UNIVERSIDADE D COIMBRA

FACULDADE DE CIÊNCIAS E TECNOLOGIA

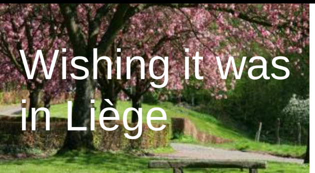
Forming defects prediction in cup drawing and embossing of a thick steel sheet

Marta C. Oliveira[1] • Diogo M. Neto[1] • P.D. Barros[2] • José L. Alves[3] • Luís F. Menezes[1]

[1] University of Coimbra, CEMMPRE, Department of Mechanical Engineering, Portugal

[2] SRAMPORT, Portugal

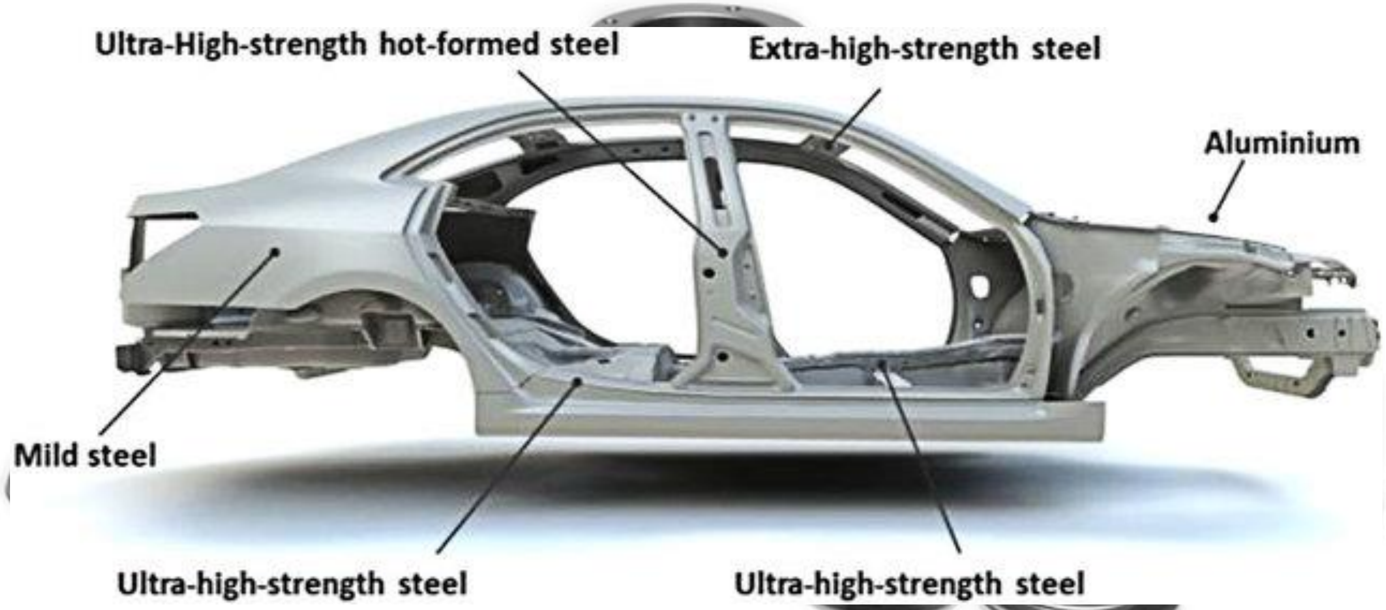
[3] University of Minho, CMEMS, Department of Mechanical Engineering, Portugal



14-16 April 2021
Online

Introduction

- Components produced from cold and hot rolled steel sheets, since they require properties of sufficient strength and formability.
- The accurate prediction of forming defects is useful in the process design to overcome problems resulting from the post-forming springback, occurrence of wrinkles and occurrence of ductile failure.
- Many of this components are axisymmetric and are produced from thick sheets.



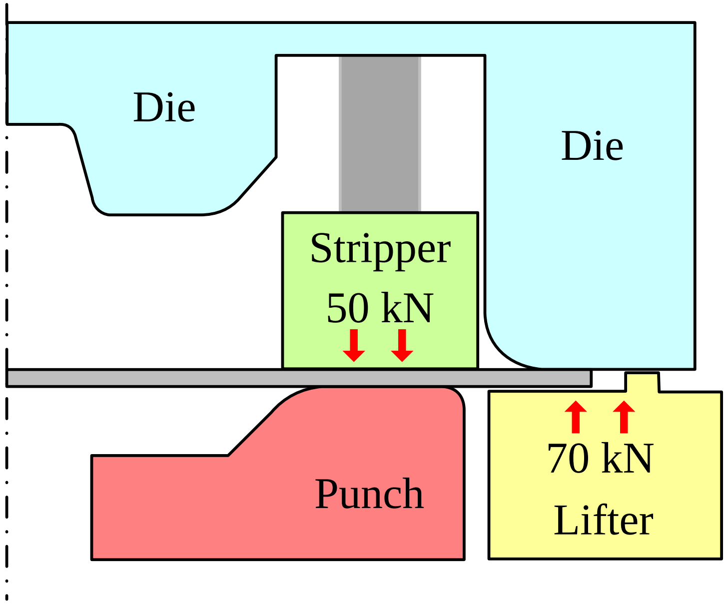
[Asnafi, N., Shams, T., Aspenberg, D. et al. 3D Metal Printing from an Industrial Perspective—Product Design, Production, and Business Models. Berg Huettenmaenn Monatsh 164, 91–100 (2019). https://doi.org/10.1007/s00501-019-0827-z]

