit solution: Belytschko-Tsay shell, implicit solution: Batoz Q4 gamma shell |
| Contact property model | explicit solution: non-linear penalty contact, implicit solution: contact 54 |
| Friction formulation | Standard Coulomb friction |

## 3. Simulation Hardware

| CPU Type               | Intel Xeon CPU E5645 approach 1, Xeon e5-2650 approach 2 |
|------------------------|--------------------------------------------------------|
| CPU clock speed        | 2.40GHz approach 1, 2.66GHz approach 2                   |
| Number of cores per CPU | 12 approach 1, 8 approach 2                              |
| Main memory            | 48 GB approach 1, 64 GB approach 2                       |
| Operating system       | Linux                                                   |
| Total CPU time         | 17 hours approach 1, 27 hours approach 2                 |

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

| Material   | AA6451-T4 |
|------------|-----------|
| Yield Function/Plastic Potential | Yld2000-2D - the parameters for Yld2000-2D used as provided |
| Hardening Rule (e.g. Isotropic, kinematic) | Kinematic hardening |
| Stress-Strain Relation (e.g. Swift, Voce) | Yoshida-Uemori (Y-U): Cyclic shear data "Cyclical.xls" transferred into stress-strain curves. And then, Y-U parameters are evaluated from them by |

## 5. Remarks

There were used 2 approaches of computation:

**Approach 1:**
Gravity - Holding - Stamping - Trimming&springback using locked nodes of model

**Approach 2:**
OP20 (Gravity-Holding-Stamping-Springback) - OP30 (Holding-Trimming-Springback)-Fixure(Clamping)
Since trimming dies and fixtures are not provided by organizer, those shapes are estimated from the specifications and provided CAD data.

For more please check video: Fixture.avi

There are submitted two result only in STL.
BM2-10

1. Benchmark Participant

| Name         | Albert Forgas         |
|--------------|-----------------------|
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| Address      | C/Gran Capità 2/4 08034 Barcelona, Spain |
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| Phone number | +342047083            |
| Fax number   |                       |

2. Simulation Software

| Name of the FEM code | Stampack V7.1.2          |
|----------------------|--------------------------|
| General aspect of the code | Finite Element Method |
| Basic formulations   | Explicit Formability, Implicit Springback |

| Element/Mesh technology |
|-------------------------|
| Number of elements      | 93099                    |
| Type of elements        | Hexahedra Special Integration |
| Contact property model  | Penalty Method           |
| Friction formulation    | Coulomb                  |

3. Simulation Hardware

| CPU Type      | Intel Core i7-3770       |
|---------------|--------------------------|
| CPU clock speed | 3.40 GHz                |
| Number of cores per CPU | 8 threads           |
| Main memory   | 16 GB                    |
| Operating system | Win 7 64 Bit         |
| Total CPU time | 3 Hour 35 Min 20 Sec |

4. Describe the material model used for each material

| Material     | AA6451-T4      |
|--------------|----------------|
| Yield Function/Plastic Potential | Yoshida Uemori |
| Hardening Rule (e.g. Isotropic, kinematic) | Isotropic |
| Stress-Strain Relation (e.g. Swift, Voce) | Voce |

5. Remarks

Variable young modulus
BM2-11

1. Benchmark Participant

| Name       | Albert Forgas                  |
|------------|-------------------------------|
| Affiliation| Quantech ATZ                   |
| Address    | C/Gran Capità 2/4 08034 Barcelona, Spain |
| Email      | aforgas@stampack.com          |
| Phone number| +342047083                    |

2. Simulation Software

| Name of the FEM code | Stampack V7.1.2 |
|----------------------|-----------------|
| General aspect of the code | Finite Element Method |
| Basic formulations | Explicit Formability, Implicit Springback |

| Element/Mesh technology |
|-------------------------|
| Number of elements | 59638         |
| Type of elements      | Basic Shell Triangle |
| Contact property model| Penalty Method  |
| Friction formulation  | Coulomb        |

