UNIVERSIDADE D COIMBRA

Study on the influence of orthotropy and tension–compression asymmetry of metal sheets in springback and formability predictions

P.D. Barros[1] • D.M. Neto[1] • J.L. Alves[2] • M.C. Oliveira[1] • L.F. Menezes[1]

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

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

NUMISHEET 2018

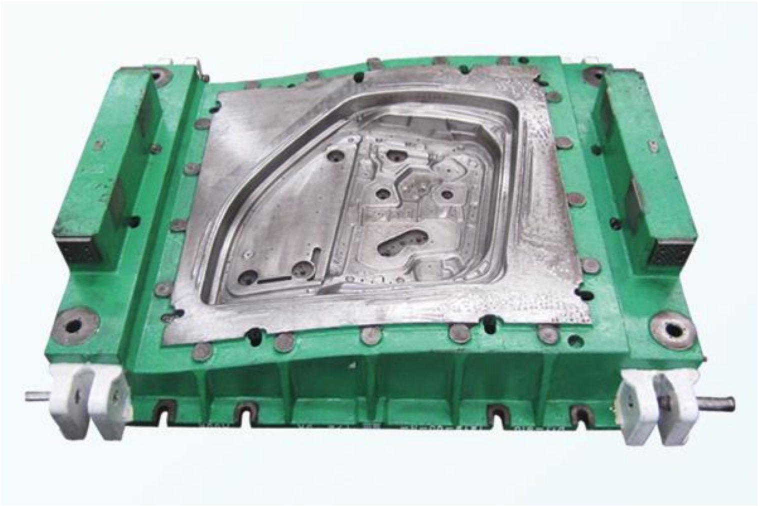
The 11th International Conference and Workshop on Numerical Simulation of 3D Sheet Metal Forming Processes

July 30–August 3, 2018
Hotel East 21 Tokyo, Tokyo, Japan

Introduction

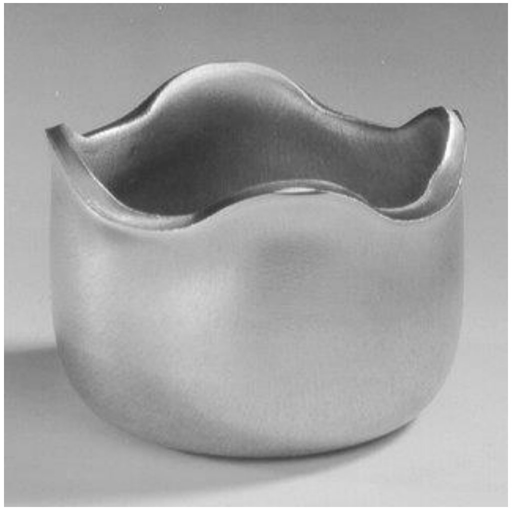
Sheet metal forming processes

- Very important manufacturing process in the **automotive industry**
- More than **90 million cars** and commercial vehicles produced worldwide in 2014
- Each car is composed by **more than 400 sheet metal parts** (closures, structural parts and reinforcements)

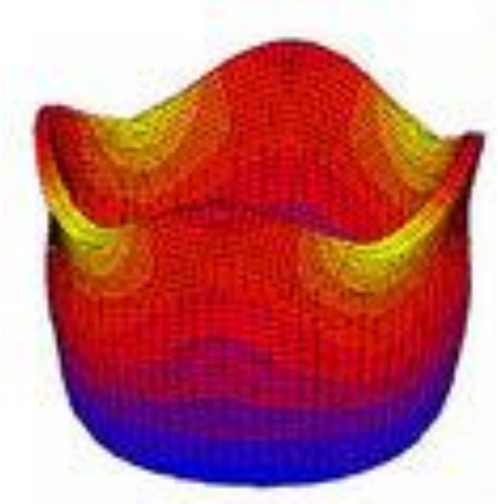


Cylindrical cup forming

- Evaluate the performance of constitutive models (**yield criteria**)
- **Earing profile** and the **thickness distribution** dictated by the in-plane distribution of both the ***r*-values** and **yield stresses** (compression stress state)
- **Difficulties** in the uniaxial in-plane **compression test** on metal sheets (buckling)