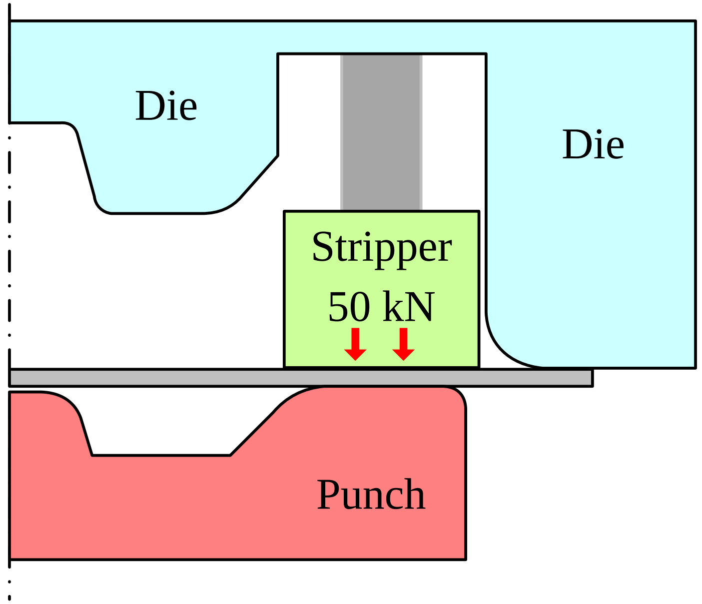
[Deep-drawn metal components, parts & products, http://www.deleonindustries.in/]

Forming defects prediction

Benchmark 2 (Numisheet 2018): Cup drawing of anisotropic thick steel sheet

- Hot rolled steel sheet (SAPH 440 in Japanese Industrial Standard)
- Circular blank with a diameter of 246 mm and a thickness of 2.8 mm
- Three different process conditions are analysed:
  - Task 1: Predict the height and cross-sectional shape of the drawn cup after springback
  - Task 2: Predict the number and locations of wrinkles in the drawn cup
  - Task 3. Predict the die height at which the blank fractures at the apex of the centre boss





Schematic illustration of the forming tools used in the cup drawing: (left) Task 1; (right) Task 2 and 3.


Task 1

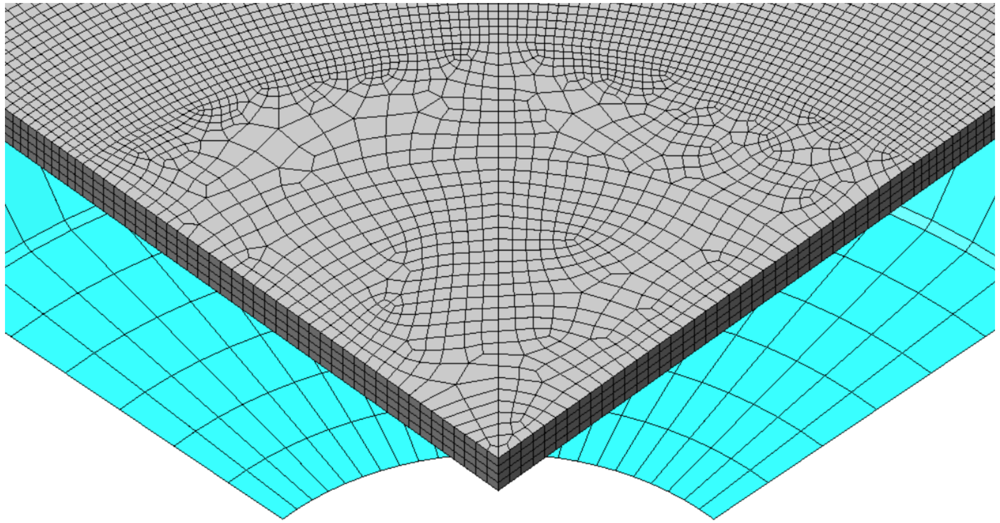

Task 2

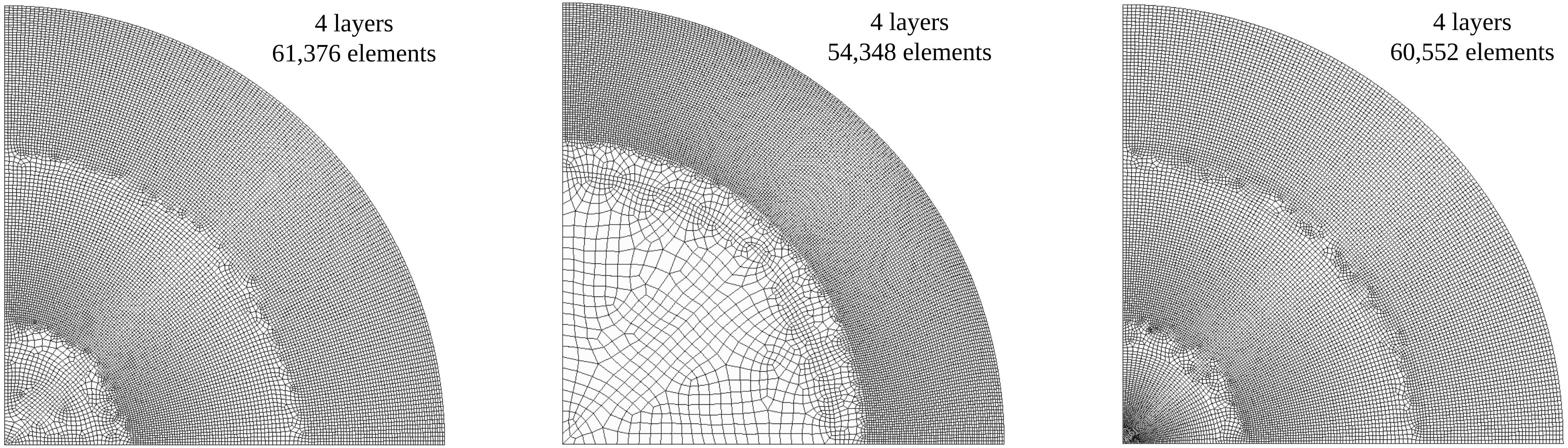

Task 3

Cup drawing of anisotropic thick steel sheet

Finite element model

- DD3IMP in-house finite element code (implicit time integration)
- 1/4 of the model (symmetry conditions)
- Forming tools are assumed rigid discretized by Nagata patches
- The Coulomb friction law is adopted, constant $\mu = 0.15$
- Blank discretized by linear hexahedral (8-nodes) finite elements (4 layers through the thickness)