3. Simulation Hardware

| CPU Type             | Intel Core i7-3770 |
|----------------------|--------------------|
| CPU clock speed      | 3.40 GHz           |
| Number of cores per CPU | 8 threads     |
| Main memory          | 16 GB              |
| Operating system     | Win 7 64 Bit       |
| Total CPU time       | 0 Hour 40 Min 10 Sec |

4. Describe the material model used for each material

| Material          | AA6451-T4 |
|-------------------|-----------|
| Yield Function/Plastic Potential | Yoshida Uemori |
| Hardening Rule    | Isotropic |
| (e.g. Isotropic, kinematic) | Voce |
| Stress-Strain Relation (e.g. Swift, Voce) |

5. Remarks

Variable young modulus
# 1. Benchmark Participant

| Name       | SARIN BABU THOKALA |
|------------|--------------------|
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| Phone number| 0044 (0) 787 554 6247 or 0044 (0) 772 481 6535 |
| Fax number | 0044 (0) 1952 222050 |

# 2. Simulation Software

| Name of the FEM code | AutoForm^plus R6 |
|----------------------|------------------|
| General aspect of the code | Stamping Simulation |
| Basic formulations | Static Implicit |

**Element/Mesh technology**

| Number of elements | Form - 205000, After Trim -88000 |
|--------------------|----------------------------------|
| Type of elements   | Triangular elastic plastic shell, 11 Integration points through thickness |
| Contact property model |                                 |
| Friction formulation | Coulomb friction (0.14) |

# 3. Simulation Hardware

| CPU Type                  | Intel®Core™i7-2760QM CPU @ 2.40GHz |
|---------------------------|-------------------------------------|
| CPU clock speed           | 2.40GHz                             |
| Number of cores per CPU   | 4                                    |
| Main memory               | 32.0GB                              |
| Operating system          | Windows 7 Professional              |
| Total CPU time            | 01Hour:20Mins:32Sec                 |

# 4. Describe the material model used for each material

| Material | AA6451-T4 |
|----------|-----------|
| Yield Function / Plastic Potential | Barlat -1989 |
| Hardening Rule (e.g. Isotropic, kinematic) | Isotropic hardening |
| Stress-Strain Relation (e.g. Swift, Voce) | Approximation (Combined Swift - Hockett-Sherby formulation) |

# 5. Remarks
BM2-13

1. Benchmark Participant

| Name         | Jan Slota, Marek Siser |
|--------------|------------------------|
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| Phone number |                        |
| Fax number   |                        |

2. Simulation Software

| Name of the FEM code | PAM-Stamp 2015.1 |
|----------------------|------------------|
| General aspect of the code | Explicit |

| Element/Mesh technology | |
|-------------------------|--|
| Number of elements      | 82000 |
| Type of elements        | Quadrilateral |
| Contact property model  | Accurate |
| Friction formulation    | 0.08  |

3. Simulation Hardware

| CPU Type          | Intel Xeon CPU E5 2670 |
|-------------------|------------------------|
| CPU clock speed   | 2.6 GHz                |
| Number of cores per CPU | 6, total 12 cores |
| Main memory       | 16 GB                  |
| Operating system  | Win 8.1 64 bit         |
| Total CPU time    | 14:30 hod.             |

4. Describe the material model used for each material

| Material   | AA6451-T4 |
|------------|-----------|
| Yield Function/Plastic Potential | Barlat2000 |
| Hardening Rule (e.g. Isotropic, kinematic) | Isotropic |
| Stress-Strain Relation (e.g. Swift, Voce) | Krupkowski/Swift |