Experimental

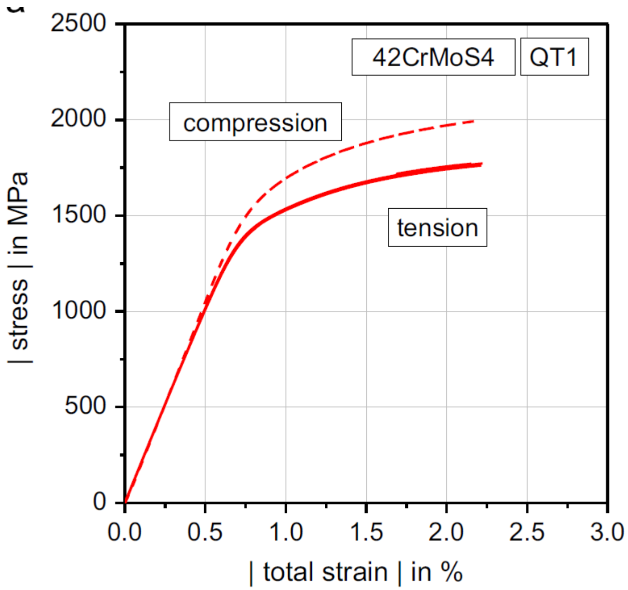


Simulation

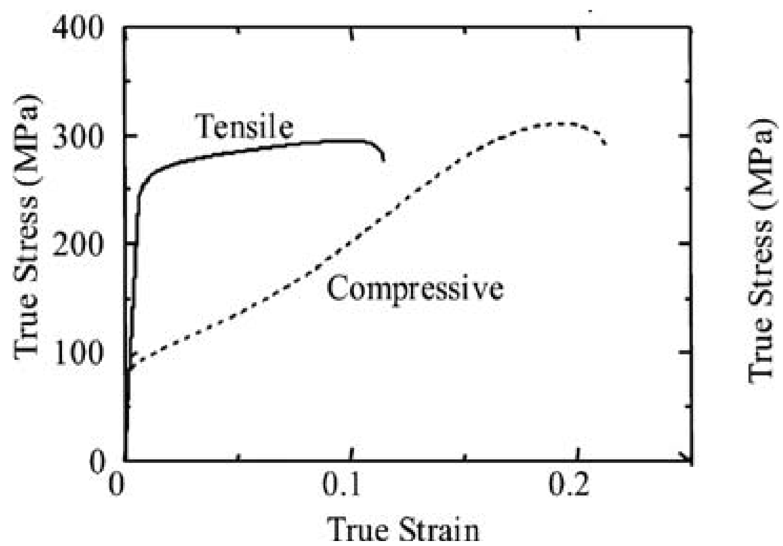
Strength differential (SD) effect

- **Asymmetry** between the yield stress in **tension and compression**
- Take it into account SD effect in the **modeling** of the sheet orthotropic behavior

Strength differential effect in the 42CrMoS4 steel



Strength differential effect in the AZ31 magnesium alloy



➢ **Objective:** influence of the **SD effect** on the prediction of the springback and the strain evolution during the **forming of a cup**

Cazacu, Plunkett and Barlat, 2006 (CPB06)

$$\bar{\sigma} = B\left[\left(|s_1| - k\,s_1\right)^a + \left(|s_2| - k\,s_2\right)^a + \left(|s_3| - k\,s_3\right)^a\right]^{\frac{1}{a}}$$

where $\mathbf{s} = \mathbf{C}\boldsymbol{\sigma}'$

$$\mathbf{C} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix}$$

$$B = \left[\frac{1}{\left(|\phi_1| - k\,\phi_1\right)^a + \left(|\phi_2| - k\,\phi_2\right)^a + \left(|\phi_3| - k\,\phi_3\right)^a}\right]^{\frac{1}{a}}$$

$$\begin{Bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{Bmatrix} = \begin{Bmatrix} (2/3)C_{11} - (1/3)C_{12} - (1/3)C_{13} \\ (2/3)C_{21} - (1/3)C_{22} - (1/3)C_{23} \\ (2/3)C_{31} - (1/3)C_{32} - (1/3)C_{33} \end{Bmatrix}$$

Anisotropy parameters

$C_{11}, C_{22}, C_{33}, C_{66}, C_{12}, C_{13}, C_{23}$

Asymmetry parameter

k

- **Two linear transformations - Plunkett, Cazacu and Barlat, 2008 (CPB06ex2)**

where $\mathbf{s}' = \mathbf{C}'\boldsymbol{\sigma}'$

DD3MAT: objective function

$$F(\mathbf{A}) = w_{\sigma_\theta^T} \sum_\theta \left(\sigma_\theta^T(\mathbf{A}, \bar{\varepsilon}^p) / \sigma_\theta^T(\bar{\varepsilon}^p) - 1 \right)^2 + w_{\sigma_\theta^C} \sum_\theta \left(\sigma_\theta^C(\mathbf{A}, \bar{\varepsilon}^p) / \sigma_\theta^C(\bar{\varepsilon}^p) - 1 \right)^2$$
$$+ w_{r_\theta^T} \sum_\theta \left(r_\theta^T(\mathbf{A}) / r_\theta^T - 1 \right)^2 + w_{r_\theta^C} \sum_\theta \left(r_\theta^C(\mathbf{A}) / r_\theta^C - 1 \right)^2$$
$$+ w_{\tau_\theta} \sum_\theta \left(\tau_\theta(\mathbf{A}, \bar{\varepsilon}^p) / \tau_\theta(\bar{\varepsilon}^p) - 1 \right)^2 + w_{\sigma_b} \left(\sigma_b(\mathbf{A}, \bar{\varepsilon}^p) / \sigma_b(\bar{\varepsilon}^p) - 1 \right)^2$$
$$+ w_{r_b} \left(r_b(\mathbf{A}) / r_b - 1 \right)^2$$