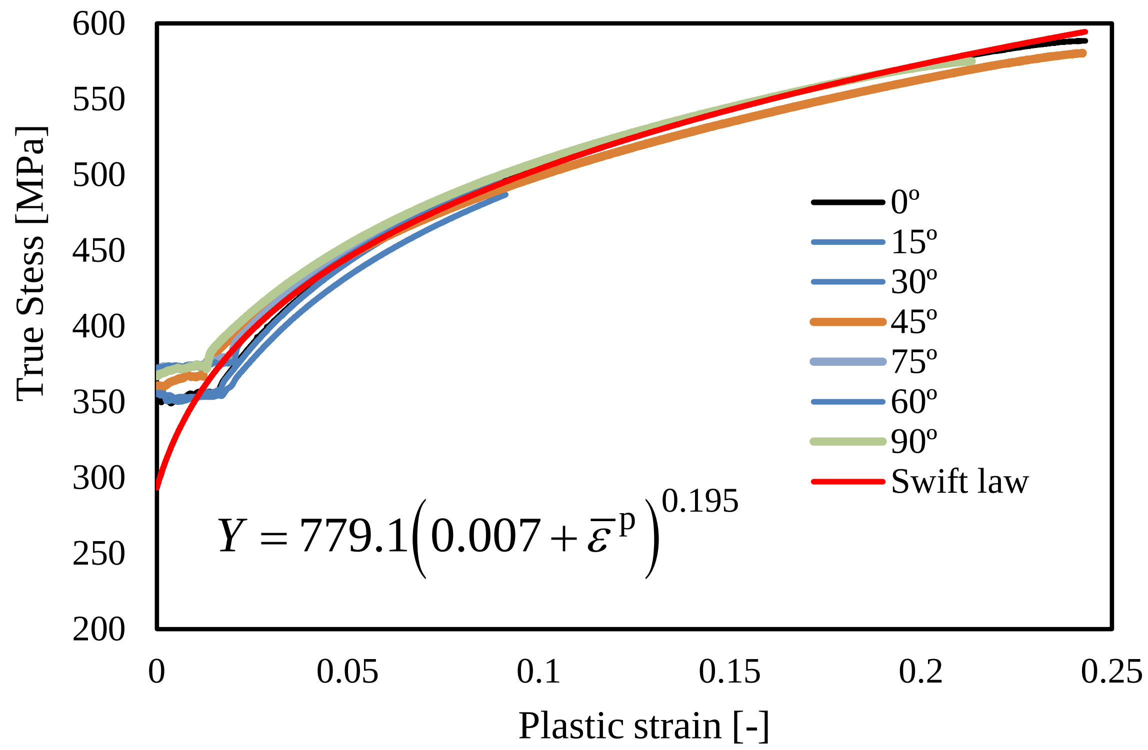


Discretization of the blank with hexahedral finite elements: (left) Task 1; (middle) Task 2; (right) Task 3.

Cup drawing of anisotropic thick steel sheet

Finite element model

- Plastic behaviour of the specimen modelled by the Swift law (isotropic work hardening), fitted neglecting the initial plateau.



Stress–equivalent plastic strain curve and hardening law fitted from the uniaxial tensile test in the rolling direction.

θ	r	σ_θ/Y_0
0º	0.659	1.000
15º	0.709	0.998
30º	0.86	0.977
45º	1.017	1.007
60º	0.978	1.008
75º	0.864	1.016
90º	0.795	1.024

r-values and normalized yield stress values extracted from uniaxial tensile tests.

Yield criterion

Cazacu and Barlat, 2001 (CB2001)

$$\left(J_2^0\right)^3 - c\left(J_3^0\right)^2 = 27\left(\frac{Y}{3}\right)^6$$

$$J_2^0 = \frac{a_1}{6}(\sigma_{11}-\sigma_{22})^2 + \frac{a_2}{6}(\sigma_{11}-\sigma_{33})^2 + \frac{a_3}{6}(\sigma_{11}-\sigma_{33})^2$$
$$+a_4\sigma_{12}^2 + a_5\sigma_{13}^2 + a_6\sigma_{23}^2$$

$$\begin{aligned}J_3^0 = {} & (1/27)(b_1+b_2)\sigma_{11}^3 + (1/27)(b_3+b_4)\sigma_{22}^3 \\ & +(1/27)[2(b_1+b_4)-b_2-b_3]\sigma_{33}^3 \\ & -(1/9)(b_1\sigma_{22}+b_2\sigma_{33})\sigma_{11}^2 - (1/9)(b_3\sigma_{33}+b_4\sigma_{11})\sigma_{22}^2 \\ & -(1/9)[(b_1-b_2+b_4)\sigma_{11}+(b_1-b_3+b_4)\sigma_{22}]\sigma_{33}^2 \\ & +(2/9)(b_1+b_4)\sigma_{11}\sigma_{22}\sigma_{33} \\ & -\left(\sigma_{13}^2/3\right)[2b_9\sigma_{22}-b_8\sigma_{33}-(2b_9-b_8)\sigma_{11}] \\ & -\left(\sigma_{12}^2/3\right)[2b_{10}\sigma_{33}-b_5\sigma_{22}-(2b_{10}-b_5)\sigma_{11}] \\ & -\left(\sigma_{23}^2/3\right)[(b_6-b_7)\sigma_{11}-b_6\sigma_{22}-b_7\sigma_{33}]+2b_{11}\sigma_{12}\sigma_{23}\sigma_{13}\end{aligned}$$

Anisotropy parameters

a_1, a_2, a_3, a_4

$b_1, b_2, b_3, b_4, b_5, b_{11}$

Weighting coefficient

c

DD3MAT: objective function

$$F(\mathbf{A}) = w_{\sigma_\theta} \sum_\theta \left(\sigma_\theta\left(\mathbf{A}, \bar{\varepsilon}^{\mathrm{p}}\right) / \sigma_\theta\left(\bar{\varepsilon}^{\mathrm{p}}\right) - 1 \right)^2 + w_{r_\theta} \sum_\theta \left(r_\theta(\mathbf{A}) / r_\theta - 1 \right)^2$$
$$+ w_{\beta_\varphi} \sum_\varphi \left(\beta_\varphi\left(\mathbf{A}, \bar{\varepsilon}^{\mathrm{p}}\right) / \beta_\varphi\left(\bar{\varepsilon}^{\mathrm{p}}\right) - 1 \right)^2$$