5. Remarks
| BM2-14 |
|---|
| **1. Benchmark Participant** |
| **Name** | Hariharasudhan Palaniswamy, Subir Roy |
| **Affiliation** | Altair Engineering |
| **Address** | 1820 E Big Beaver road, Troy, MI, 48085, USA |
| **Email** | hpalaniswamy@altair.com, subir@altair.com |
| **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** | Penalty based contact formulations |
| **Friction formulation** | Coulomb’s Law |

| **3. Simulation Hardware** |
| **CPU Type** | HPC Cluster |
| **CPU clock speed** | 2.50GHz |
| **Number of cores per CPU** | 13 Node, 24 cores per node. 24 cpu’s used for the simulation |
| **Main memory** | 128 GB of RAM per core |
| **Operating system** | Linux |
| **Total CPU time** | Forming: 16118 Secs, Trimming: 0 Sec, springback : 390 Secs |

| **4. Describe the material model used for each material** |
| **Material** | AA6451-T4 |
| **Yield Function/ Plastic Potential** | Barlat 3 parameter model |
| **Hardening Rule** | Combined hardening rule |
| **Stress-Strain Relation** | Voce hardening law |

| **5. Remarks** | |
**BM2-15**

### 1. Benchmark Participant

| Name | Affiliation | Address | Email | Phone number | Fax number |
|------|-------------|---------|-------|--------------|------------|
| 1Yasuyoshi Umezu, 1Toshiro Amaishi, 2Wan-Jin Chung | 1JSOL Corporation, 2Seoul National University of Science & Technology | 1Tosabori Daibiru Building, 2-2-4, Tosabori Nishi-ku, Osaka 550-0001, Japan 2232 Gongneung-ro, Nowon-gu, Seoul, 01811, Korea | umezu.yasu@jsol.co.jp, amaishi.toshirou@jsol.co.jp, wjchung@seoultech.ac.kr | +81-6-4803-5820 | +81-6-6225-3517 |

### 2. Simulation Software

| Name of the FEM code | General aspect of the code | Basic formulations |
|----------------------|----------------------------|--------------------|
| ASTAMP(for Forming), JOH/NIKE(for Spring back) | Press Simulation Software Optimized for GPGPU | Forming:Dynamic Explicit, Spring back:Static Implicit |

**Element/Mesh technology**

| Number of elements | Type of elements | Contact property model | Friction formulation |
|--------------------|------------------|------------------------|---------------------|
| 466544 (for Blank) | Quadrilateral Belytschko-Tsay and C0 Triangular | Penalty Method, Node to Surface | Coulomb's friction law |

### 3. Simulation Hardware

| CPU Type | CPU clock speed | Number of cores per CPU | Main memory | Operating system | Total CPU time |
|----------|-----------------|-------------------------|-------------|-----------------|----------------|
| GPGPU(TESLA-K20) | 706MHz (TESLA-K20) | 2496 cores (TESLA-K20) | 5Gb (TESLA-K20) | Windows 7 Professional | 15226 sec (4 hours 14 min 46sec) for 194124 Binder&Forming steps, 551 sec for Springback |

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

| Material | Yield Function | Plastic Potential | Hardening Rule | Stress-Strain Relation |
|----------|---------------|-------------------|----------------|------------------------|
| AA6451-T4 | Hill 48       |                   | Isotropic Hardening | Voce                  |

### 5. Remarks

Binder Closure and Forming steps are not separated in this calculation, 60% of computation times was required for Binder Closure and 40% for Forming.
Figure 6.1. Profile after springback for Section I: BM2_01, BM2_02, BM2_03.
Figure 6.2. Profile after springback for Section I: BM2_04, BM2_05, BM2_06.
Figure 6.3. Profile after springback for Section I: BM2_08, BM2_09.
Figure 6.4. Profile after springback for Section I: BM2_10, BM2_11, BM2_12.
Figure 6.5. Profile after springback for Section I: BM2_13, BM2_14, BM2_15.
Figure 6.6. Profile after springback for Section II: BM2_01, BM2_02, BM2_03.
Figure 6.7. Profile after springback for Section II: BM2_04, BM2_05, BM2_06.
Figure 6.8. Profile after springback for Section II: BM2_08, BM2_09.
Figure 6.9. Profile after springback for Section II: BM2_10, BM2_11, BM2_12.
Figure 6.10. Profile after springback for Section II: BM2_13, BM2_14, BM2_15.
Figure 6.11. Profile after springback for Section III: BM2_01, BM2_02, BM2_03.
Figure 6.12. Profile after springback for Section III: BM2_04, BM2_05, BM2_06.
Figure 6.13. Profile after springback for Section III: BM2_08, BM2_09.
Figure 6.14. Profile after springback for Section III: BM2_10, BM2_11, BM2_12.
Figure 6.15. Profile after springback for Section III: BM2_13, BM2_14, BM2_15.
Figure 6.16. Thickness for Section I: BM2_01, BM2_02, BM2_03.