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

σ_θ^T and σ_θ^C – yield stresses in uniaxial tension and compression

r_θ^T and r_θ^C – anisotropy coefficients in uniaxial tension and compression

τ_θ – shear stress

σ_b and r_b – biaxial yield stress and anisotropy coefficient

θ – angle from the rolling direction

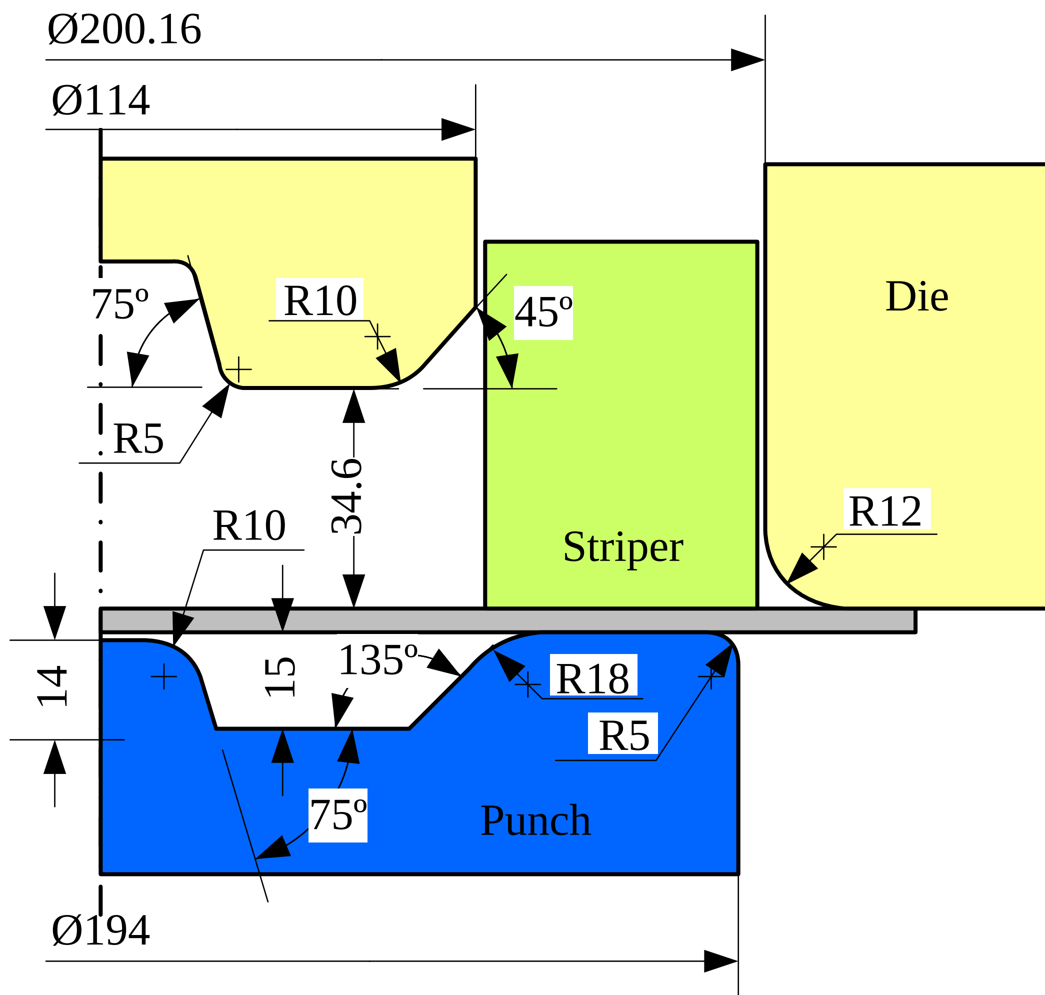
w_i – weighting coefficients

- Minimized with a downhill simplex method

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

- Hot rolled steel sheet (**SAPH 440**) with **2.8 mm thickness**

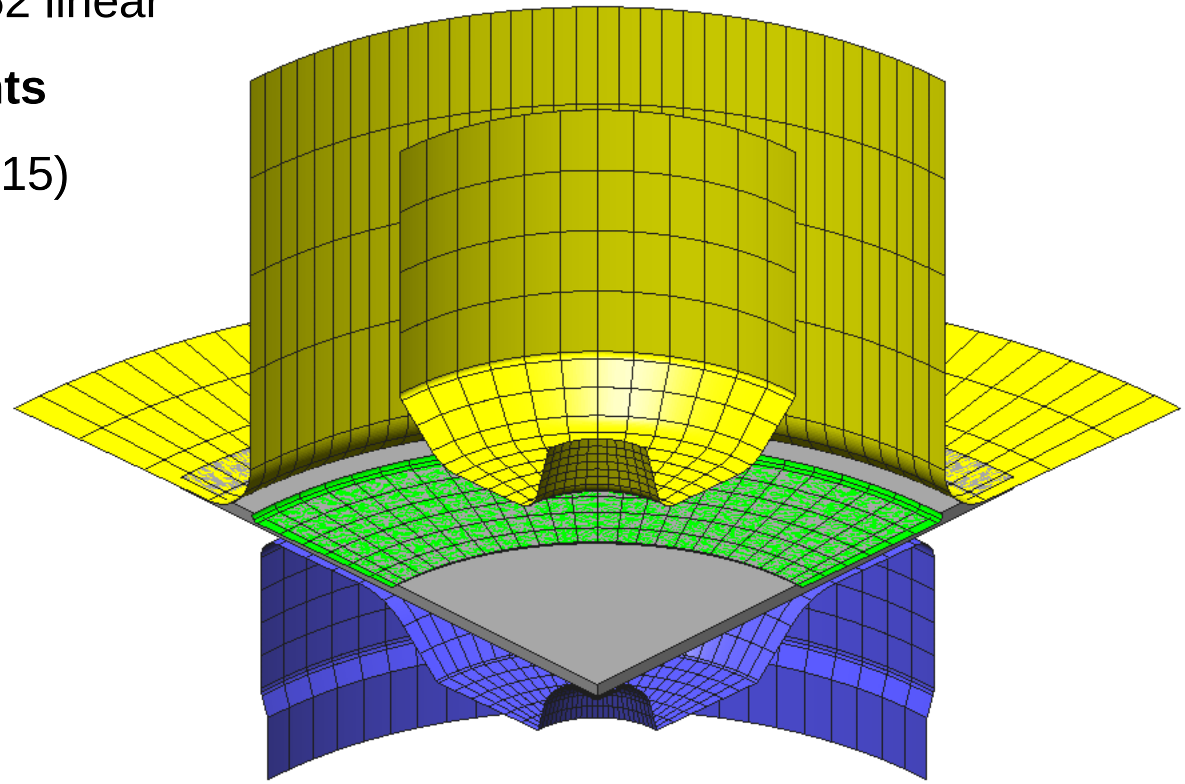
- Constant stripper force (50 kN)
- Vertical displacement of the die
- Blank diameter of 246 mm



Cup forming (axisymmetric)