$\mathbf{A}$ – set of anisotropy parameters

σ_θ – yield stresses in uniaxial tension

r_θ – anisotropy coefficients in uniaxial tension

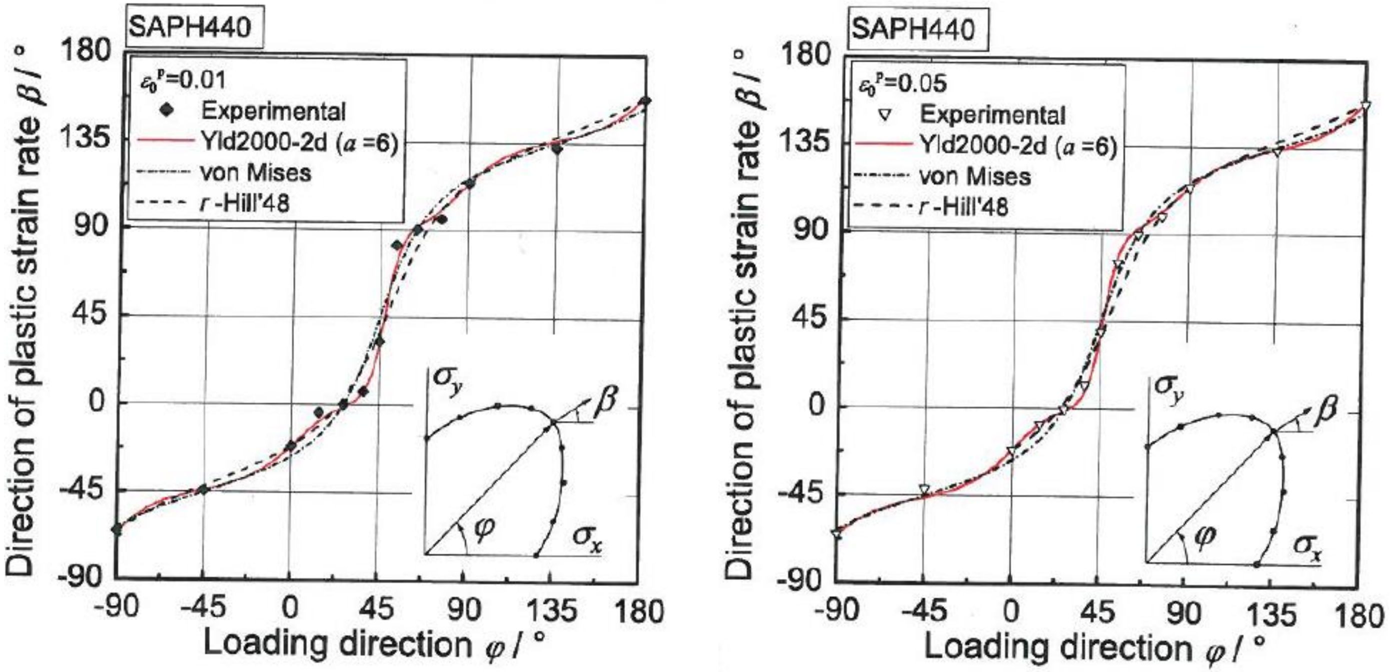
β_φ – direction of plastic strain rate in biaxial tension

θ – angle from the rolling direction

φ – loading direction

w_i – weighting coefficients

- Minimized with a downhill simplex method



Directions of the plastic strain rates measured at (left) ε^{p}_{0}=0.01 and (b) ε^{p}_{0}=0.05, compared with those calculated using the von Mises, Hill '48, and the Yld2000-2d yield functions [Kuwabara *et al.* 20018, *Benchmark 2 – Cup Drawing of anisotropic thick steel sheet, Part B: Material data*].

SAPH 440 orthotropic behaviour

Identification of the anisotropy parameters

- **CB2001**: Based on the *r*-value and yield stress in-plane directionalities and on the β values (ε^p_0=0.05).

c	a_1	a_2	a_3	a_4	b_1	b_2	b_3	b_4	b_5	b_{10}	**Others**
0.517	0.872	1.039	1.183	1.120	1.617	0.259	0.204	0.822	2.227	2.266	1.00000

- **Hill48**: Based only on r_{0^o}, r_{45^o} and r_{90^o} (assuming $G+H$ = 1).

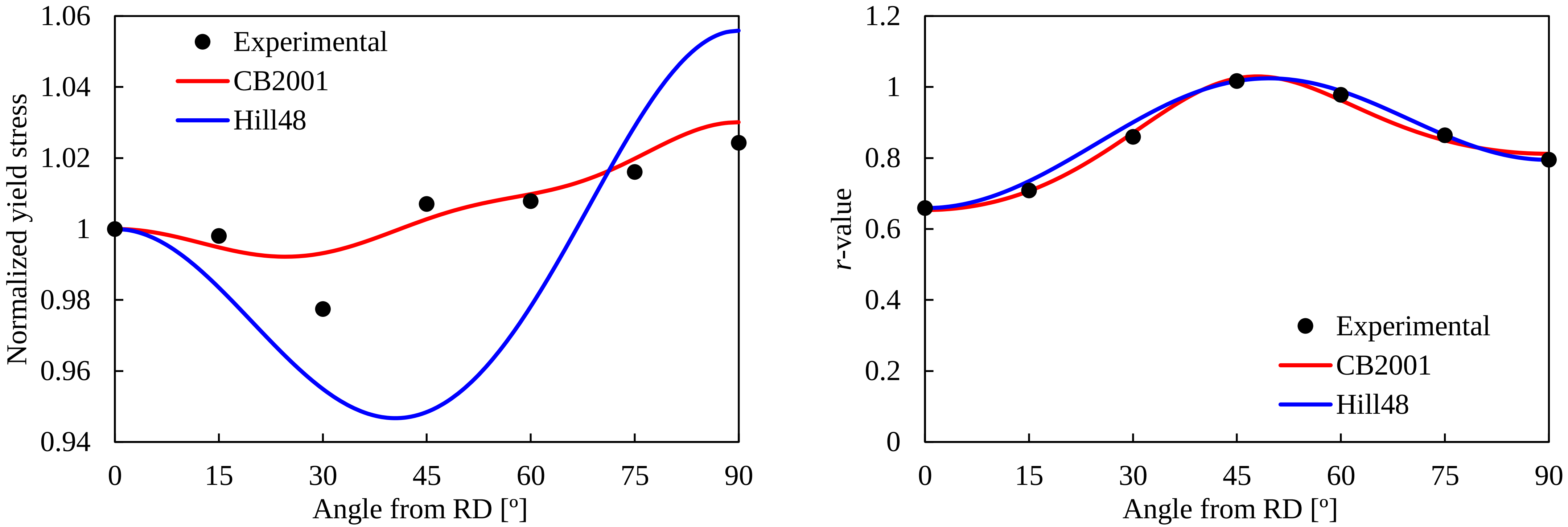
F	G	H	L	M	N
0.500	0.603	0.397	1.5	1.5	1.672

$$H\left(\sigma_{xx}-\sigma_{yy}\right)^2+F\left(\sigma_{yy}-\sigma_{zz}\right)^2+G\left(\sigma_{zz}-\sigma_{xx}\right)^2+2N\tau_{xy}^2+2L\tau_{yz}^2+2M\tau_{zx}^2=Y^2$$