Figure 6.17. Thickness for Section I: BM2_04, BM2_05, BM2_06.
Figure 6.18. Thickness for Section I: BM2_08, BM2_09.

Figure 6.19. Thickness for Section I: BM2_10, BM2_11, BM2_12.
Figure 6.20. Thickness for Section I: BM2_13, BM2_14, BM2_15.
Figure 6.21. Thickness for Section II: BM2_01, BM2_02, BM2_03.

Figure 6.22. Thickness for Section II: BM2_04, BM2_05, BM2_06.
Figure 6.23. Thickness for Section II: BM2_08, BM2_09.

Figure 6.24. Thickness for Section II: BM2_10, BM2_11, BM2_12.
Figure 6.25. Thickness for Section II: BM2_13, BM2_14, BM2_15.
Figure 6.26. Thickness for Section III: BM2_01, BM2_02, BM2_03.

Figure 6.27. Thickness for Section III: BM2_04, BM2_05, BM2_06.
Figure 6.28. Thickness for Section III: BM2_08, BM2_09.

Figure 6.29. Thickness for Section III: BM2_10, BM2_11, BM2_12.
Figure 6.30. Thickness for Section III: BM2_13, BM2_14, BM2_15.
Figure 6.31. Punch Force: BM2_01, BM2_02, BM2_03.
Figure 6.32. Punch Force: BM2_04, BM2_05, BM2_06.
Figure 6.33. Punch Force: BM2_08, BM2_09.
Figure 6.34. Punch Force: BM2_10, BM2_11, BM2_12.
Figure 6.35. Punch Force: BM2_13, BM2_14, BM2_15.
Benchmark 2 – Springback of a Jaguar Land Rover Aluminium Panel

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The editor would like to add additional material that was omitted from the original paper. The introduction of the new material results in all of the figures appearing after the new material being renumbered, the figures are not being overwritten. The new material and all renumbered figures are as follows:
1. Benchmark Participant

| Name                        | Bart Carleer, Dave Ling, Igor Burchitz |
|-----------------------------|----------------------------------------|
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| Fax number                  |                                        |

2. Simulation Software

| Name of the FEM code         | AutoForm^plus R6                       |
|------------------------------|----------------------------------------|
| General aspect of the code   | Static Implicit                        |
| Basic formulations           |                                        |
| Element/Mesh technology      | Initial number of elements - 31555     |
|                              | Final number of elements due to adaptive mesh refinement - 213120 |
|                              | Type of elements, Triangular elastic plastic shell, 11 integration points through thickness |
|                              | Contact property model, Penalty method |
|                              | Friction formulation, Coulomb friction |

3. Simulation Hardware

| CPU Type                     | Intel Core i7-5960X                    |
|-------------------------------|----------------------------------------|
| CPU clock speed               | 3.0 GHz                                |
| Number of cores per CPU       | 8 cores used to run a simulation       |
| Main memory                   | 64 GB                                  |
| Operating system              | Windows 7 Pro                          |
| Total CPU time                | Elapsed Time - 23 minutes 13 seconds   |

4. Describe the material model used for each material

| Material | AA6451-T4 |
|----------|-----------|
| Yield Function/Plastic Potential | BBC Model (Banabic 2005). R-values are based on raw tensile test data provided by the organizing committee upon request |
| Hardening Rule (e.g., Isotropic, kinematic) | Isotropic hardening |
| Stress-Strain Relation (e.g., Swift, Voce) | Combined Swift - Hockett-Sherby formulation based on raw tensile test data provided by the organizing committee upon request |