Finite element model

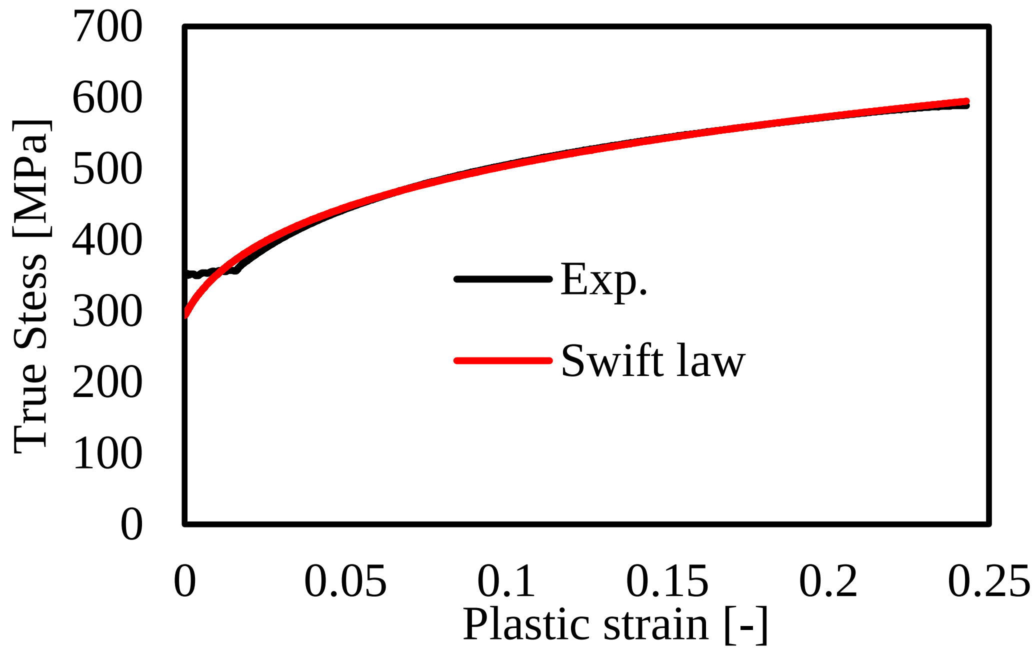
- **DD3IMP** in-house finite element code (implicit time integration)
- **1/4 of the model** (symmetry conditions)
- Forming tools are assumed **rigid** (described by Nagata patches)
- Blank discretized by 60,552 linear **hexahedral finite elements**
- Coulomb friction law (*μ*=0.15)



Cup forming (axisymmetric)

Finite element model

- Plastic behavior of the blank modelled by the **Swift law** (isotropic work hardening)

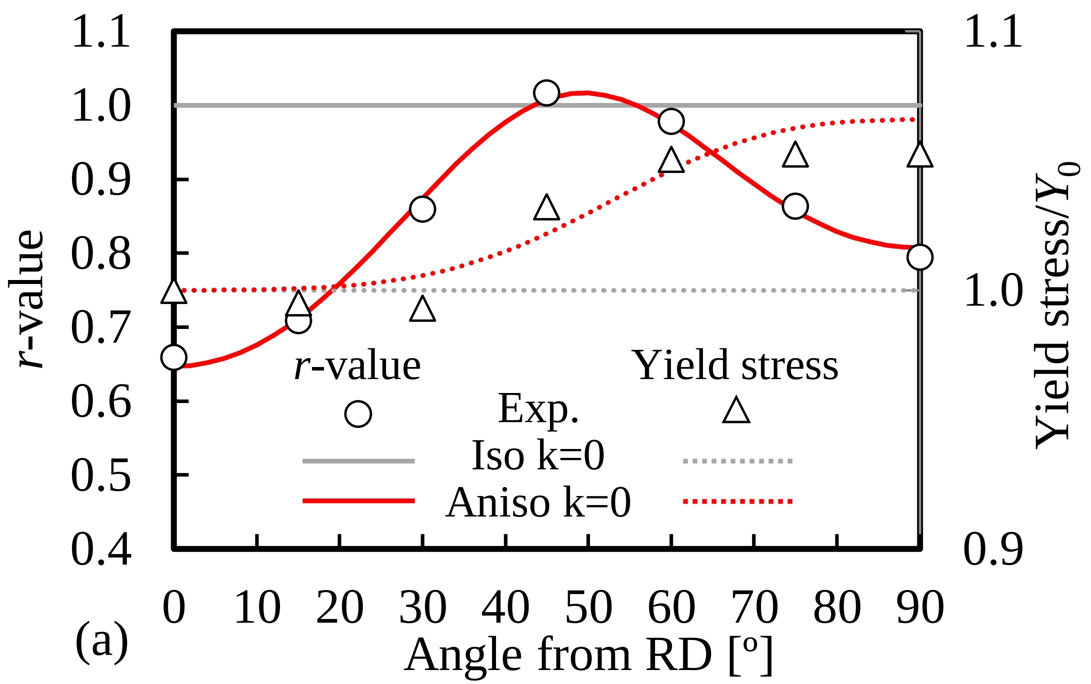


- **CPB06(ex2) yield criterion** (orthotropic behavior and SD effect)
  - Stress–strain curve from the uniaxial tensile test performed along the RD
  - Anisotropy coefficients from uniaxial tensile tests
  - Biaxial data extracted from biaxial tension test
  - Tension-compression asymmetry extracted form the in-plane uniaxial compression test

Cup forming (axisymmetric)