SAPH 440 orthotropic behaviour

Identification of the anisotropy parameters

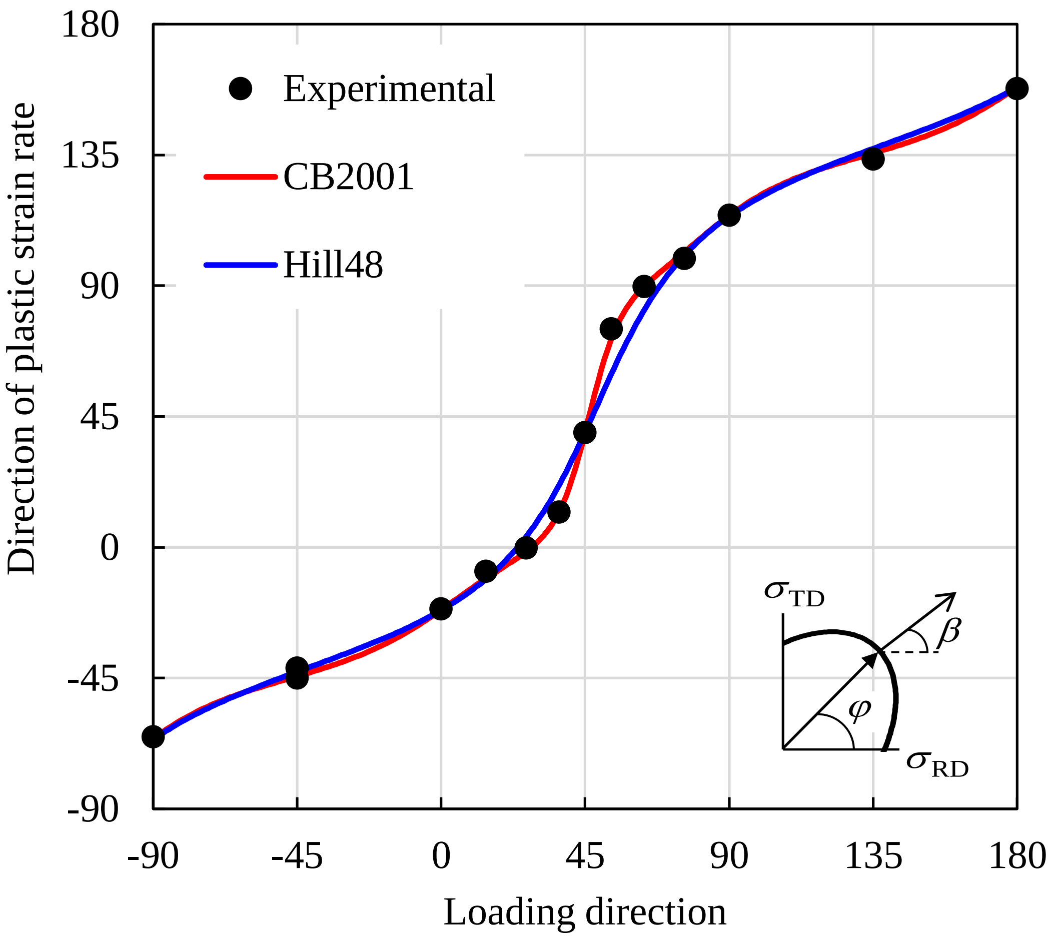
- The CB2001 yield criterion enables the proper description of the normalized yield stresses and *r*-values
- As expected the Hill48 leads to a wider variation of the normalized yield stresses, with a maximum error at 45º to RD.