5. Remarks

Although boundary conditions were requested for analysis of springback, real measurement fixture was used in this submission. The main goal was to have a better comparison to reality. Simulated fixture included two pilots, supporting clamps and one double sided clamp. These elements were used to represent pin support, slot support and the simple clamp used in the real fixture.
BM2-17

1. Benchmark Participant

| Name          | Bart Carleer, Dave Ling, Igor Burchitz |
|---------------|----------------------------------------|
| Affiliation   | AutoForm Engineering B.V.              |
| Address       | Industrieweg 2, 2921 LB Krimpen aan den IJssel, The Netherlands |
| Email         | igor.burchitz@autoform.nl              |
| Phone number  | 0031 180 668 255                       |

2. Simulation Software

| Name of the FEM code | AutoForm^plus R6 |
|----------------------|------------------|
| General aspect of the code | Static Implicit |
| Basic formulations   |                  |
| Element/Mesh technology |               |
| Number of elements   | Initial number of elements - 31555 |
|                      | Final number of elements due to adaptive mesh refinement - 211850 |
| Type of elements     | Triangular elastic plastic shell, 11 integration points through thickness |
| Contact property model | Penalty method |
| Friction formulation | Coulomb friction |

3. Simulation Hardware

| CPU Type       | Intel Core i7-5960X |
|----------------|---------------------|
| CPU clock speed| 3.0 GHz             |
| Number of cores per CPU | 8 cores used to run a simulation |
| Main memory    | 64 GB               |
| Operating system | Windows 7 Pro |
| Total CPU time | Elapsed Time - 24 minutes 44 seconds |

4. Describe the material model used for each material

| Material      | AA6451-T4          |
|---------------|--------------------|
| Yield Function/Plastic Potential | BBC Model [Banabic 2005]. R-values are based on raw tensile test data provided by the organizing committee upon request |
| Hardening Rule (e.g. Isotropic, kinematic) | Kinematic hardening considering early re-plastification, transient softening and work hardening stagnation formulated under plane stress condition |
| Stress-Strain Relation (e.g. Swift, Voce) | Combined Swift - Hockett-Sherby formulation based on raw tensile test data provided by the organizing committee upon request |

5. Remarks

In this submission, springback analysis was performed with boundary conditions requested in the benchmark briefing.
**BM2-18**

1. **Benchmark Participant**

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|--------------------|----------------------------------------|
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| Email              | igor.burchitz@autoform.nl              |
| Phone number       | 0031 180 668 255                       |
| Fax number         |                                        |

2. **Simulation Software**

| Name of the FEM code | AutoForm*plus R6 |
|----------------------|------------------|
| General aspect of the code | Static Implicit |
| Basic formulations |                   |

**Element/Mesh technology**

- **Number of elements**
  - Initial number of elements - 31555
  - Final number of elements due to adaptive mesh refinement - 211460
- **Type of elements**
  - Triangular elastic plastic shell, 11 integration points through thickness
- **Contact property model**
  - Penalty method
- **Friction formulation**
  - Pressure dependent coefficient of friction

3. **Simulation Hardware**

| CPU Type          | Intel Core i7-5960X |
|-------------------|---------------------|
| CPU clock speed   | 3.0 GHz             |
| Number of cores per CPU | 8 cores used to run a simulation |
| Main memory       | 64 GB               |
| Operating system  | Windows 7 Pro       |
| Total CPU time    | Elapsed Time - 25 minutes 58 seconds |

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

| Material   | AA6451-T4 |
|------------|-----------|
| Yield Function/Plastic Potential | BBC Model (Banabic 2005). R-values are based on raw tensile test data provided by the organizing committee upon request |
| Hardening Rule | Kinematic hardening considering early re-plastification, transient softening and work hardening stagnation formulated under plane stress condition |
| Stress-Strain Relation | Combined Swift - Hockett-Sherby formulation based on raw tensile test data provided by the organizing committee upon request |