Finite element model

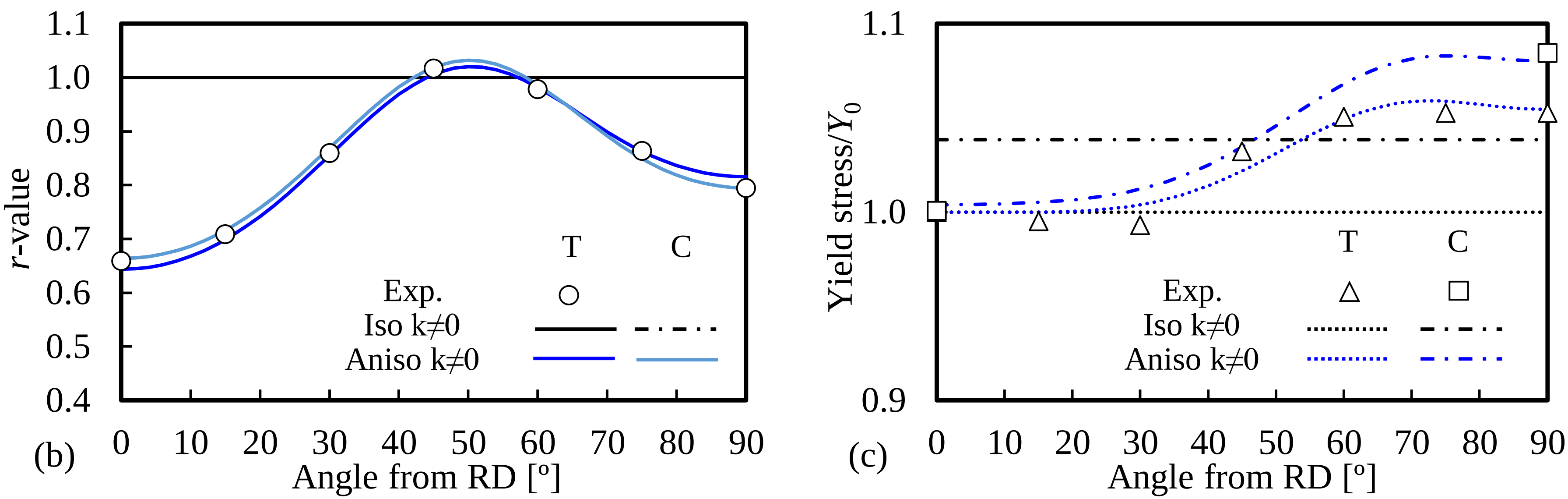
- CPB06 yield criterion **without SD effect**
  - Two linear transformations were considered in order to capture both the *r*-value and the yield stress in-plane directionalities



Experimental and predicted *r*-values and normalized yield stresses **without SD effect**

Finite element model

- CPB06 yield criterion **with SD effect**
  - The in-plane evolution of the compression *r*-values was carefully monitored
  - For Iso_k≠0 the *k* value was identified considering the ratio reported for the TD direction, i.e. σ^T/σ^C=0.9630 (*k*=-0.0315)

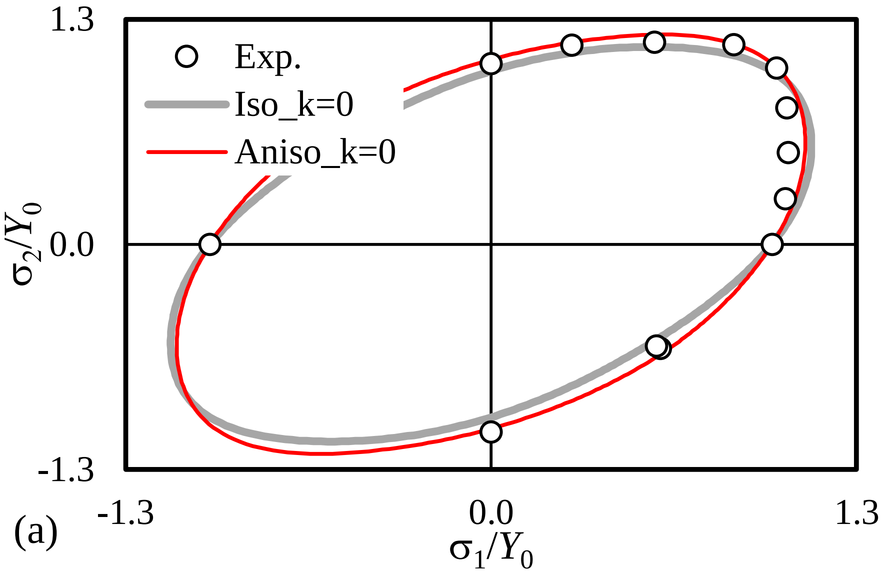


Experimental and predicted *r*-values and normalized yield stresses **with SD effect**

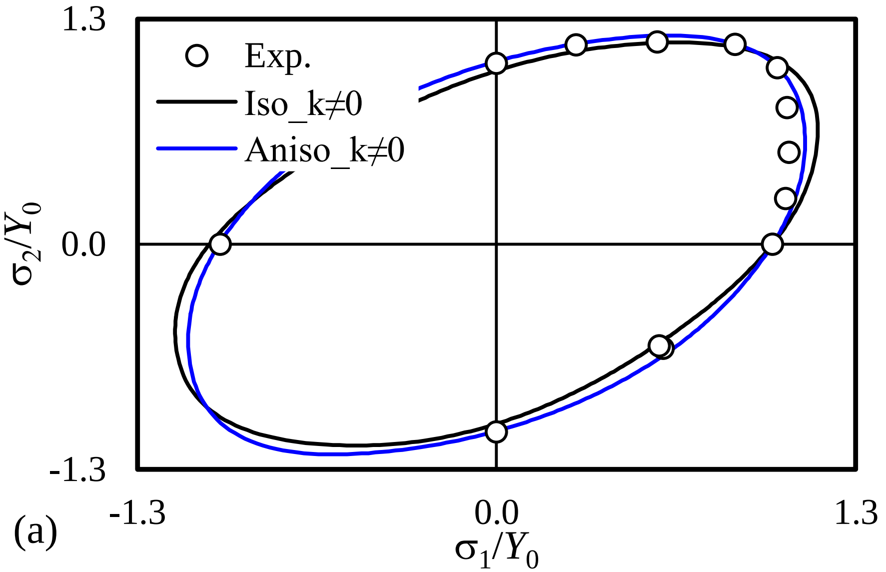
Cup forming (axisymmetric)