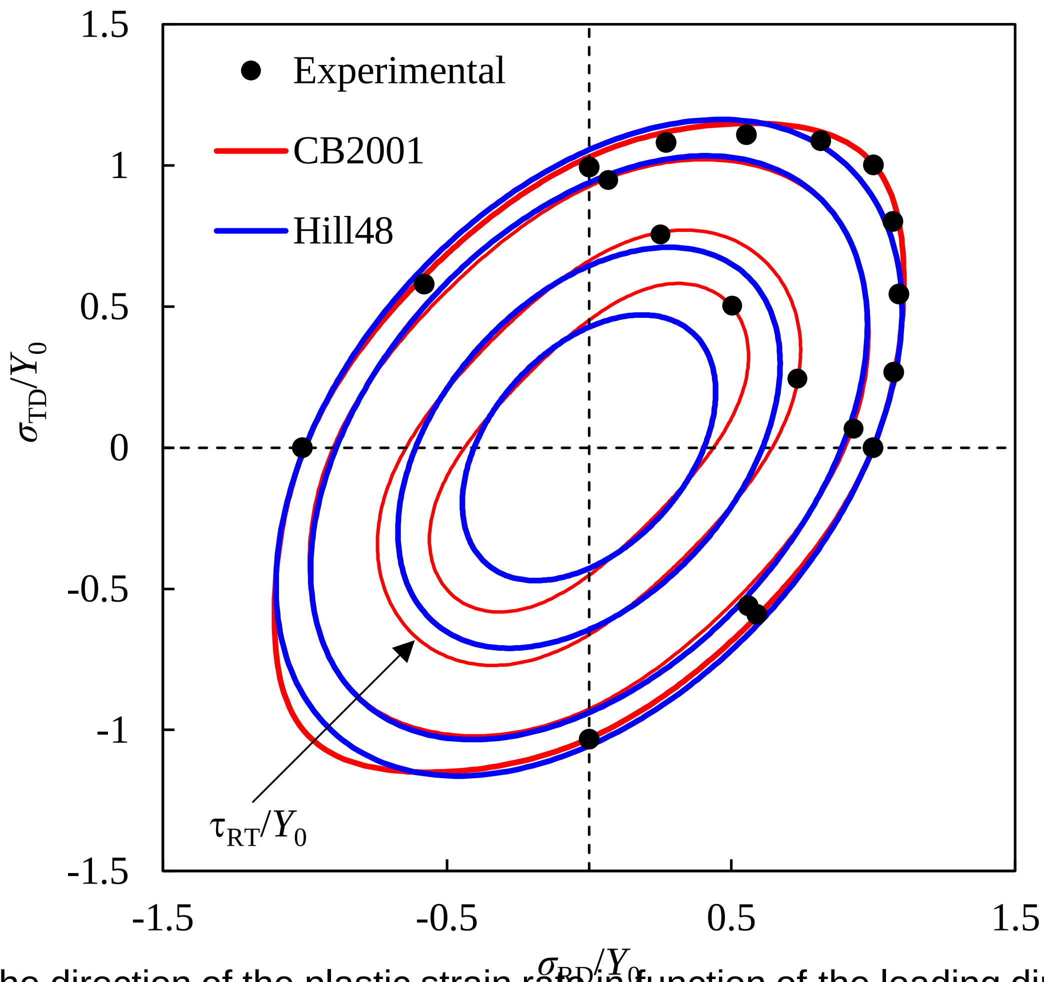


Comparison between experimental and predicted: (left) distribution of the normalized yield stresses in the sheet plane; (right) distribution of the *r*-values in the sheet plane.

SAPH 440 orthotropic behaviour

Identification of the anisotropy parameters





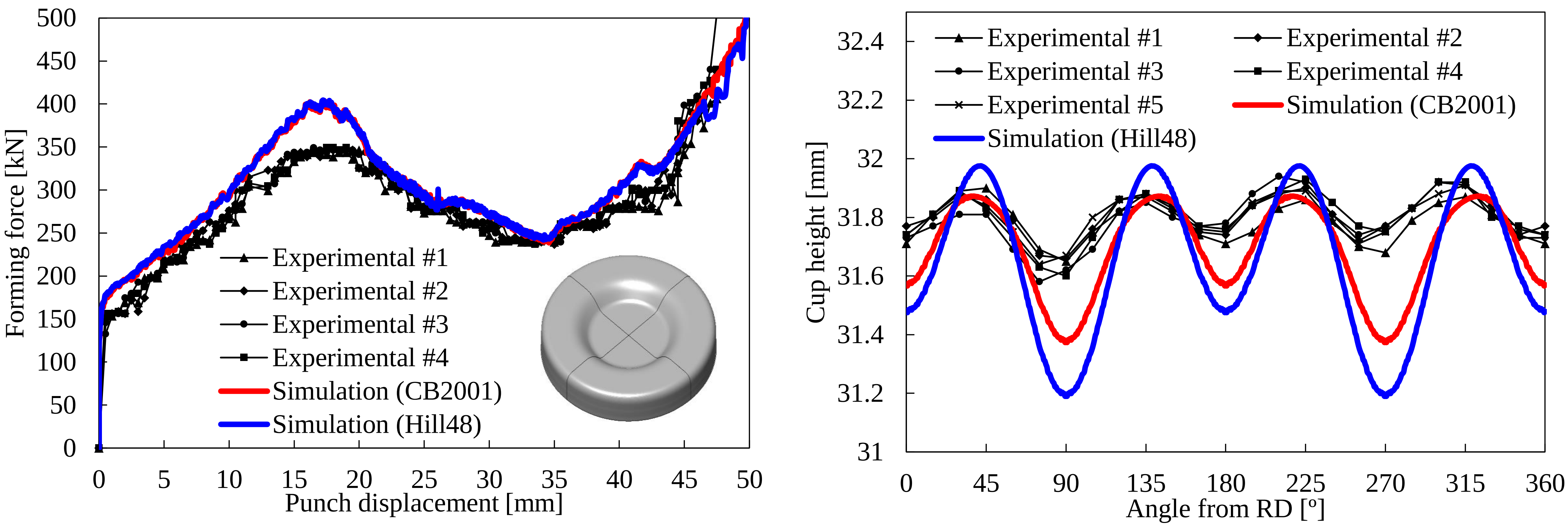
Comparison between experimental and predicted: (left) distribution of the direction of the plastic strain rate in function of the loading direction; (right) normalized projection of the yield surfaces in the σ_{RD}-σ_{TD} plane, with null values for all the other stress components. For the CB2001 yield criterion, the projections are also shown for the levels of the shear stress component in the plane of: $0.25Y_0$; $0.4(3)Y_0$ and $0.50Y_0$.

M.C. Oliveira (marta.oliveira@dem.uc.pt)

Cup drawing of anisotropic thick steel sheet

Earing profile (Task 1)

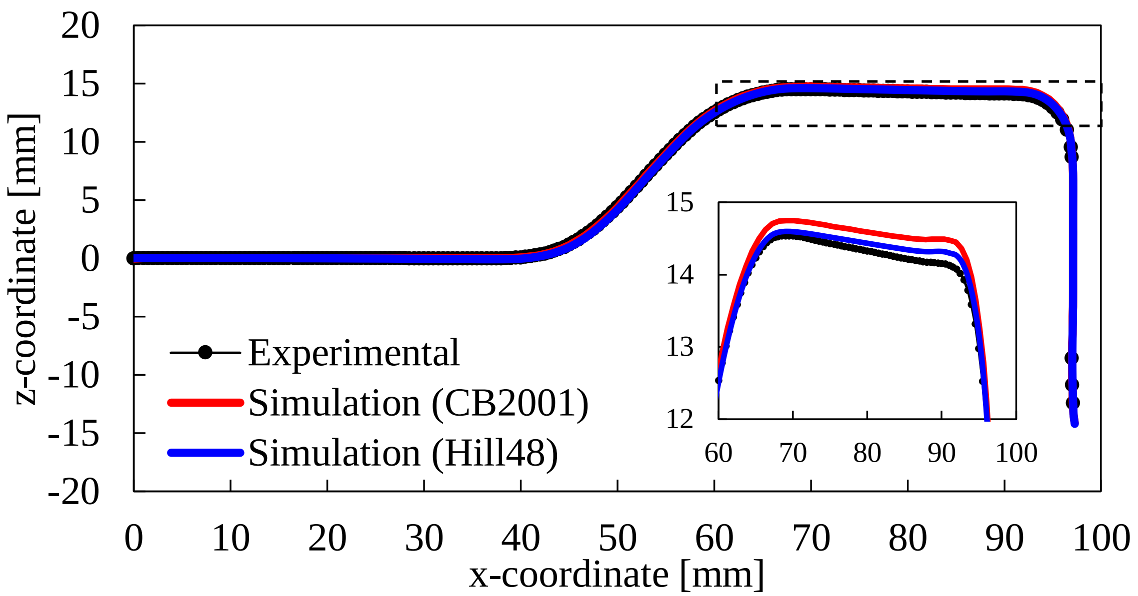
- Although the forming force is globally overestimated, the numerical result are in good agreement with the experimental measurements (4 tests under identical conditions)
- The number of ears (4) is accurately predicted, while the amplitude of the earing profile is overestimated