5. **Remarks**

Main goal was to investigate influence of friction on springback prediction of the part. Pressure dependent friction was described by a power law, i.e. Reference Pressure – 4MPa; Pressure Exponent – 0.85; Reference friction coefficient – 0.12. In this submission, springback analysis was performed with boundary conditions requested in the benchmark briefing.
Figure 6.1. Profile after springback for Section I: BM2_01, BM2_02, BM2_03.
Figure 6.2. Profile after springback for Section I: BM2_04, BM2_05, BM2_06.
Figure 6.3. Profile after springback for Section I: BM2_08, BM2_09.
Figure 6.4. Profile after springback for Section I: BM2_10, BM2_11, BM2_12.
Figure 6.5. Profile after springback for Section I: BM2_13, BM2_14, BM2_15.
Figure 6.6. Profile after springback for Section I: BM2_16, BM2_17, BM2_18.
Figure 6.7. Profile after springback for Section II: BM2_01, BM2_02, BM2_03.
Figure 6.8. Profile after springback for Section II: BM2_04, BM2_05, BM2_06.
Figure 6.9. Profile after springback for Section II: BM2_08, BM2_09.
Figure 6.10. Profile after springback for Section II: BM2_10, BM2_11, BM2_12.
Figure 6.11. Profile after springback for Section II: BM2_13, BM2_14, BM2_15.
Figure 6.12. Profile after springback for Section II: BM2_16, BM2_17, BM2_18.
Figure 6.13. Profile after springback for Section III: BM2_01, BM2_02, BM2_03.
Figure 6.14. Profile after springback for Section III: BM2_04, BM2_05, BM2_06.
Figure 6.15. Profile after springback for Section III: BM2_08, BM2_09.
Figure 6.16. Profile after springback for Section III: BM2_10, BM2_11, BM2_12.
Figure 6.17. Profile after springback for Section III: BM2_13, BM2_14, BM2_15.
Figure 6.18. Profile after springback for Section III: BM2_16, BM2_17, BM2_18.
Figure 6.19. Thickness for Section I: BM2_01, BM2_02, BM2_03.

Figure 6.20. Thickness for Section I: BM2_04, BM2_05, BM2_06.
Figure 6.21. Thickness for Section I: BM2_08, BM2_09.

Figure 6.22. Thickness for Section I: BM2_10, BM2_11, BM2_12.
Figure 6.23. Thickness for Section I: BM2_13, BM2_14, BM2_15.

Figure 6.24. Thickness for Section I: BM2_16, BM2_17, BM2_18.
Figure 6.25. Thickness for Section II: BM2_01, BM2_02, BM2_03.

Figure 6.26. Thickness for Section II: BM2_04, BM2_05, BM2_06.
Figure 6.27. Thickness for Section II: BM2_08, BM2_09.

Figure 6.28. Thickness for Section II: BM2_10, BM2_11, BM2_12.
Figure 6.29. Thickness for Section II: BM2_13, BM2_14, BM2_15.

Figure 6.30. Thickness for Section II: BM2_16, BM2_17, BM2_18.
Figure 6.31. Thickness for Section III: BM2_01, BM2_02, BM2_03.

Figure 6.32. Thickness for Section III: BM2_04, BM2_05, BM2_06.
Figure 6.33. Thickness for Section III: BM2_08, BM2_09.

Figure 6.34. Thickness for Section III: BM2_10, BM2_11, BM2_12.
Figure 6.35. Thickness for Section III: BM2_13, BM2_14, BM2_15.

Figure 6.36. Thickness for Section III: BM2_16, BM2_17, BM2_18.
Figure 6.37. Punch Force: BM2_01, BM2_02, BM2_03.
Figure 6.38. Punch Force: BM2_04, BM2_05, BM2_06.
Figure 6.39. Punch Force: BM2_08, BM2_09.
Figure 6.40. Punch Force: BM2_10, BM2_11, BM2_12.
Figure 6.41. Punch Force: BM2_13, BM2_14, BM2_15.
Figure 6.42. Punch Force: BM2_16, BM2_17, BM2_18.