Finite element model

- **Normalized yield surfaces** with and without SD effect



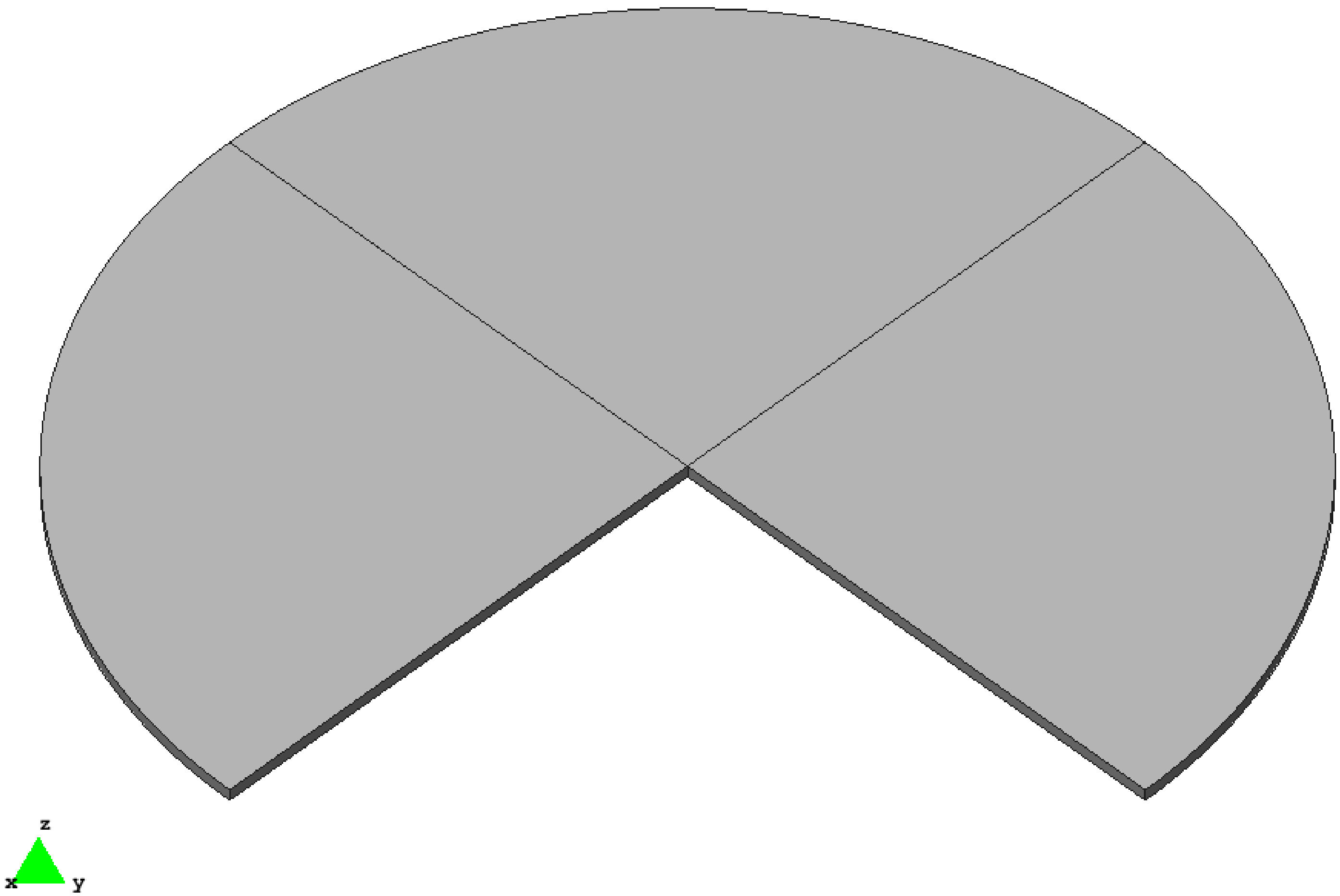
Without SD effect



With SD effect

			σ^T/σ^C		
	r_b (Exp=0.6390)	σ_b (Exp=1.0200)	RD (Exp=1.0000)	TD (Exp=0.9630)	ND
Aniso_k=0	0.6453	1.0176	1.0000		
Aniso_k≠0	0.6515	1.0184	0.9962	0.9762	0.9942

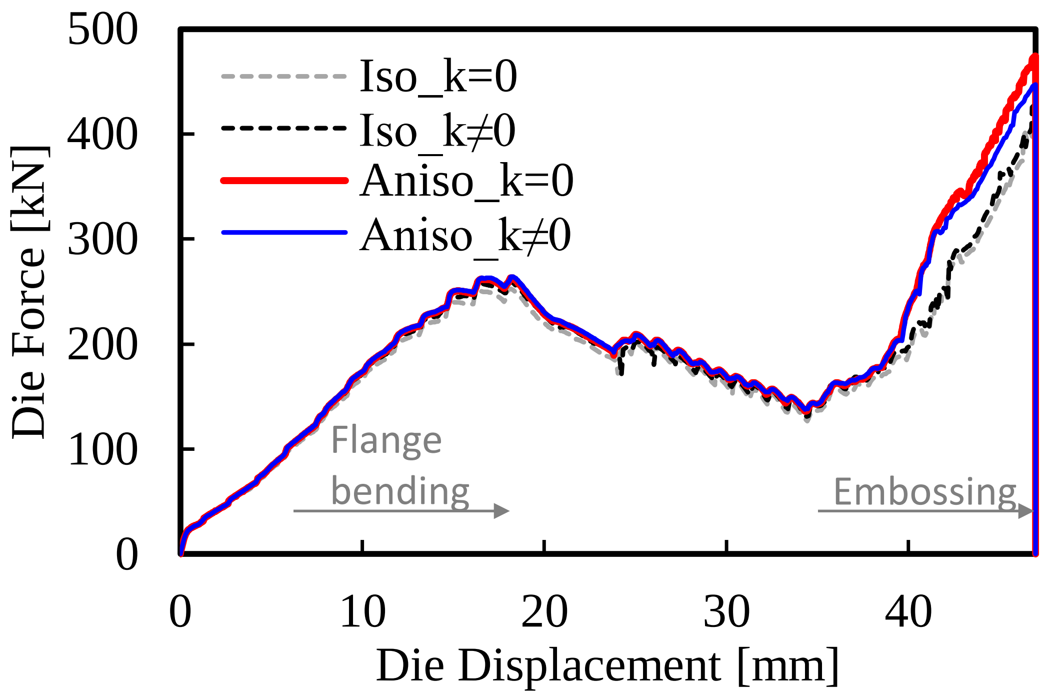
Overview of the cup drawing simulation



Equivalent plastic strain distribution

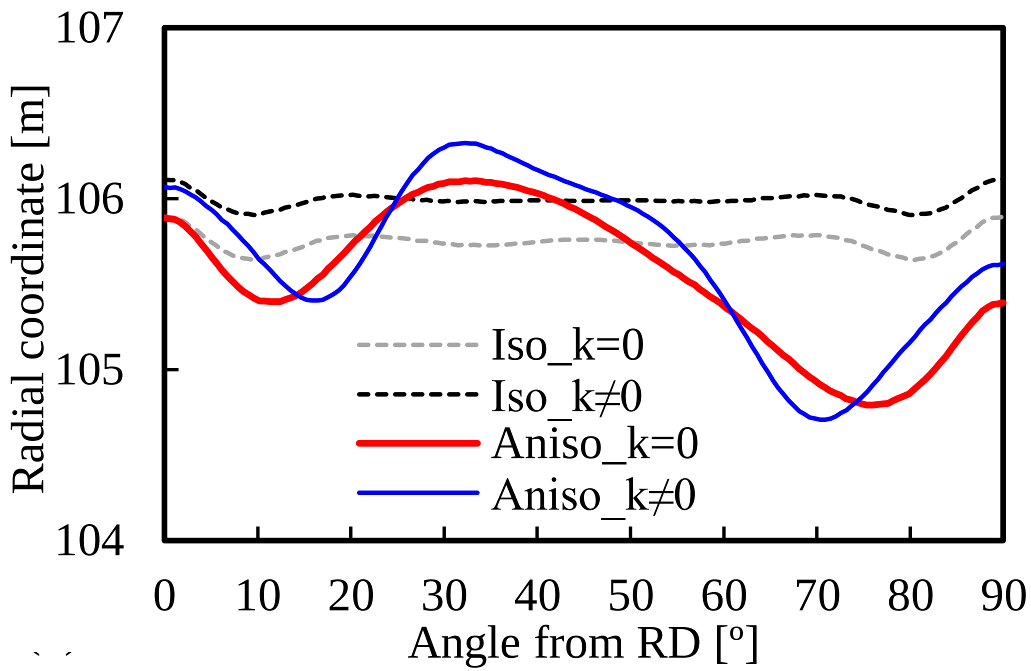
Die force evolution

- All models predict a similar die force evolution, except in the last stage
- Considering the isotropic models, the die force is slightly higher for the model that takes into account the SD effect, which is in agreement with the small increase of the compressive yield stress



Radial coordinate of the inner surface of the cup wall

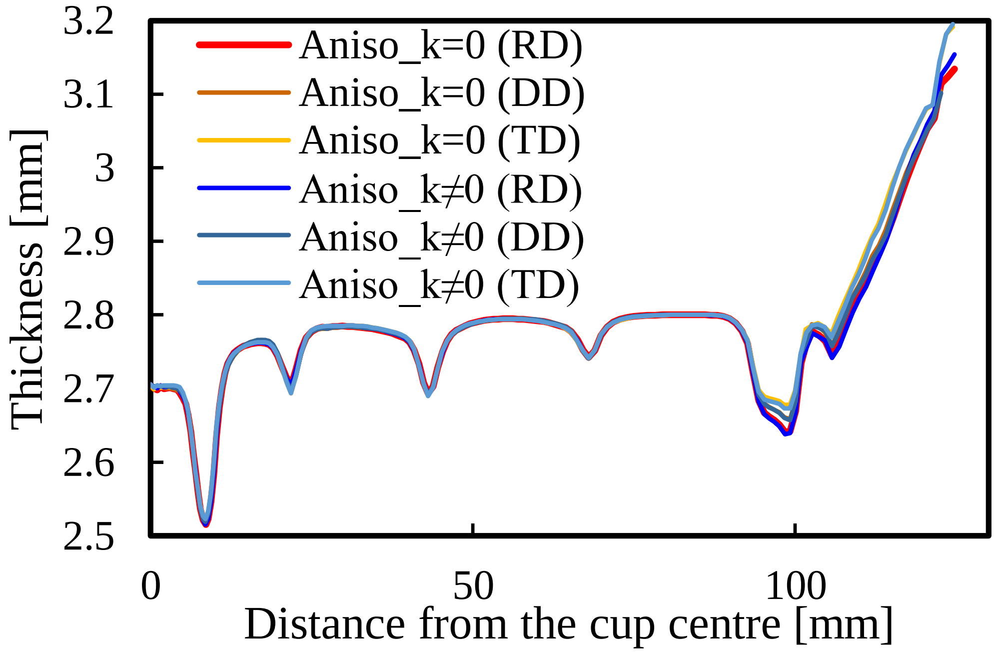
- During the bending process, the unsupported flange develops some wrinkles, as shown for 25 mm of die displacement
- Considering the isotropic models, the small increase of the compressive yield stress justifies the higher radial coordinate of the inner surface of the cup wall



Results and discussion

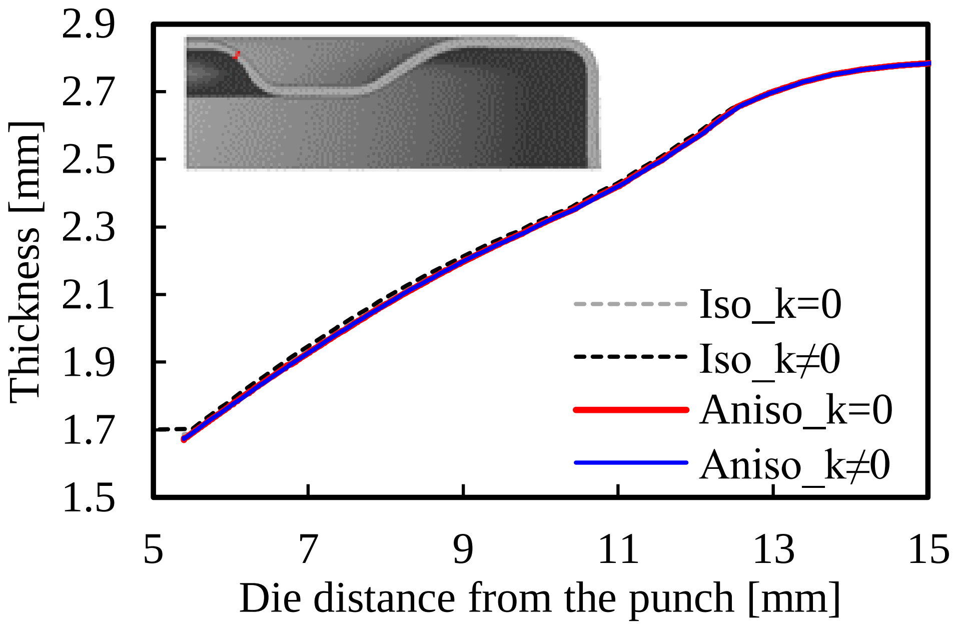
Thickness distribution

- For a die displacement of 40 mm, there are regions in the unsupported flange with a thickness higher than the gap between the punch and the die (3.08 mm).
- This means that some ironing will occur, which justifies the slightly higher values for the die force predicted by the models that take into account the orthotropic behavior



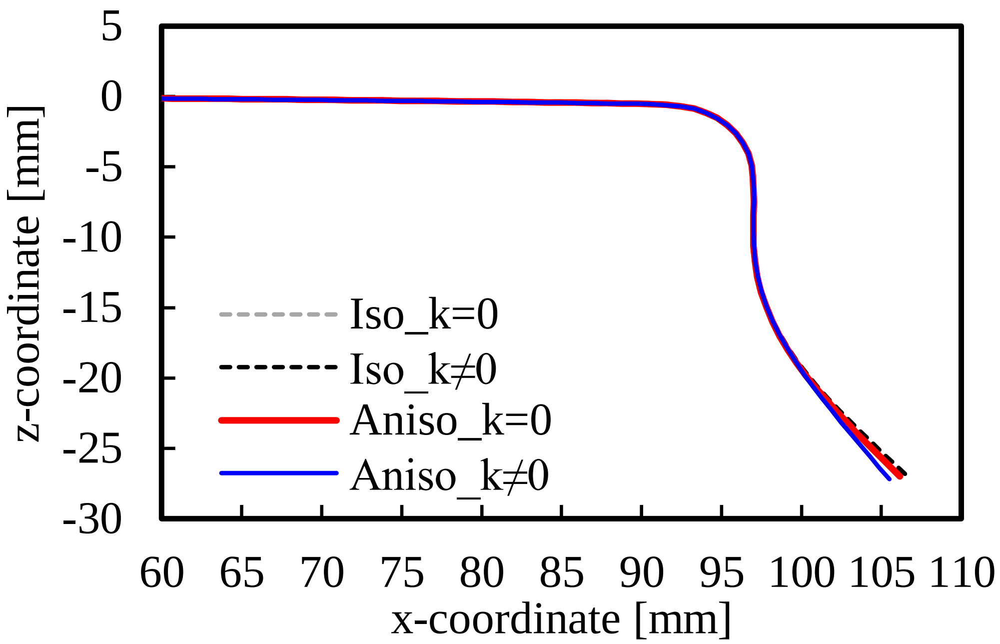
Thickness evolution in the apex

- The analysis of the thickness evolution was performed until a thinning of approximately 50%, i.e. a total displacement of 47 mm was imposed to the die
- The evolution of the predicted thickness at the apex of the center boss is similar for all models



Profile of the cross section

- Inner surface of the cup (RD), after 25 mm of die displacement and springback
- Springback mainly changes the geometry of the parts bottom (becomes less flat)
- Mainly dictated by the fact that the model takes or not into account the orthotropic behavior of the material, i.e. the SD effect is small



Conclusions

- It is known that the tension-compression asymmetry can influence the neutral line position in bending dominated processes and, consequently, the strain distribution and springback
- For the part under analysis, the influence of both the orthotropic behavior and the SD effect on the predicted springback is small
- The thickness distribution in the initially unsupported flange of the part is mainly controlled by the orthotropic behavior of the material, but it has a negligible effect at the apex of the center boss

➢ This work assumed an equal in-plane distribution of the *r*-values for both uniaxial tension and compression stress states, which should be further studied in future works.

Acknowledgements

This research work was sponsored by national funds from the Portuguese Foundation for Science and Technology (FCT) under the projects with reference P2020-PTDC/EMS-TEC/0702/2014 (POCI-01-0145-FEDER-016779) and P2020-PTDC/EMS-TEC/6400/2014 (POCI-01-0145-FEDER-016876) by UE/FEDER through the program COMPETE 2020

Thank you for your attention!