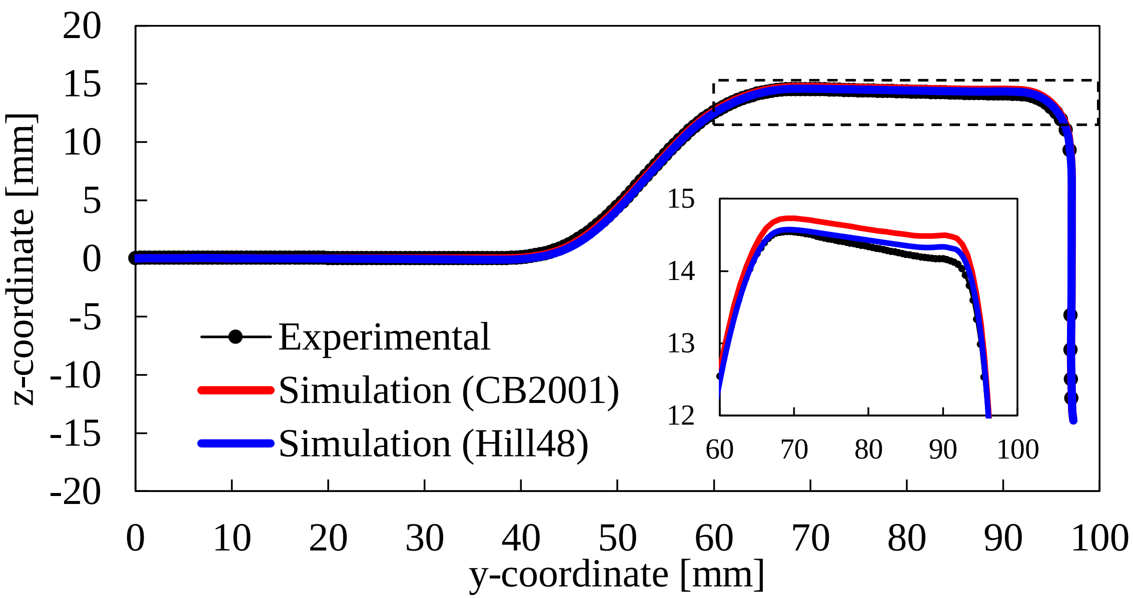


Comparison between experimental measurement and numerical prediction in Task 1: (left) forming force evolution; (right) earing profile.

Springback (Task 1)

- The numerical predictions are in very good agreement with the experimental measurements since the springback is very low in this axisymmetric component
- Nevertheless, the detail of the cup profile highlights the accurate prediction of the slope of the cup's bottom, which can be an important aspect when dealing with the assembly of this type of components
- Although the CB2001 yield criterion predicts this slope better, it overestimates the global deviation.

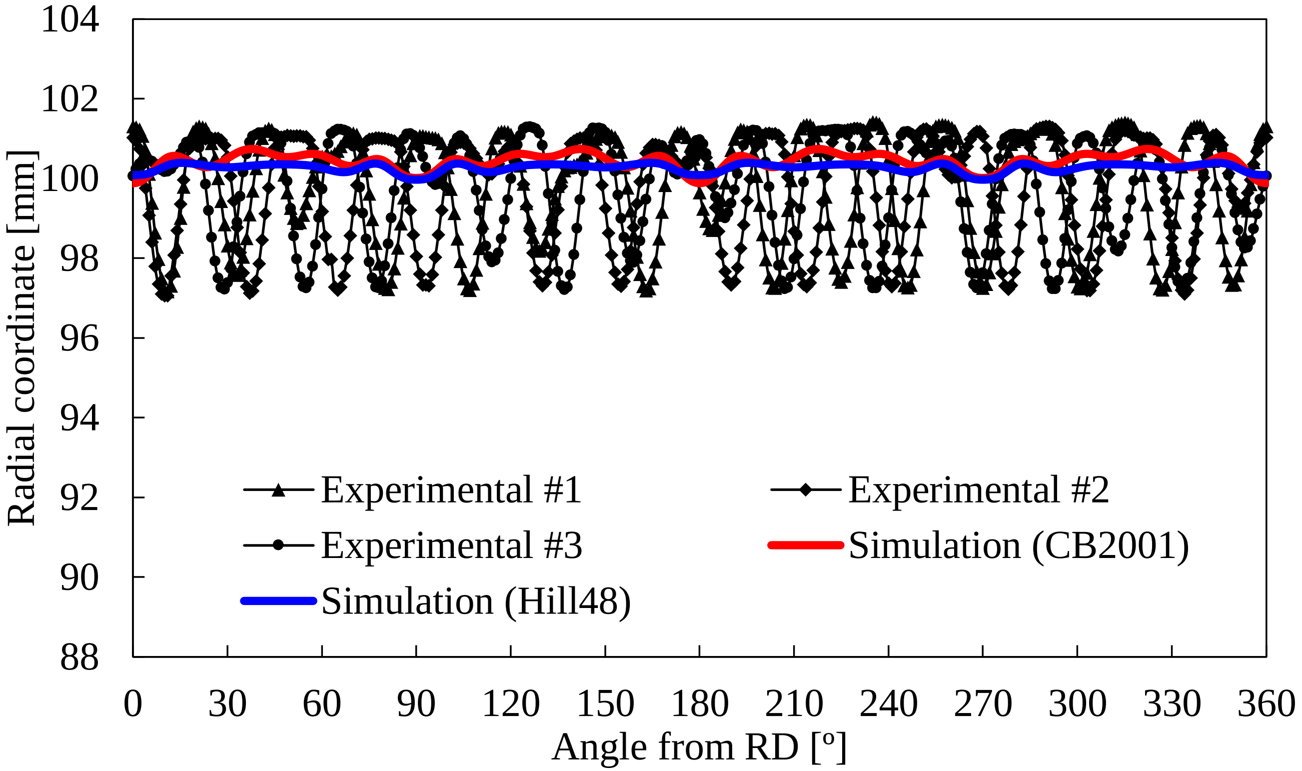




Comparison between experimental and predicted springback in Task 1: (left) cup profile in the xOz plane; (right) cup profile in the plane transverse to the RD (yOz).

Wrinkling in the cup wall (Task 2)

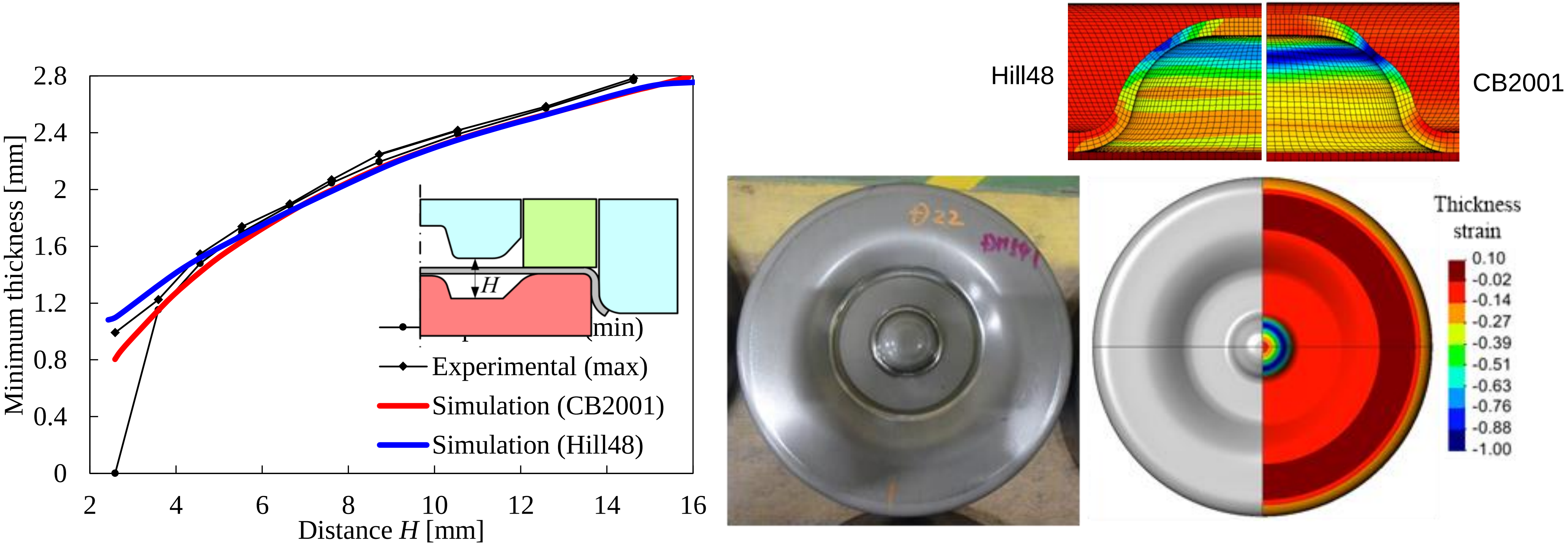
- The amplitude of wrinkles is significantly underestimated by the numerical model. In fact, the wrinkling amplitude measured in the experimental cups is about 4 mm, while the numerical prediction provides an amplitude lower than 1 mm
- The CB2001 yield criterion predicts 16 wrinkles (within the experimental range of 15-18)



Analysis of cup wall wrinkling in Task 2: (left) comparison between experimental and predicted radial coordinate evaluated in the inner surface at 25 mm from the cup base; (right) geometry of the cup with wrinkles.

Tearing in the center boss (Task 3)

- The fracture is observed experimentally in the range 2.6<H<3.6 mm, as shown through the dispersion in the measured thickness value
- These results highlight the importance of the plasticity model in the prediction of ductile fracture.



Comparison between experimental and predicted results in Task 3: (left) evolution of the minimum thickness in the apex of the center boss in function of the distance, H, between the punch and the die; (right-top) predicted thickness strain for H =2.4 mm; (right-bottom) cup geometry and predicted thickness strain for H =3.6 mm (CB2001).

Conclusions

- The earing profile is accurately predicted since the in-plane distribution of both the *r*-values and the yield stresses is accurately described by the CB2001 yield criterion. Nevertheless, the earing amplitude is overestimated, which can be related overestimation of the force.

- Since the springback is typically slight in axisymmetric cups, both yield criteria lead to similar prediction, although the CB2001 presents a higher overestimation of the deviation.

- The amplitude of the wrinkles developed in the flange (when no blank holding force is applied) is clearly underestimated by the numerical model. This can be related with the static implicit time integration approach, where sometimes the initiation of the wrinkles requires an initial imperfection.

- The thinning in the apex of the center boss is accurately predicted by the numerical model that uses the CB2001 yield criterion, i.e. the difference between experimental and numerical thickness is always inferior to 4%. Besides, the predicted thickness strain is in good agreement with the location of the necking observed in the cup.

Acknowledgements

The authors gratefully acknowledge the financial support of the **Portuguese Foundation for Science and Technology** (FCT) under the projects with reference PTDC/EME-EME/30592/2017 and PTDC/EME-EME/31657/2017 and by European Regional Development Fund (ERDF) through the Portugal 2020 program and the Centro 2020 Regional Operational Programme (CENTRO-01-0145-FEDER-031657) under the project MATIS (CENTRO-01-0145-FEDER-000014) and UIDB/00285/2020. We also would like to acknowledge the benchmark committee to make available the experimental data used in the present study.

Projetos Cofinanciados pela UE: