Global Research and Development

Modelling of plastic material behavior in line pipe

Steven Cooreman

ArcelorMittal

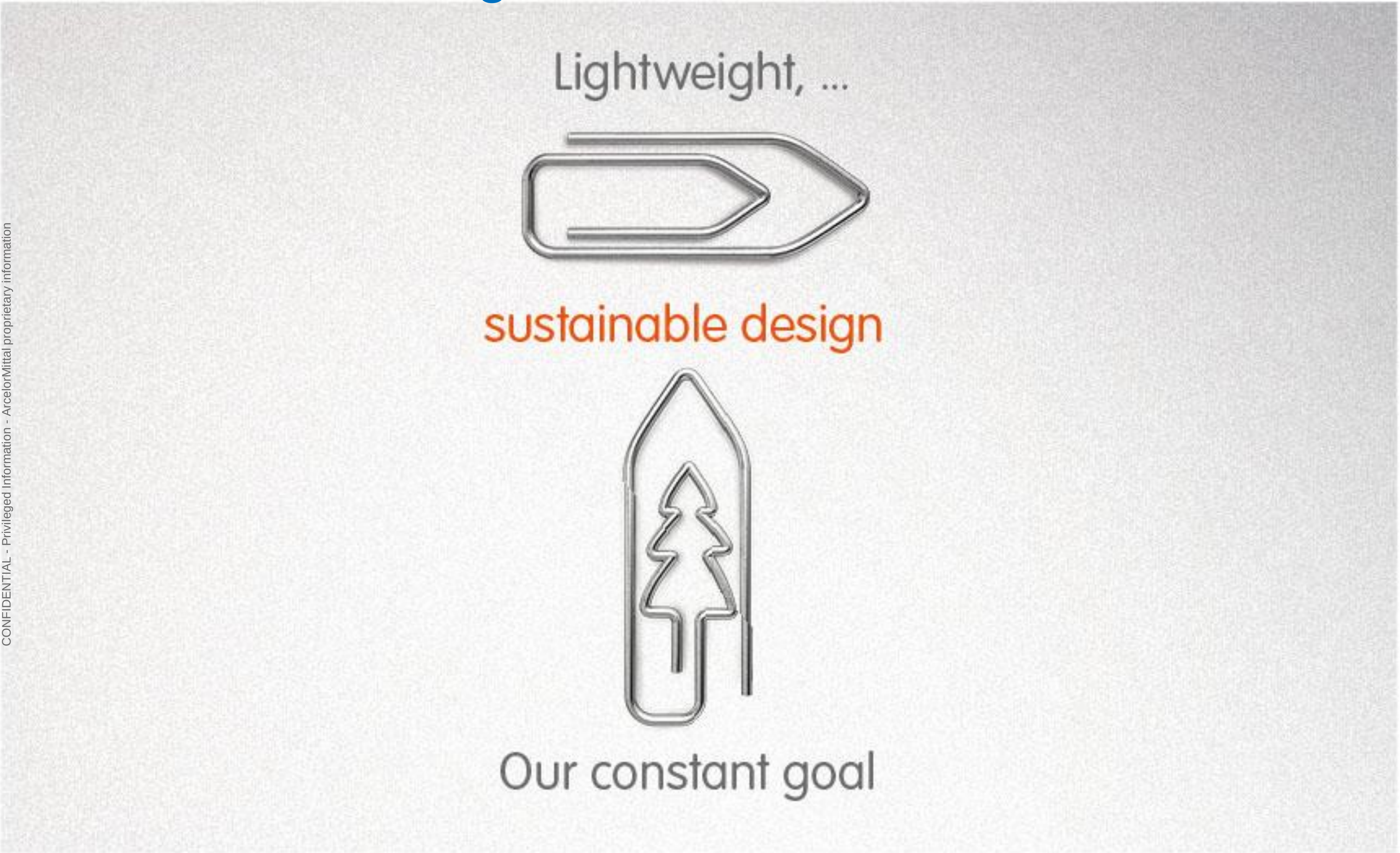
steven.cooreman@ocas.be

+32 477 02 60 59

www.ocas.be

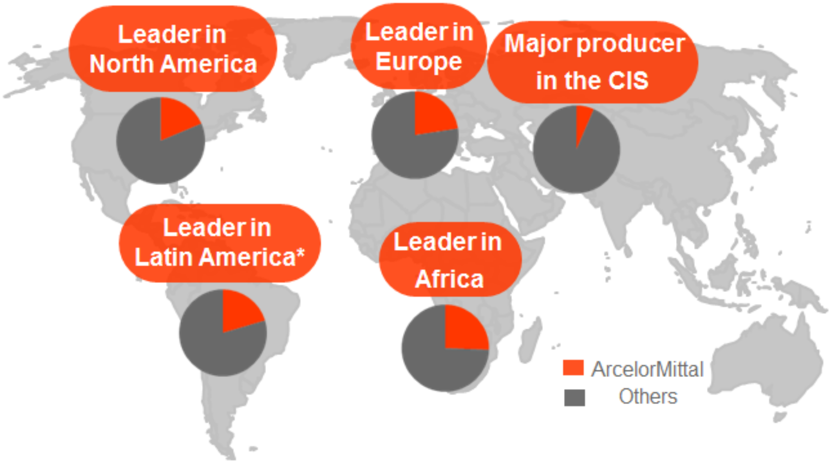
The right formula
for the steels of the future

ArcelorMittal
Some facts and figures



ArcelorMittal
The world's leading steel and mining company

Market position by region



- ArcelorMittal is the world's leading steel and mining company, with around 222,000 employees in more than 60 countries.
- ArcelorMittal is the leader in all major global steel markets, including automotive, construction, household appliances and packaging, with leading R&D and technology, as well as sizeable captive supplies of raw materials and outstanding distribution networks.
- We are the largest producer of steel in the EU, North and South America and Africa, a significant steel producer in the CIS region, and have a growing presence in Asia, including investments in China and India.

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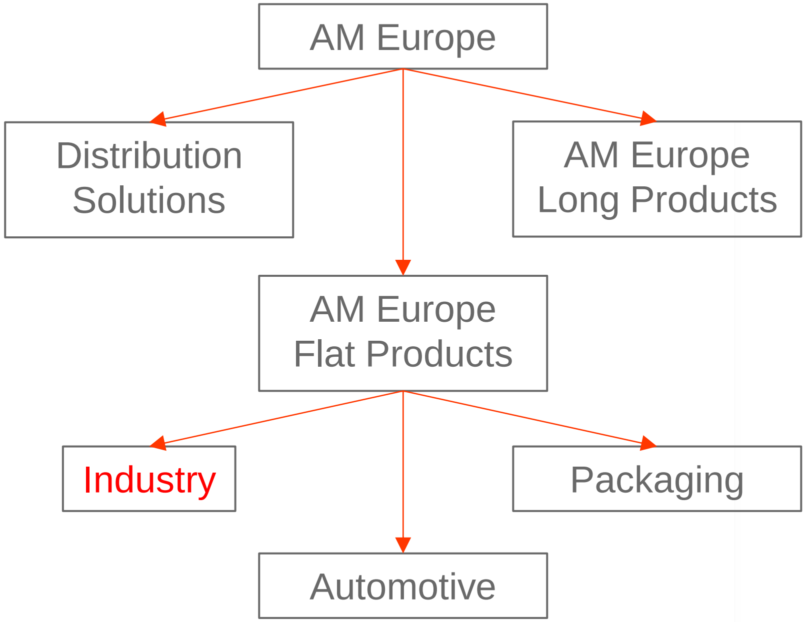
ArcelorMittal Europe



AM Europe

Distribution Solutions

AM Europe Long Products

AM Europe Flat Products

Industry

Packaging

Automotive

- ● Sales
- ● Mills
- ● R&D

ArcelorMittal Global R&D

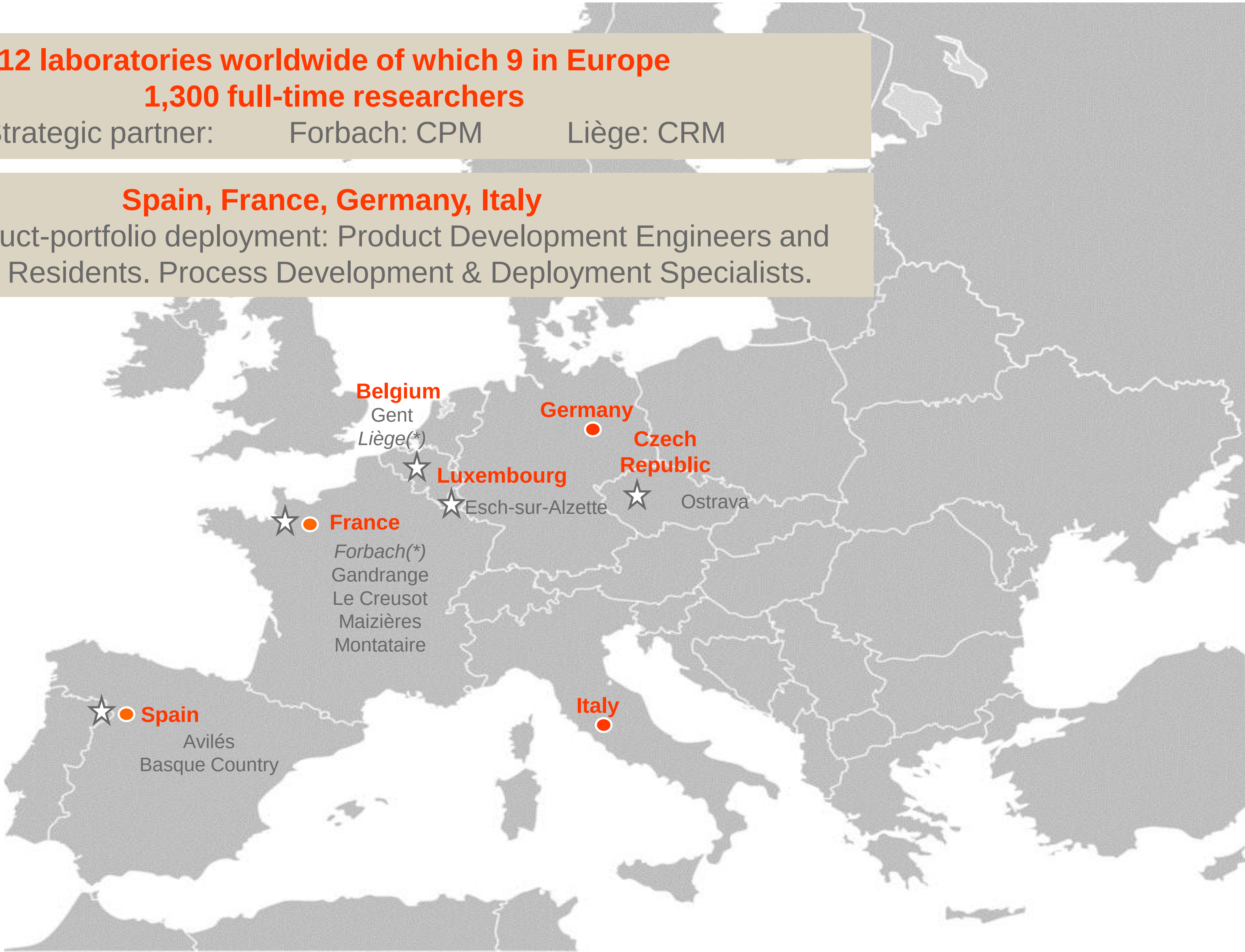
☆ **12 laboratories worldwide of which 9 in Europe**

1,300 full-time researchers

(*) Strategic partner: Forbach: CPM Liège: CRM

● **Spain, France, Germany, Italy**

On-site product-portfolio deployment: Product Development Engineers and Automotive Residents. Process Development & Deployment Specialists.



9/06/2017

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Markets

- Industry market, which includes:
  - appliances, mechanical construction and engineering, heavy plate, tubes and pipes, HVAC, radiators, drums, furniture, electro-magnetic applications, energy generation, transport and storage systems, off-shore applications etc.
  - Covering product mix from 0.2 to 300 mm

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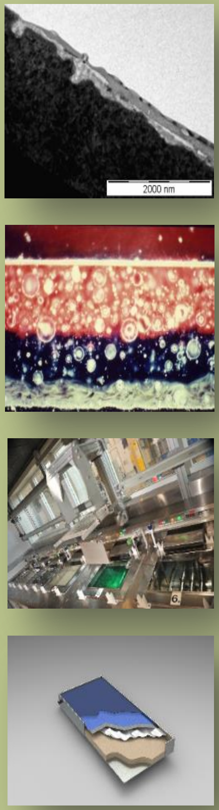
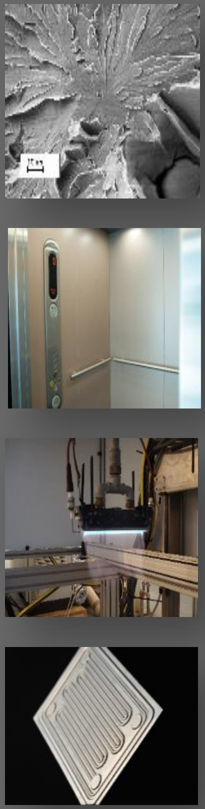
Energy

Durability

Environment



Technical Support & Entrepreneurial R&D



Metallurgy

Surfaces

Applications & Solutions

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Facts 2016

140
employees

40
trainees

25
scientific papers

15
nationalities

13
PhD students & post-docs

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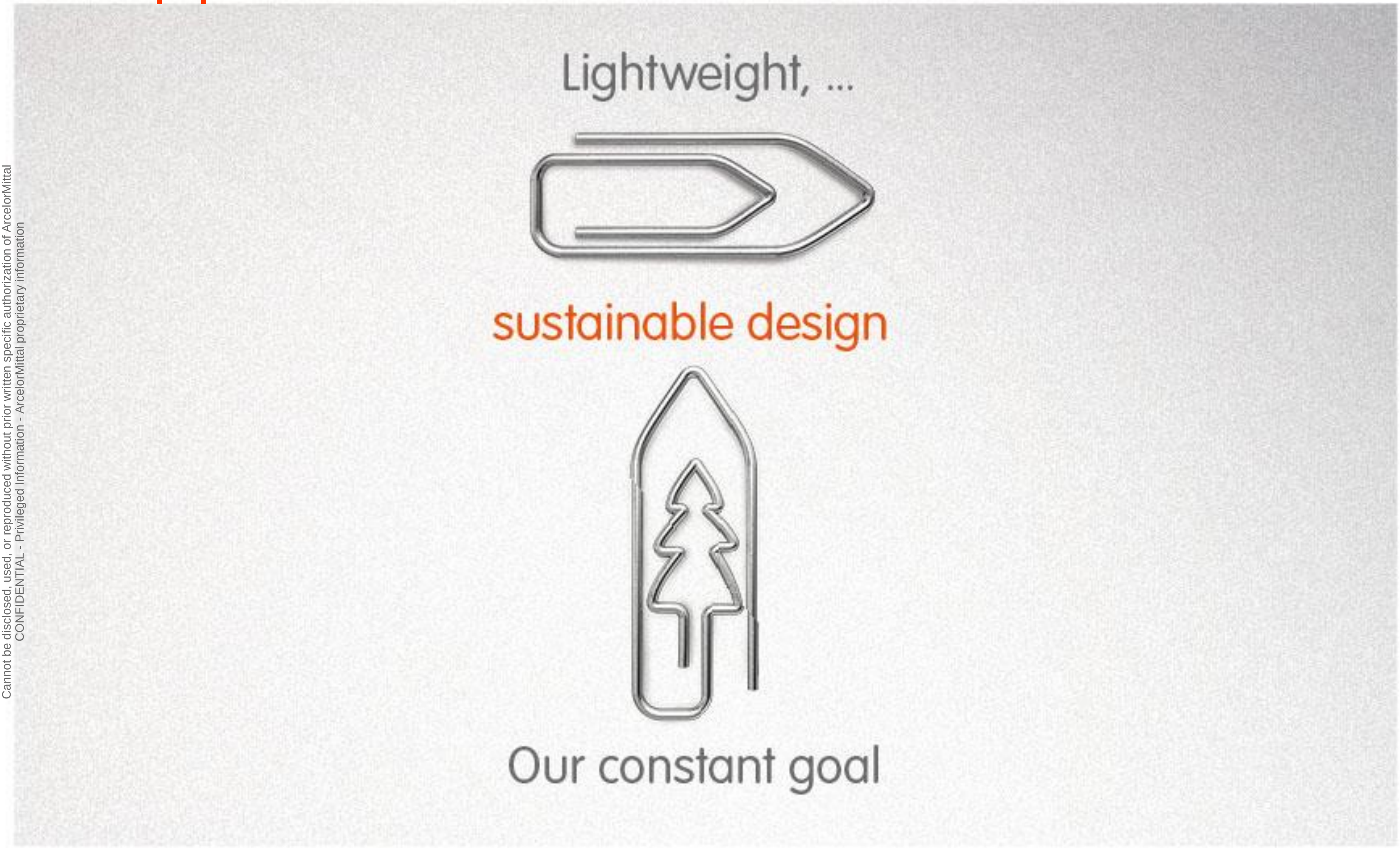
Sites

Site Zelzate
Pres. J. F. Kennedylaan 3
B-9060 Zelzate
BELGIUM

Site Zwijnaarde
Technologiepark 903B and 935
B-9052 Zwijnaarde
BELGIUM

+ 32 9 345 12 11
services@ocas.be
www.ocas.be

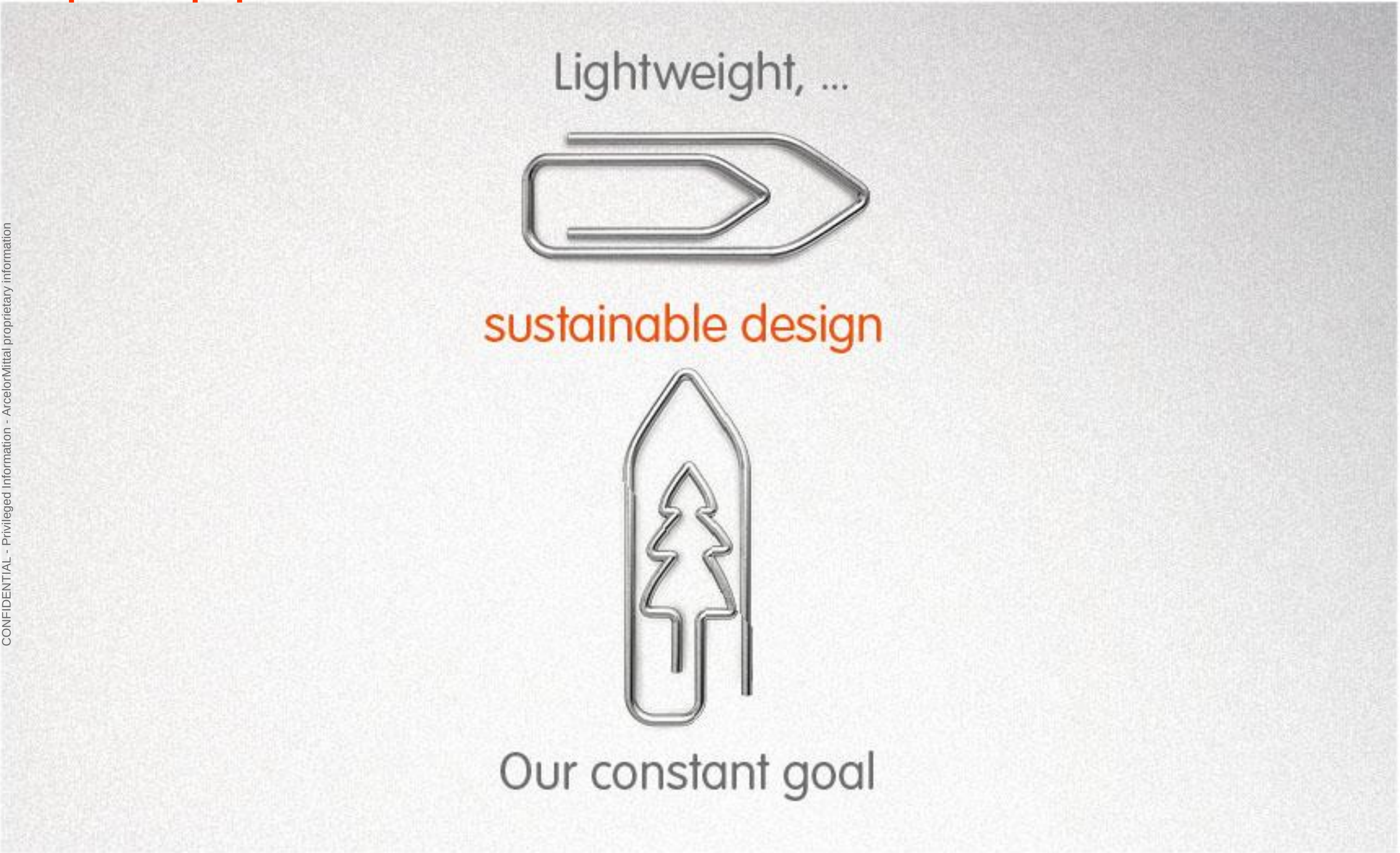
Modelling of plastic material behavior in line pipe



Modelling of plastic material behavior in line pipe

- Two applications:
  - Prediction of mechanical properties on spiral pipe
  - Prediction of ovalization during reel-lay of seamless pipes

Prediction of mechanical properties on spiral pipe



Large diameter pipes

- Large diameter (coated) steel pipes:
  - Cost effective transport of oil and gas
  - Different types:
    - HSAW: spirally welded pipes
    - LSAW: longitudinally welded pipes
  - Steel grades:
    - X42 (YS = 290 MPa) to X100 (YS = 690 MPa)
  - Large European projects:
    - TANAP
    - TAP

Image courtesy of: Nabucco Gas Pipeline International GmbH

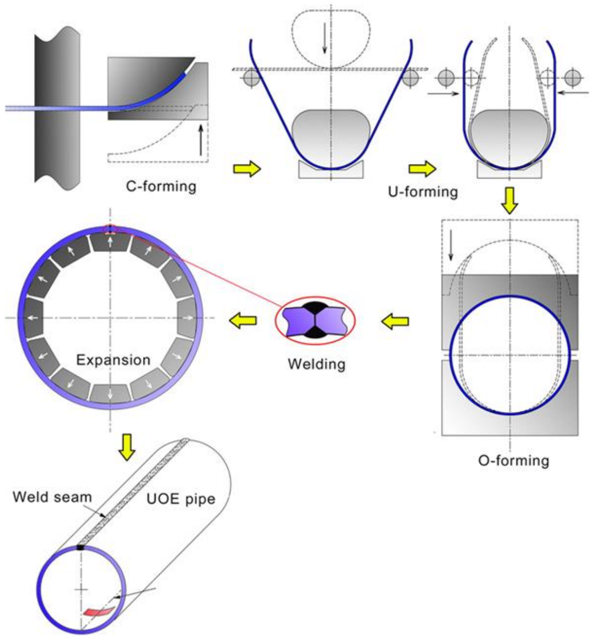
Large European linepipe projects

- TANAP: Trans-Anatolian Natural Gas Pipeline
  - Natural gas pipeline from Georgia through Turkey to Greece
  - ±1850 km; > 1 Mt of steel
  - Capacity: 16 bcm/year to 31 bcm/year
- TAP: Trans Adriatic Pipeline
  - Natural gas pipeline from Greek-Turkish border through Greece, Albania and Adriatic Sea to Southern Italy
  - ±880 km; > 400 kt of steel
  - Capacity: 10 bcm/year to 20 bcm/year

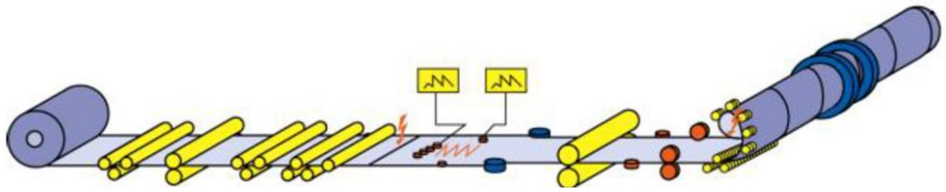
HSAW vs LSAW

- LSAW pipe:
  - Produced from plate
  - Different production routes: roll bending, UOE, JCOE
  - Typical dimensions:
    - OD: 406.4 mm (16”) to 1524 mm (60”)
    - WT: 6.4 mm (0.25”) to 45 mm (1.77”)
- HSAW pipe:
  - Produced from coil (continuous process!)
  - Production process: 3-roll forming
  - Typical dimensions:
    - OD: 508 mm (20”) to 3048 mm (120”)
    - WT: 5.2 mm (0.203”) to 25.4 mm (1”)

UOE forming*



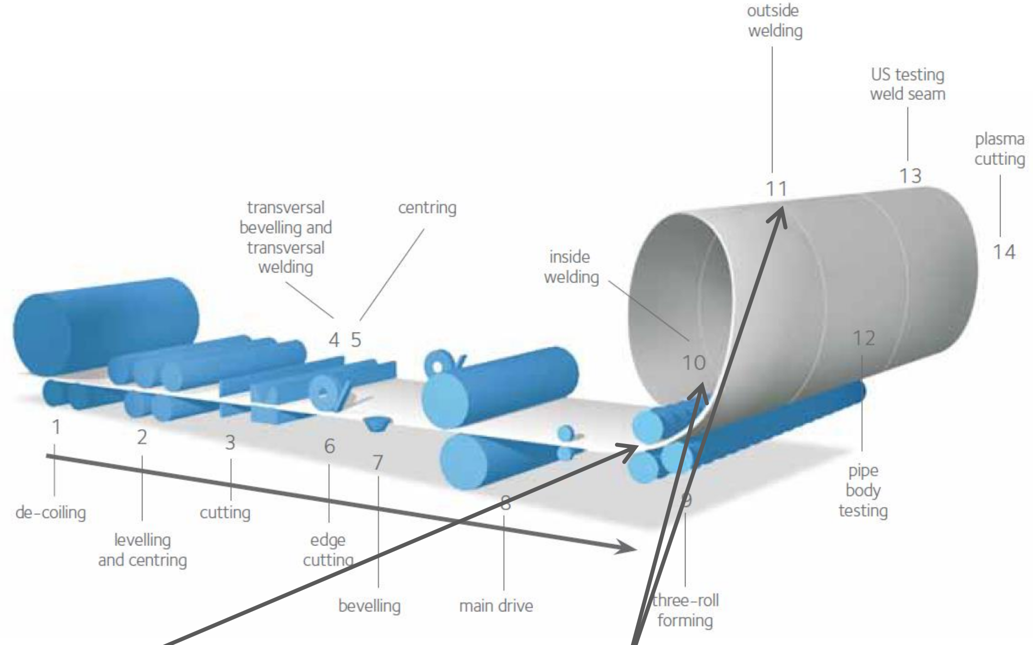
Spiral pipe forming**

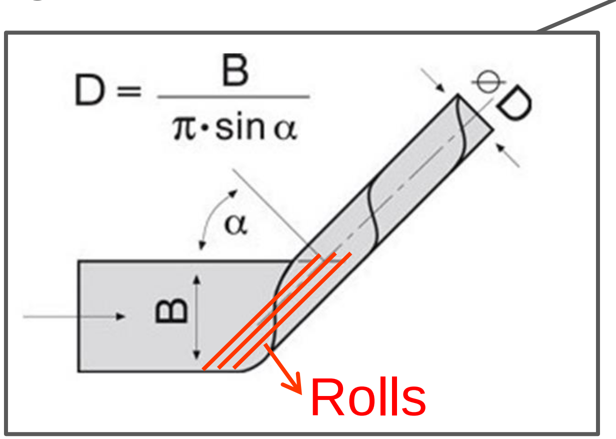


*T. Zou et al., “Yield strength development from high strength steel plate to UOE pipe”, Materials and Design, Vol. 89, 2016
** F.M. Knoop et al., “Production of Helical Two Step Pipe”, 2013 Charles Hatchett Seminar, July 2013, London, UK

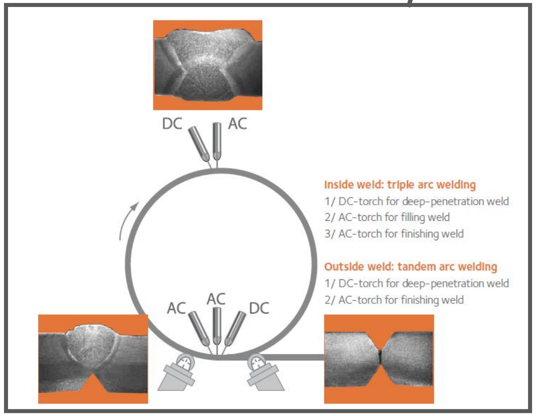
Spiral pipe forming
Production process

- Main production steps:
  - Decoiling and levelling
  - Bevelling (edge preparation for welding)
  - 3-roll forming (coil enters under a certain angle)
  - Inside and outside welding
  - Hydrotesting





$$D = \frac{B}{\pi \cdot \sin \alpha}$$



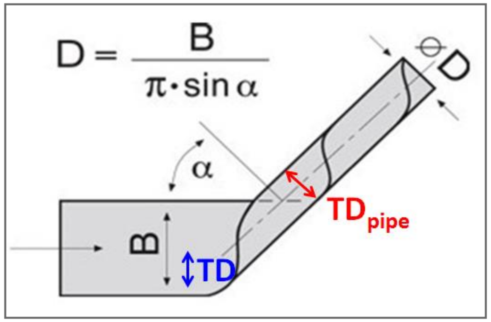
Inside weld: triple arc welding
1/ DC-torch for deep-penetration weld
2/ AC-torch for filling weld
3/ AC-torch for finishing weld

Outside weld: tandem arc welding
1/ DC-torch for deep-penetration weld
2/ AC-torch for finishing weld

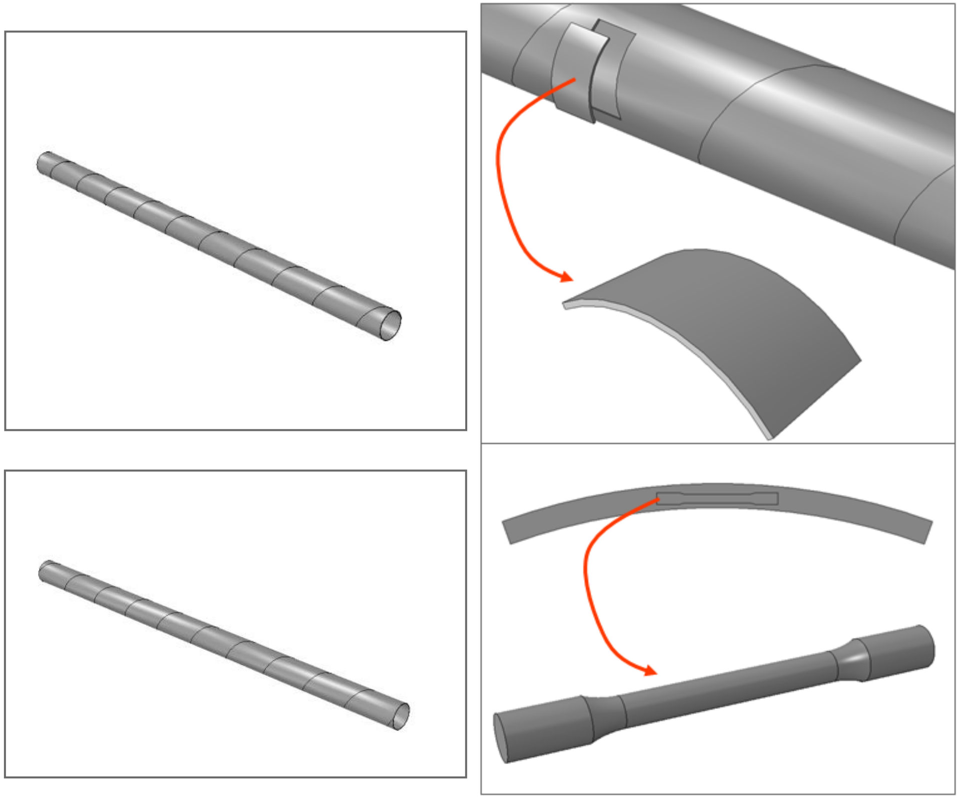
Spiral pipe forming
Measurement of mechanical properties

- The mechanical properties have to be measured along the transverse direction on pipe (TD_{pipe}), i.e. the hoop direction.

- Three measurement methodologies:
  - Ring expansion testing
  - Tensile tests on non-flattened round bar samples
  - Tensile tests on flattened, full-thickness samples



$$D = \frac{B}{\pi \cdot \sin \alpha}$$



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Spiral pipe forming

- Spiral pipe forming obviously affects mechanical properties as the material experiences a rather complex deformation history – including several strain reversals – when transforming a coil into a pipe.
- For higher strength steels, the yield strength on pipe is typically lower than the yield strength on coil: $R_{t0.5_{TD_{pipe}}} < R_{t0.5_{TD_{coil}}}$
- Steel makers only guarantee properties on coil, while pipe makers have to reach specified minimum values on pipe.

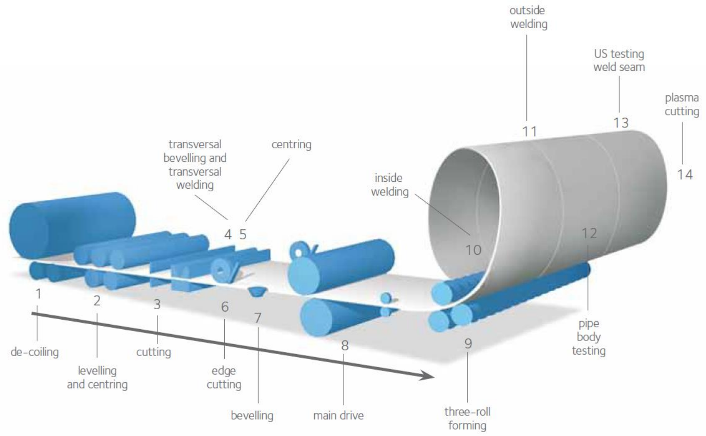
→ How do mechanical properties evolve during spiral pipe forming?

→ Which properties are required on coil to obtain the desired strength on pipe?

⇨ FE model to simulate spiral pipe forming and to predict mechanical properties on pipe

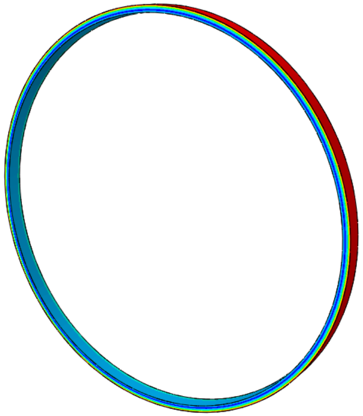
Spiral pipe forming

FE model

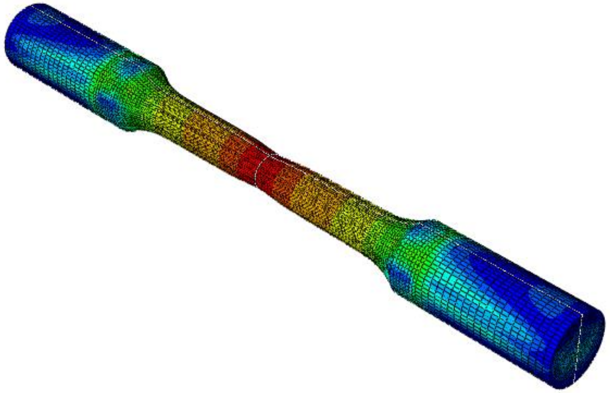


- Approach:
  - Spiral pipe forming mainly involves bending deformation:
    - Decoiling and levelling
    - 3-roll forming
    - Flattening
  - It is assumed that these steps can be simulated as pure bending under plane strain conditions
  - A separate model is used for each step. The material state (stresses, strains, …) obtained at the end of one simulation is imposed as initial condition when simulating the next step.
  - FE software: Abaqus

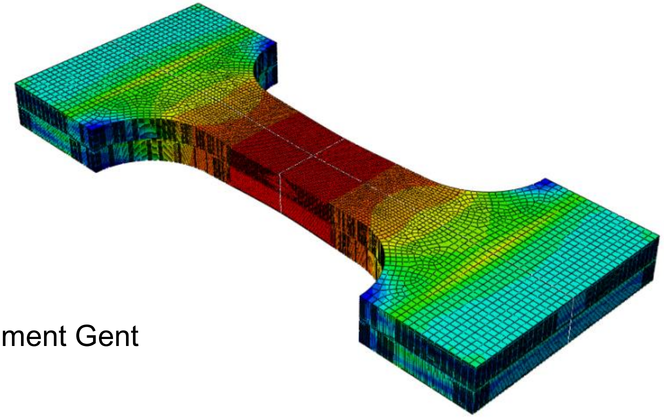
Mechanical testing after pipe forming
FE model



- Mechanical testing after pipe forming
  - Ring expansion test
  - Tensile test on non-flattened round bar samples



- Mechanical testing after pipe flattening:
  - Tensile test on flattened, full-thickness sample

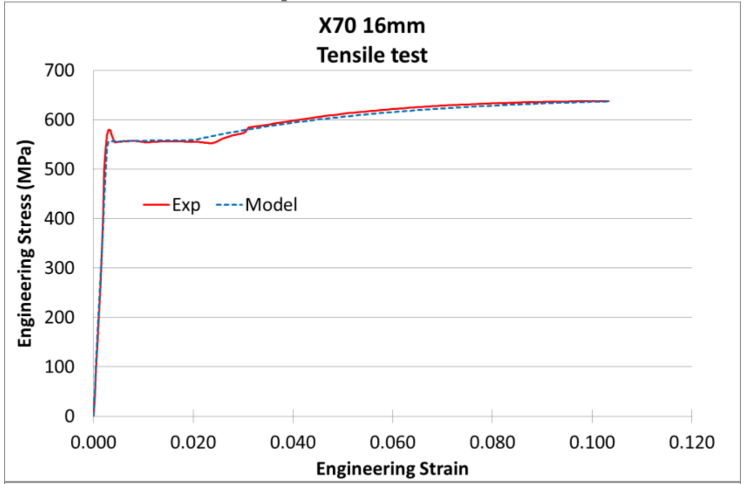


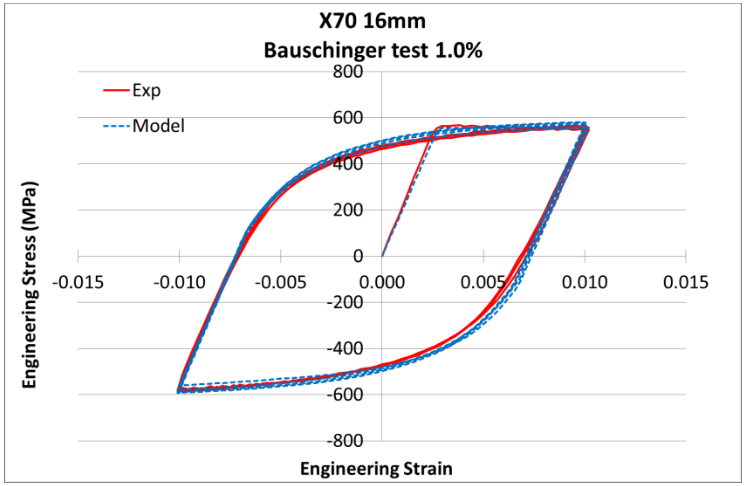
FE model
Mechanical material behaviour

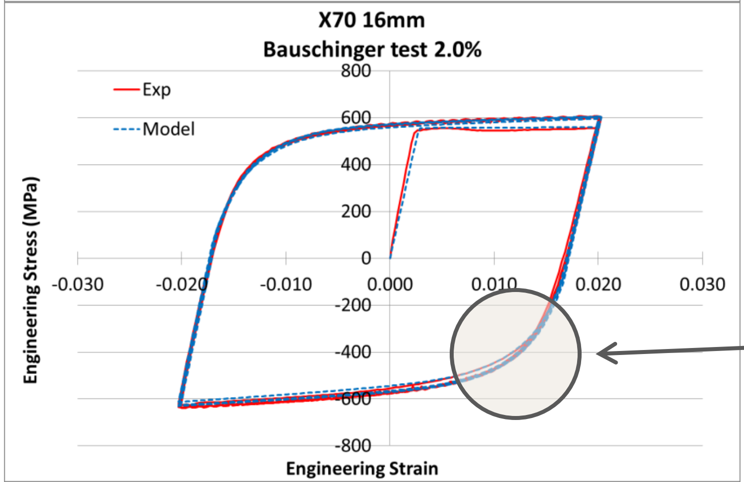
- To accurately predict the mechanical properties on pipe, one needs a constitutive model capable of describing the cyclic stress-strain behaviour:
  - Von Mises yield surface
  - Combined non-linear kinematic-isotropic hardening model
    - Lemaître-Chaboche model for kinematic hardening:
      - $\alpha_{ij} = \sum_k \alpha_{ij}^k$
      - $\dot{\alpha}_{ij}^k = \frac{C_k}{\sigma_y}(\sigma_{ij} - \alpha_{ij})\dot{\varepsilon}_{eq}^{pl} - \gamma_k \alpha_{ij}^k \dot{\varepsilon}_{eq}^{pl}$

FE model
Mechanical material behaviour

- Material parameter calibration







- **Good agreement between model and experimental data**
- Model can capture yield plateau and Bauschinger phenomenon
- Cyclic tension-compression tests:

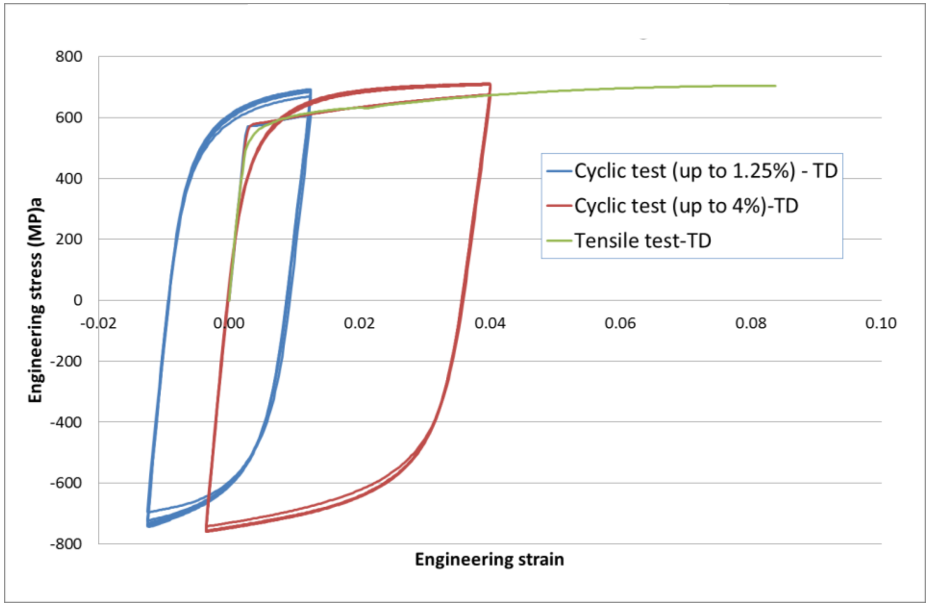
{
  - Early re-yielding
  - Transient behaviour
  - Barely any cyclic hardening

Validation of FE model
Case study 1

- Pipe dimensions:
  - 48” x 23.7 mm SAWH pipe
  - Pipe forming angle: 28°
- Steel grade: X80
- Mechanical testing on pipe (experimental results):
  - Ring expansion tests
  - Tensile tests on flattened samples (flattening via 4-point bending)

Base material properties (TD):

- R_{t05}: 580 MPa to 610 MPa
- Continuous yielding



Validation of FE model

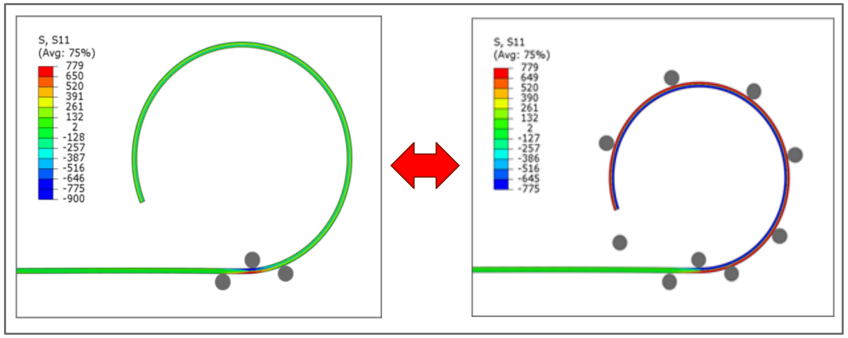
Case study 1

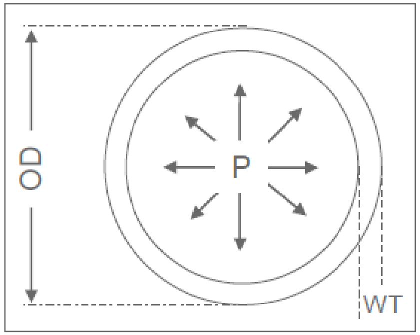
- The actual pipe forming conditions were not known. Therefore different conditions were simulated.
  - Residual stress level after 3 roll forming

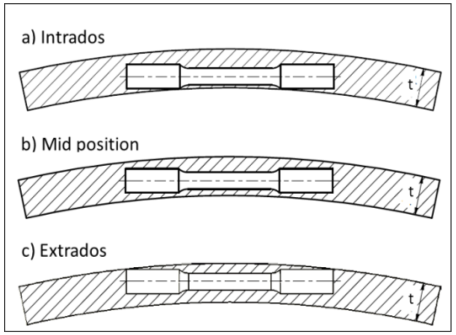
    → Two extreme conditions were simulated.
  - Pressure applied during hydrotesting

$$P = \frac{2 \times S \times WT}{OD}$$

  - Position of round bar sample in wall thickness







Validation of FE model

Case study 1

- Analysis: Predicted drop vs. measured drop

$$\Delta R_{t0.5} = (R_{t0.5})_{TD_{pipe}} \text{-} (R_{t0.5})_{TD_{coil}}$$

  - Good agreement between FEA and experimental results for tests on flattened, full-thickness samples
  - More difficult to draw conclusions for ring expansion tests, as one can observe a large effect of the amount of springback (and thus the residual stress level) after 3-roll forming on the resulting R_{t05}

ΔRt05 (MPa)		FE results						Experimental results	
		No springback			Springback			Max	Min
		NoHydro	Hydro90%	Hydro100%	NoHydro	Hydro90%	Hydro100%		
Ring Expansion		-75	-34	-22	-26	-14	-7	-39	-11
Flattened full-thickness sample	Extrados	-41	-41	-39	-39	-40	-39	-44	-33
	Intrados	-47	-45	-44	-43	-44	-43		
	Average Ex-In	-44	-44	-42	-41	-42	-42		
Round bar	Extrados	-28	-4	0	-18	-7	-8		
	Mid	-42	-41	-35	-42	-42	-44		
	Intrados	-96	-106	-95	-105	-89	-79		

Validation of FE model

Case study 1

- Analysis FE results
  - Hydrotesting and the amount of springback (after 3-roll forming) significantly affect the yield strength measured via ring expansion testing

    ➔ Drop of $R_{t0.5}$ is smaller when residual stress is lower (after hydro and/or springback)

  - In general, the yield strength resulting from a ring expansion test is above the yield strength resulting from tests on flattened full-thickness samples.

    ➔ Results on flattened samples are conservative

  - The yield strength measured by means of round bar samples largely depends on the actual through thickness position at which the sample is taken.

ΔRt05 (MPa)		FE results						Experimental results	
		No springback			Springback			Max	Min
		NoHydro	Hydro90%	Hydro100%	NoHydro	Hydro90%	Hydro100%		
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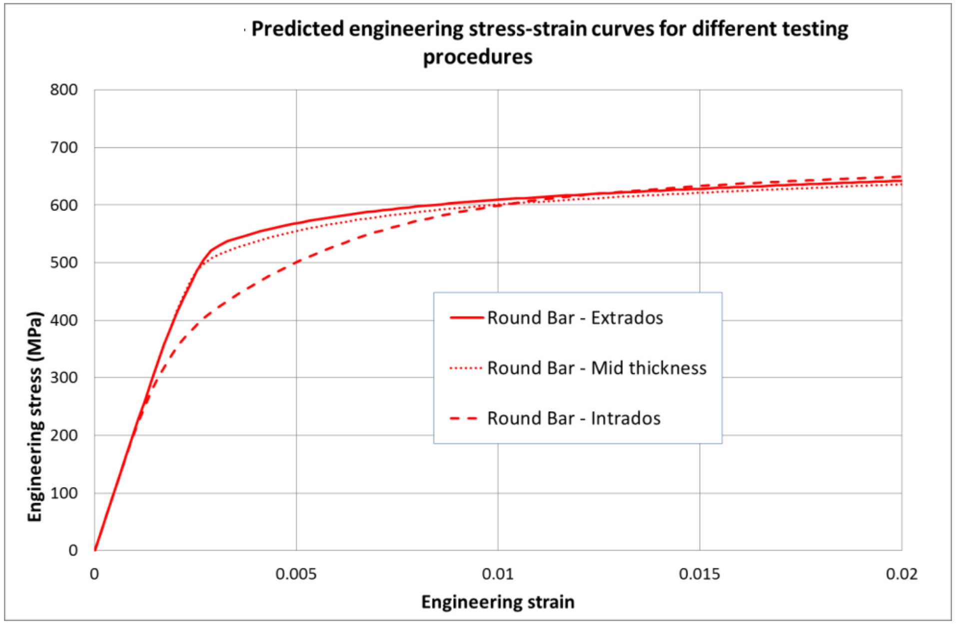
	Mid	-42	-41	-35	-42	-42	-44		
	Intrados	-96	-106	-95	-105	-89	-79		

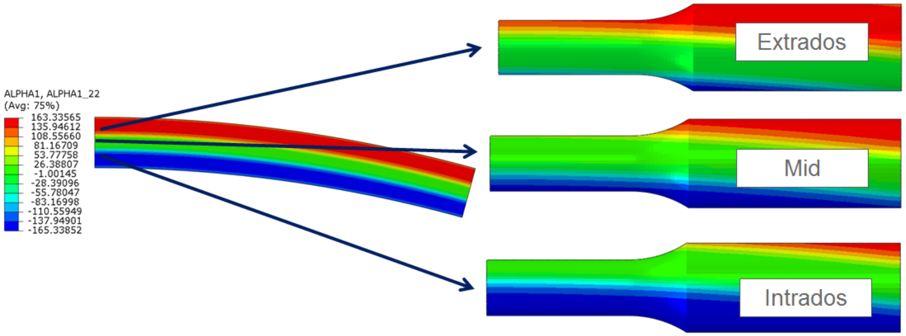
Validation of FE model
Case study 1

- Analysis FE results: effect of position of round bar samples in wall thickness on resulting yield strength:
  - Intrados side:
    - loaded in compression during pipe forming

    ➔ sample taken at Intrados side suffers from Bauschinger effect during tensile testing
  - Extrados side:
    - loaded in tension during pipe forming

    ➔ sample taken at Extrados side does not show any Bauschinger effect during tensile testing



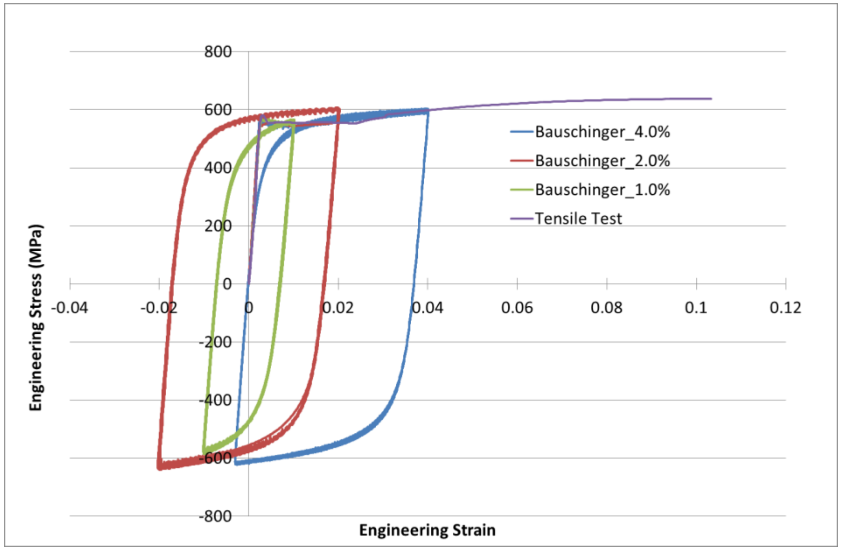


Validation of FE model
Case study 2

- Pipe dimensions:
  - 36” x 16 mm SAWH pipe, pipe forming angle = 41°
  - 28” x 16 mm SAWH pipe, pipe forming angle = 58°
- Steel grade: X70
- Mechanical testing on pipe (experimental results):
  - After pipe forming:
    - Tensile tests on non-flattened round bar samples
    - Tensile tests on full thickness samples oriented along LD_{pipe} (not flattened)
  - After pipe flattening
    - Tensile tests on flattened samples (flattening via 4-point bending)

Base material properties (TD):

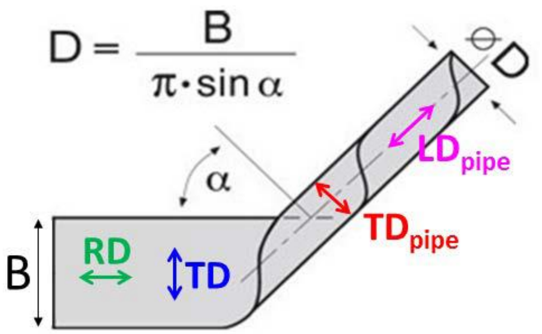
- R_{t05}: 535 MPa to 570 MPa
- Yield plateau



Validation of FE model

Case study 2

- Analysis: predicted $R_{t0.5}$ vs measured $R_{t0.5}$
  - The FE model provides accurate predictions for the properties along TD_{pipe}, both after pipe forming and pipe flattening.
  - However, the numerical model considerably underestimates the properties along LD_{pipe}.



$R_{t0.5}$ (MPa)	Direction		28" x 16 mm	36" x 16 mm
After pipe forming	FEA (LD_{pipe})		477	484
	Experiment (LD_{pipe})	Min	532	535
		Max	547	551
	FEA (Round bar tension TD_{pipe})	Intrados	443	453
		Mid thickness	482	503
		Extrados	517	529
	Experiment (Round bar tension TD_{pipe})	Min	474	470
		Max	478	481
After pipe flattening	FEA (TD_{pipe})		492	491
	Experiment (TD_{pipe})	Min	498	479
		Max	499	493

Prediction of mechanical properties on spiral pipe

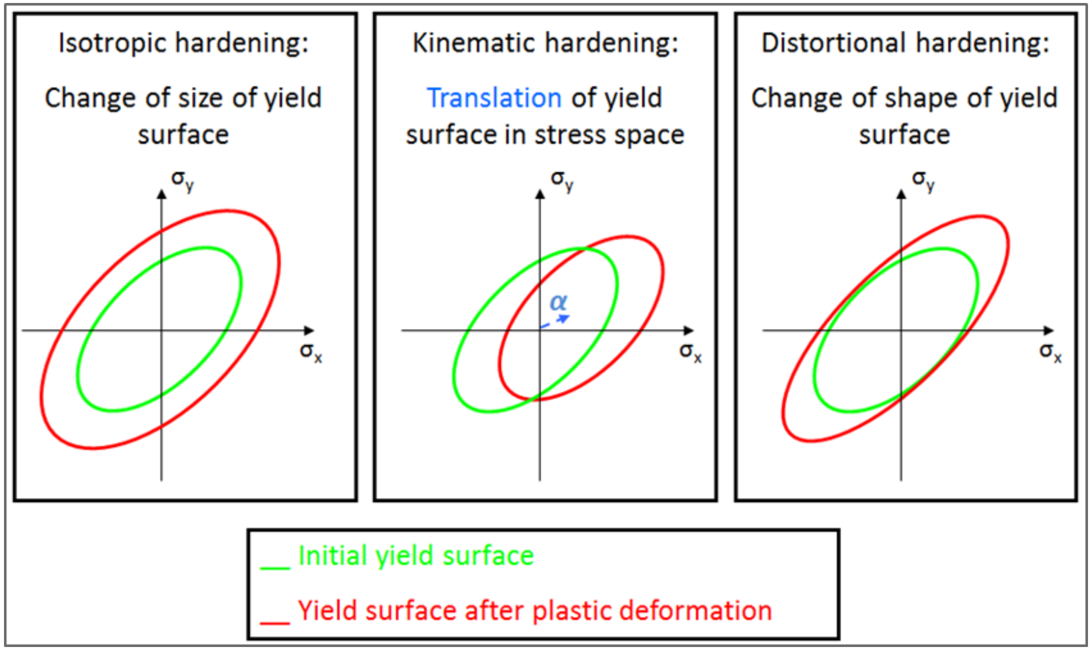
Conclusions and future work

- Conclusions:
  - A numerical model capable of simulating spiral pipe forming and subsequent mechanical testing has been presented.
  - The model provides quite accurate predictions for the mechanical properties along the transverse direction on pipe (TD_{pipe}), but fails to predict the properties along the longitudinal direction (LD_{pipe}).
- Future work:
  - A more advanced constitutive model, more specifically the Levkovitch-Svendsen model, has been implemented in Abaqus by means of a UMAT subroutine.
  - The simulations will be rerun, using this model, to verify if we manage to get more accurate predictions for the longitudinal direction.

Levkovitch-Svendsen model

- The Levkovitch-Svendsen model accounts for isotropic, kinematic and distortional hardening

  → this model can describe cross-hardening



Isotropic hardening:

Change of size of yield surface

Kinematic hardening:

Translation of yield surface in stress space

Distortional hardening:

Change of shape of yield surface

🟩 Initial yield surface

🟥 Yield surface after plastic deformation

Levkovitch-Svendsen model

- Constitutive model:
  - Yield criterion:

$$\sigma_{eq} = \sqrt{(\boldsymbol{\sigma}^{dev} - \boldsymbol{\alpha}^{dev}) : (\boldsymbol{M} + \boldsymbol{H}) : (\boldsymbol{\sigma}^{dev} - \boldsymbol{\alpha}^{dev})}$$

    - $\boldsymbol{\sigma}^{dev}$: deviatoric part of 2nd order Cauchy stress tensor
    - $\boldsymbol{\alpha}^{dev}$: deviatoric part of 2nd backstress tensor
    - $\boldsymbol{M}$: 4th order tensor, describing initial anisotropy
    - $\boldsymbol{H}$: 4th order tensor, describing aniostropy evolution
  - Associative flow rule:

$$\boldsymbol{D}^{pl} = \dot{\lambda} \frac{\partial \Phi}{\partial \boldsymbol{\sigma}^{dev}}$$

Levkovitch-Svendsen model

- Constitutive model:
  - Hardening behaviour
    - Backstress tensor: Lemaître-Chaboche hardening law

$$\dot{\boldsymbol{\alpha}} = C_x\left(X_{sat}\boldsymbol{D}^{pl} - \boldsymbol{\alpha}\dot{\lambda}\right) = \dot{\lambda}C_x\left(X_{sat}\frac{\partial \Phi}{\partial \boldsymbol{\sigma}^{dev}} - \boldsymbol{\alpha}\right)$$

- Distortional hardening tensor:

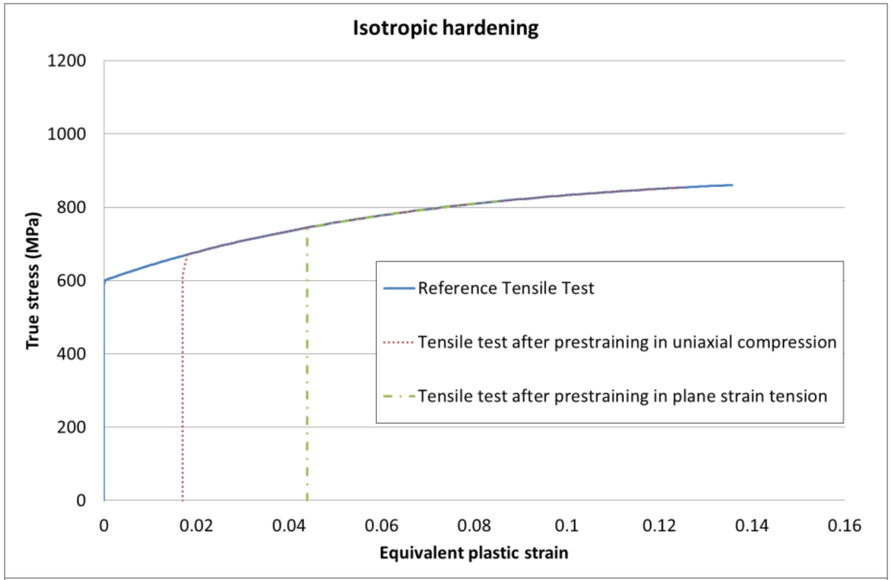
$$\dot{\boldsymbol{H}} = \dot{\lambda}C_D(D_{sat} - H_D)\boldsymbol{N}\otimes\boldsymbol{N} + \dot{\lambda}C_L\left[L_{sat}(\boldsymbol{I}_{dev} - \boldsymbol{N}\otimes\boldsymbol{N}) - \boldsymbol{H}_L\right]$$

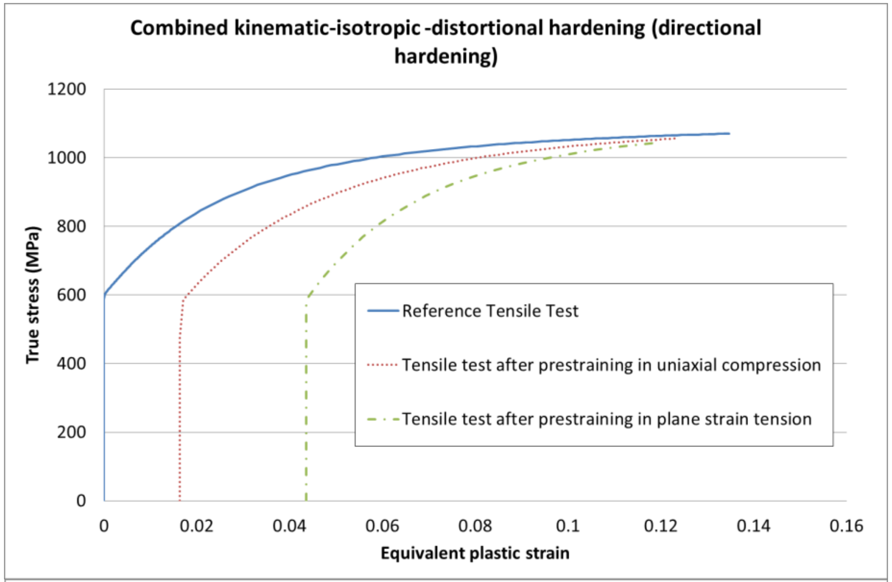
Directional hardening

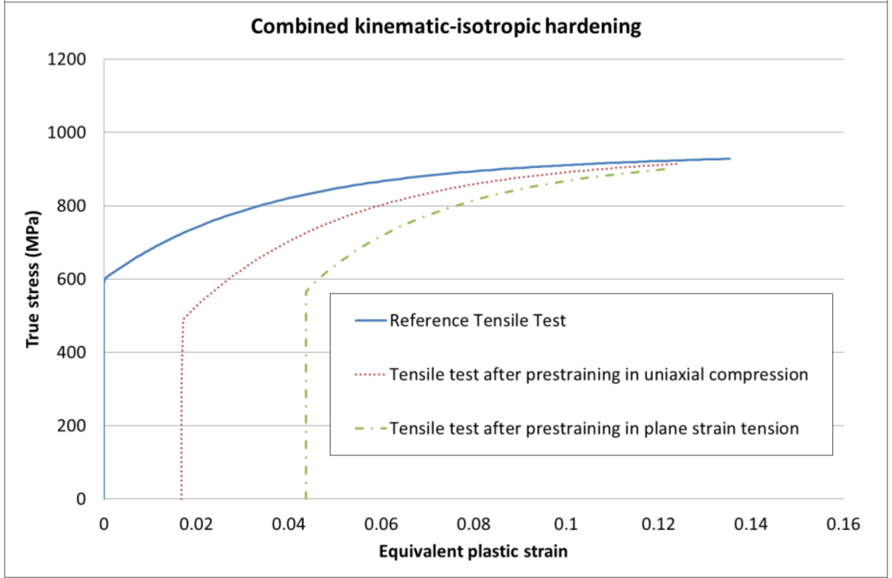
Latent hardening

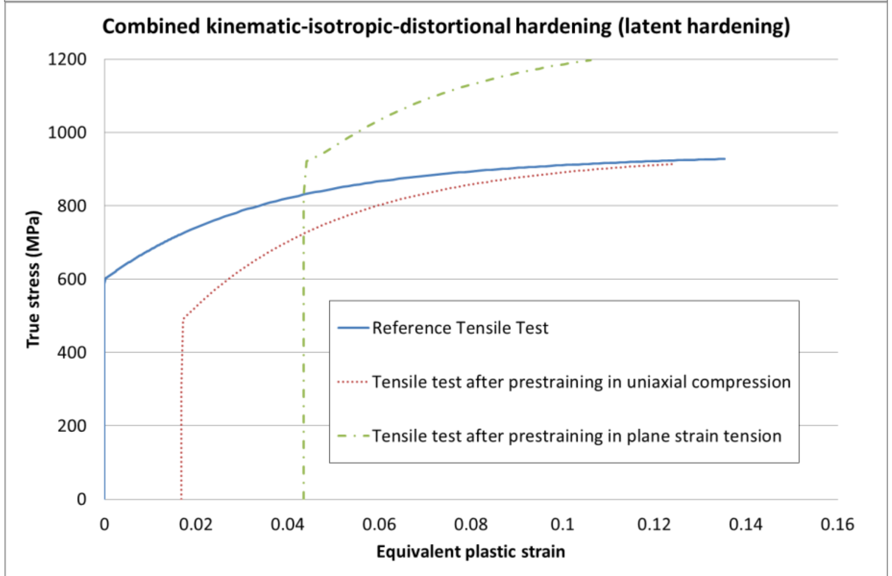
- $\boldsymbol{N}$: 2nd order unit tensor // $\boldsymbol{D}^{pl}$
- $\boldsymbol{N}\otimes\boldsymbol{N}$: 4th order tensor
- H_D: projection of $\boldsymbol{H}$ on $\boldsymbol{N}\otimes\boldsymbol{N} \rightarrow H_D = H_{ijkl}N_{ij}N_{kl}$
- $\boldsymbol{H}_L = \boldsymbol{H} - H_D\boldsymbol{N}\otimes\boldsymbol{N}$
- $\boldsymbol{I}_{dev}$: deviatoric 4th order unit tensor

Levkovitch-Svendsen model
Predicted behaviour

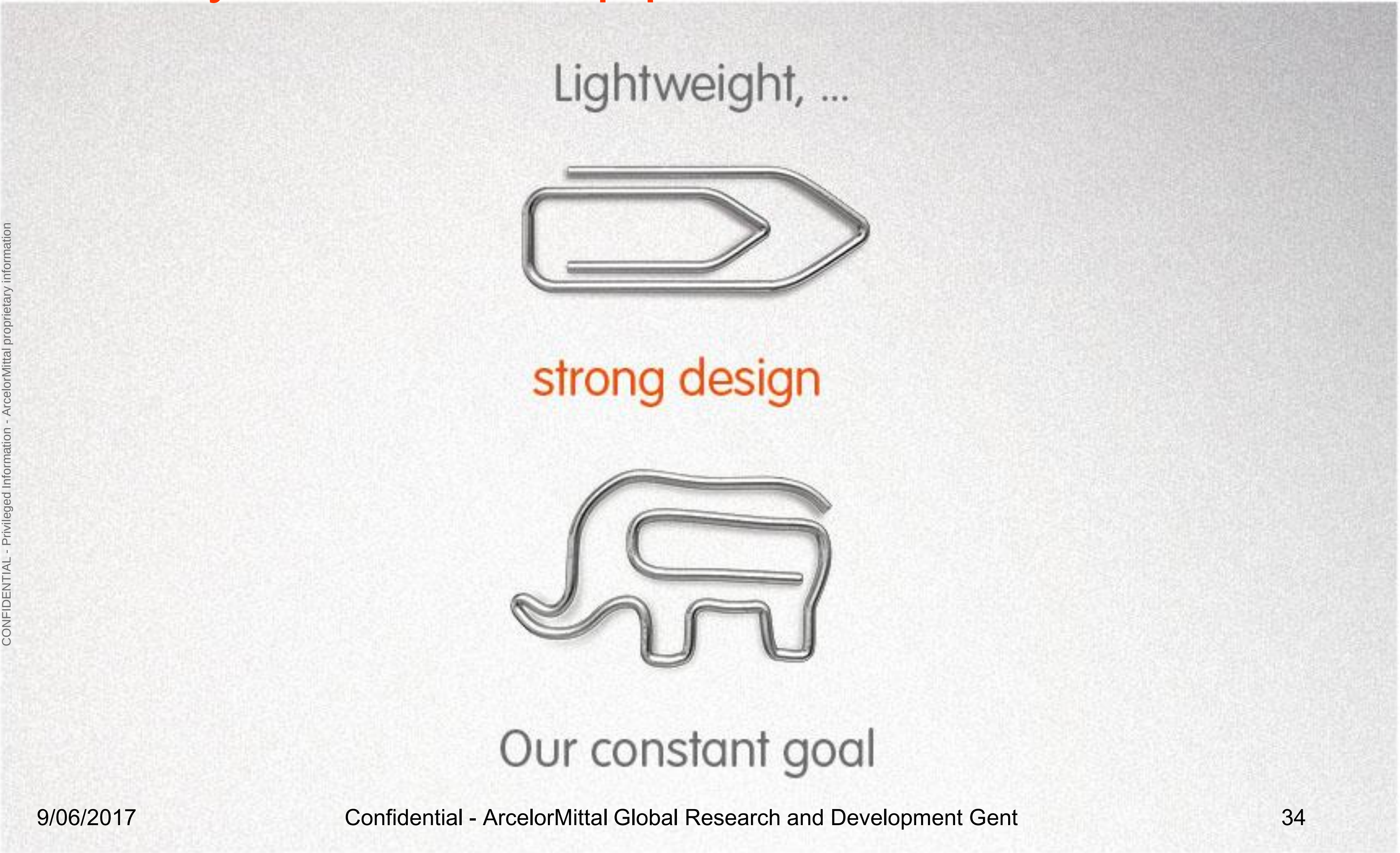

Isotropic hardening


Combined kinematic-isotropic -distortional hardening (directional hardening)


Combined kinematic-isotropic hardening


Combined kinematic-isotropic-distortional hardening (latent hardening)

Prediction of ovalization during reel-lay of seamless pipes



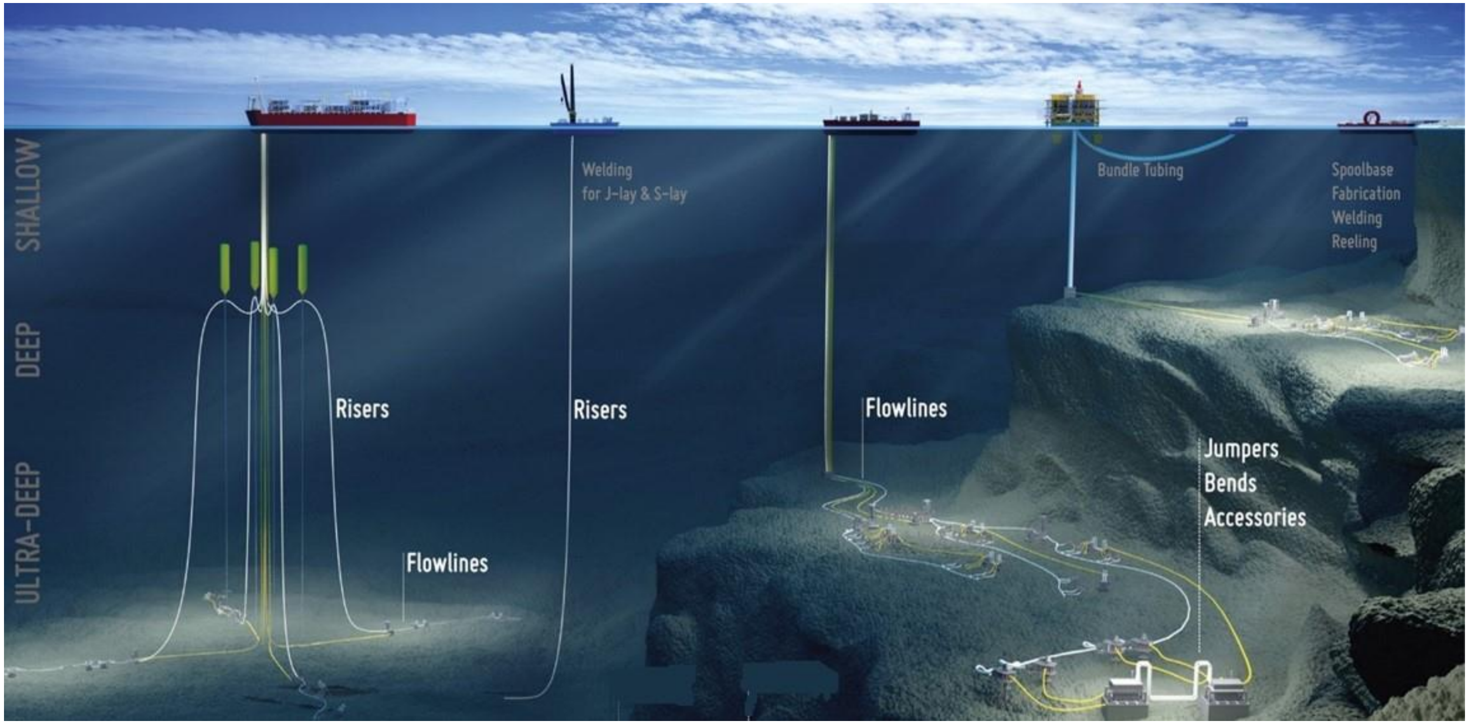
Prediction of ovalization during reel-lay of seamless pipes

ArcelorMittal

- Collaboration with Heerema Marine Contractors (HMC)
- Ocas:
  - Small scale testing
  - Calibration of material model
- HMC:
  - Large scale testing (partly outsourced to Heriot-Watt University)
  - FEA of reel-lay process

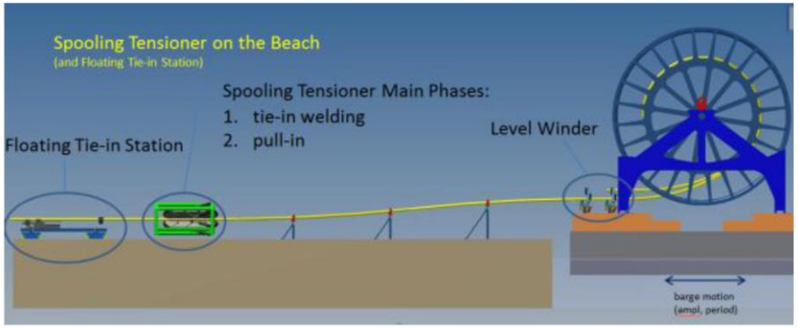
Flowlines and risers

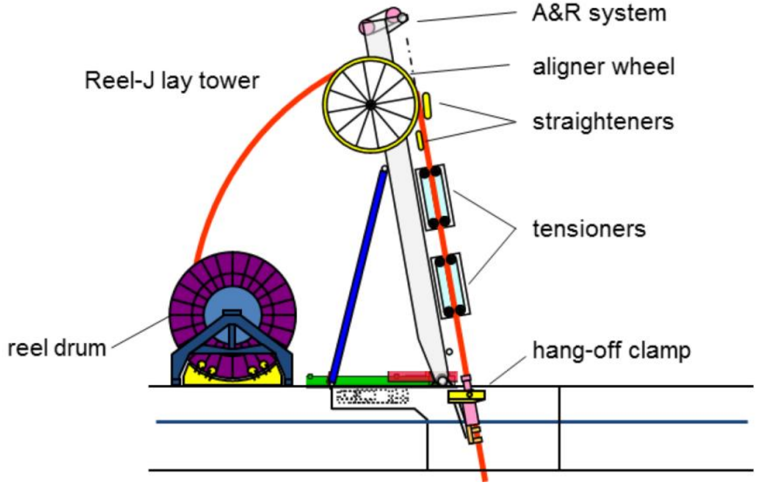
- Subsea flowlines and risers are used for the transportation of crude oil and gas from subsea wells to off-shore platforms and vesels and even to shore. They are also used to re-inject water and gas into the reservoir.



Installation of flowlines and risers

- Different installation methods: J-lay, S-lay, reel-lay, etc.
- Reel-lay:
  - Seamless pipes (typical OD: 6” to 16”, WT: 15 mm to 25 mm) are welded together on-shore and spooled onto a reel (inner radius ≥ 7.5 m).
  - This reel is then installed onto a vessel and unspooled to install the pipe string onto the seabed.
  - This procedure involves cyclic bending and induces plastic straining (2 % to 5 %).





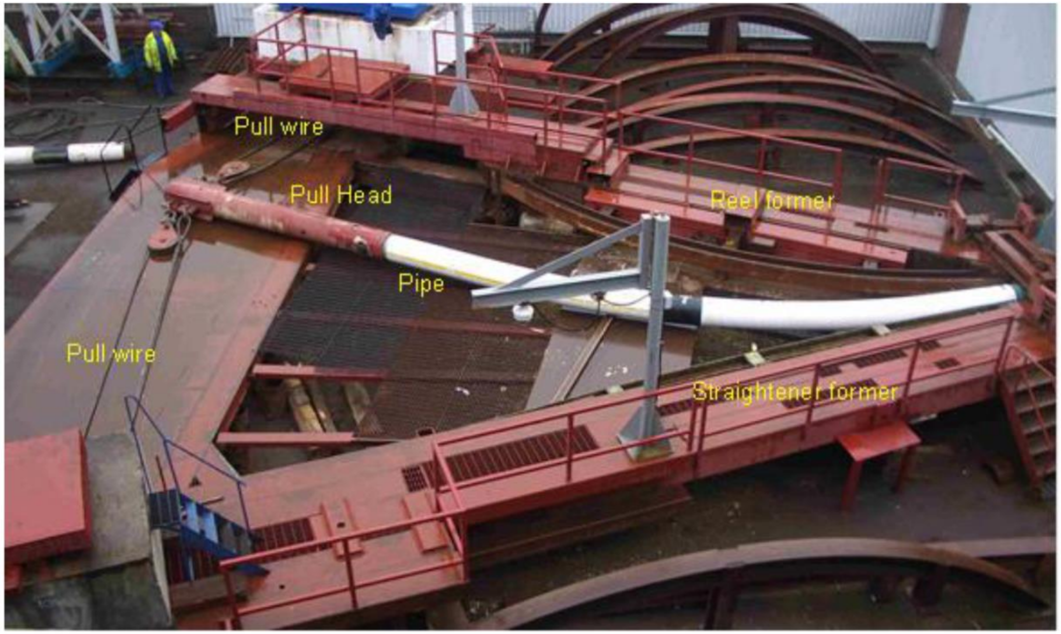
E. Karjadi et al., “Development on Aegir reeling pipeline analyses by test validation”, OMAE2013, June 9-14, 2013, Nantes, France

Ovalization during reel-lay of flowlines and risers

- As reel-lay introduces cyclic, plastic bending, the ovality of the pipe will evolve during installation.
- The level of residual ovality after reeling may be governing to prevent local buckling in the catenary sagbend when lowering the reeled pipe to the seabed or to avoid collapse in the case of deep water applications.
- Having an FE model, capable of predicting ovalization during reel-lay, would be helpful to optimize the reel-lay process and the pipe dimensions.

Large scale testing to simulate reel-lay process

- Large scale cyclic bending experiments performed at Heriot-Watt University (Edinburgh):
  - 16” x 21.4 mm X65 seamless pipe
  - Both ovality and strain are recorded during testing

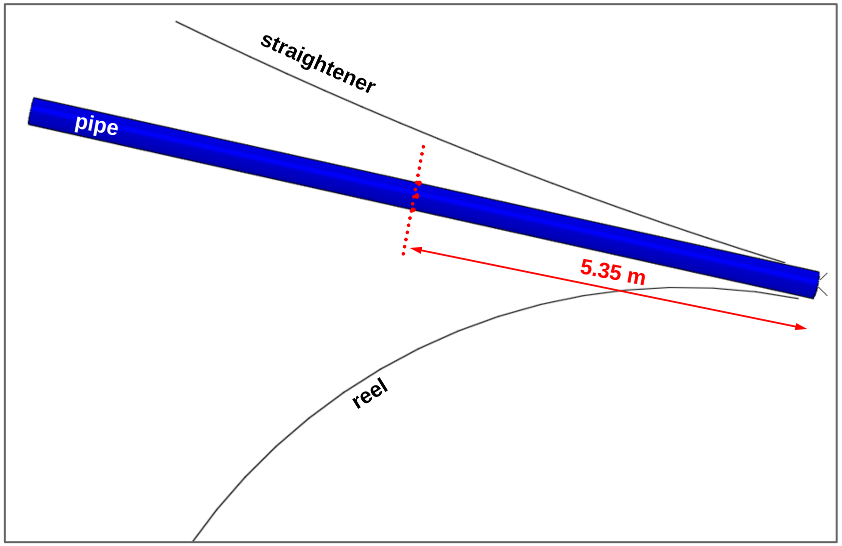


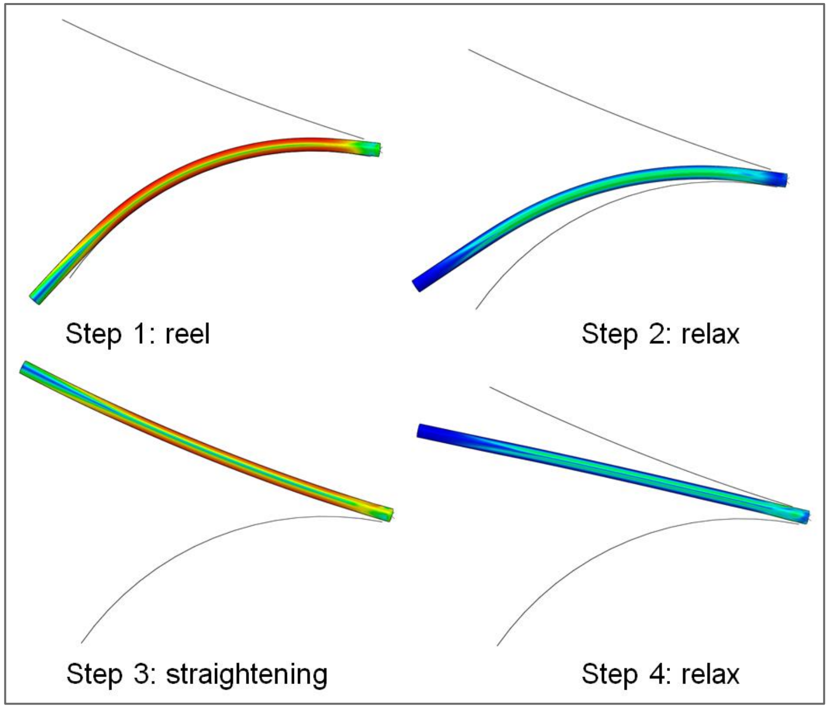
E. Karjadi et al., “Reeling pipeline material characterization – testing, material modeling and offshore measurement validation”, OMAE2015, May 31- June 5, 2014, St- John’s, Newfoundland, Canada

FE model

Setup

- Abaqus/Implicit
  - Pipe: shell (S4R) elements
  - Straightener and reel: rigid bodies



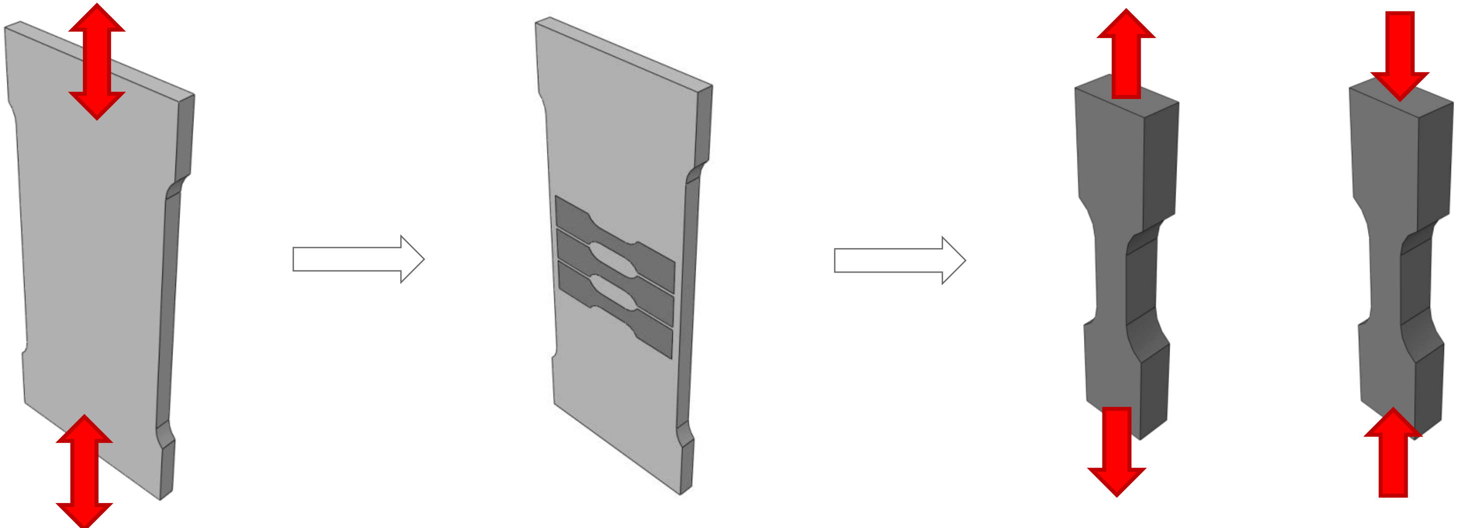


FE model
Constitutive model

- Different constitutive models were applied:
  - Von Mises yield criterion + isotropic hardening
  - Von Mises yield criterion + linear, kinematic hardening:
    - Ziegler hardening law
  - Von Mises yield criterion + non-linear kinematic-isotropic hardening:
    - Kinematic hardening: Lemaître-Chaboche type of model, 2 back stresses
  - Von Mises yield criterion + non-linear kinematic-isotropic hardening:
    - Kinematic hardening: Lemaître-Chaboche type of model, 2 back stresses
    - Isotropic hardening: yield surface shrinkage during initial plastic deformation to capture yield plateau
  - Levkovitch-Svendsen model:
    - Isotropic hardening: Voce equation
    - Kinematic hardening: Lemaître-Chaboche, 1 back stress
    - Distortional hardening

Experimental work
Calibration of constitutive model

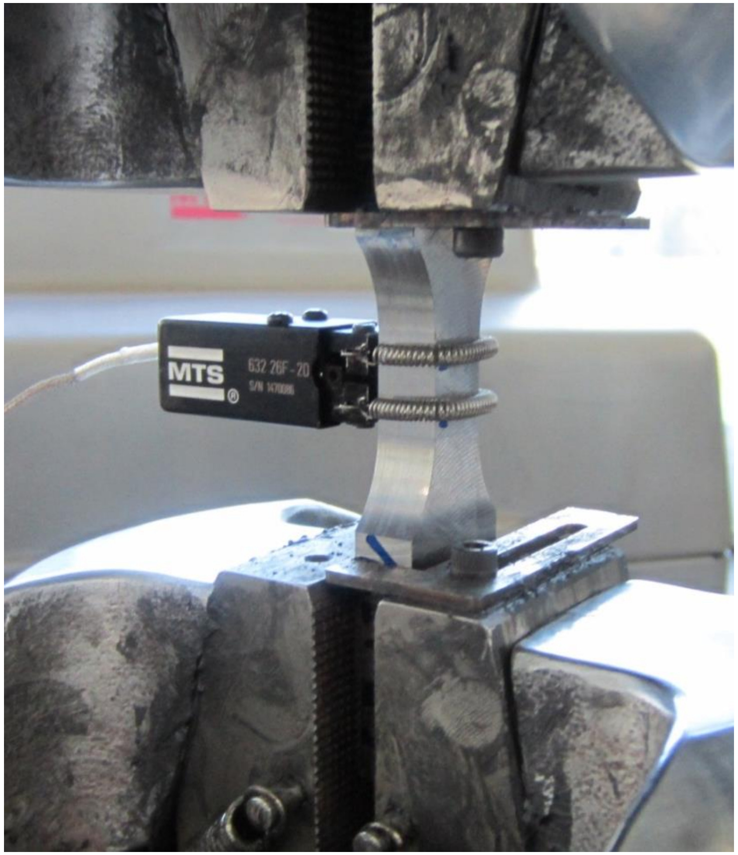
- Experiments performed to calibrate constitutive model:
  - Standard tensile tests along the pipe’s axial and transverse direction
  - Uni-axial tension compression tests with different strain amplitudes to quantify the Bauschinger effect
  - Tests with changing strain path, to measure cross-hardening behavior:
    - Pre-straining of large samples: tension, compression and cyclic tension/compression
    - Machining of small samples from large, pre-strained samples
    - Testing of small samples in tension and compression

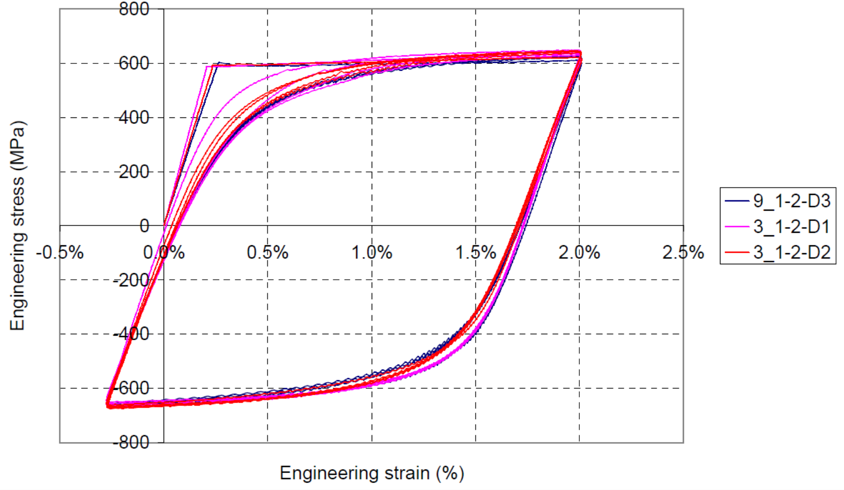


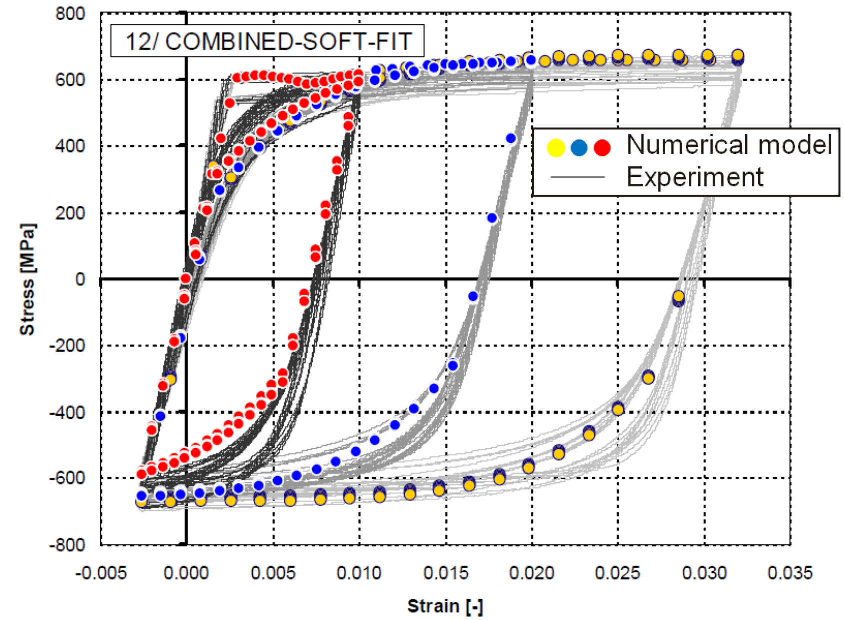
Experimental work

Calibration of constitutive model

- Uni-axial tension-compression tests:
  - Yield plateau
  - Significant Bauschinger effect



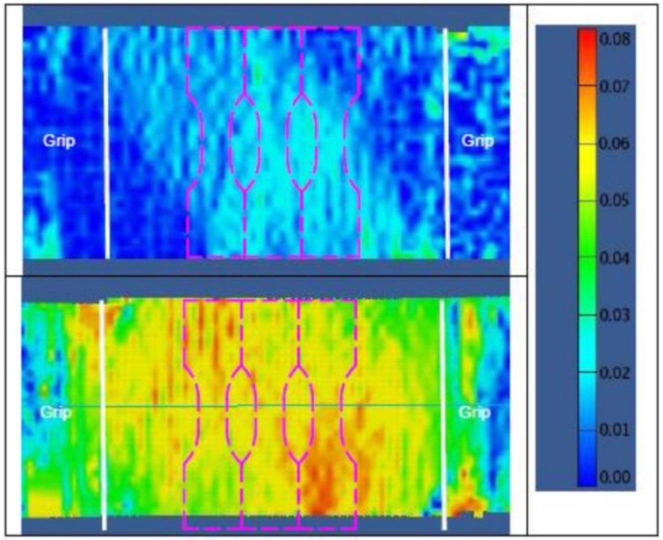


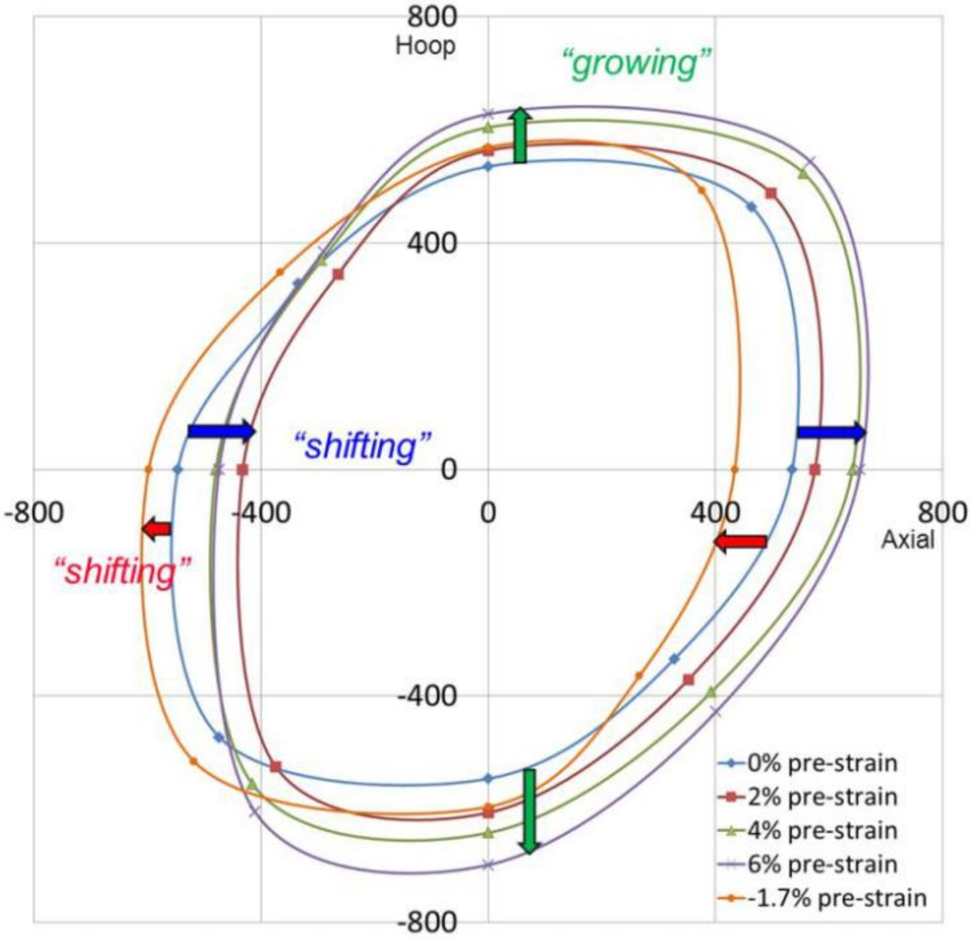


Non-linear kinematic-isotropic hardening, including yield surface shrinkage during initial plastic deformation

Experimental work
Calibration of constitutive model

- Cross-hardening tests
  - Movement of yield surface along axial direction (i.e. pre-straining direction)
  - Expansion of yield surface along hoop direction.





E. Karjadi et al., "Reeling pipeline material characterization – testing, material modeling and offshore measurement validation", OMAE2015, May 31- June 5, 2014, St- John's, Newfoundland, Canada

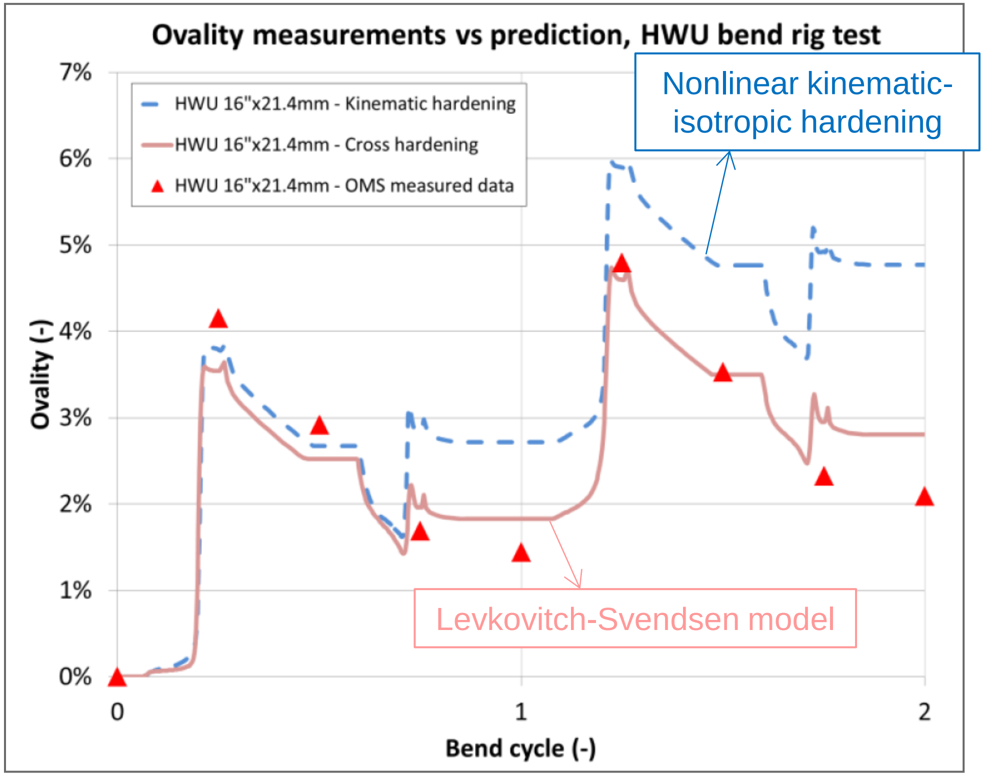
Prediction of ovalization during reel-lay

FE vs experiment

- Pipe ovality:

$$Ovality = \frac{OD_{max} - OD_{min}}{OD_{nom}}$$

- Ovalization can be predicted with much higher accuracy by accounting for distortional hardening.



Nonlinear kinematic-isotropic hardening

Levkovitch-Svendsen model

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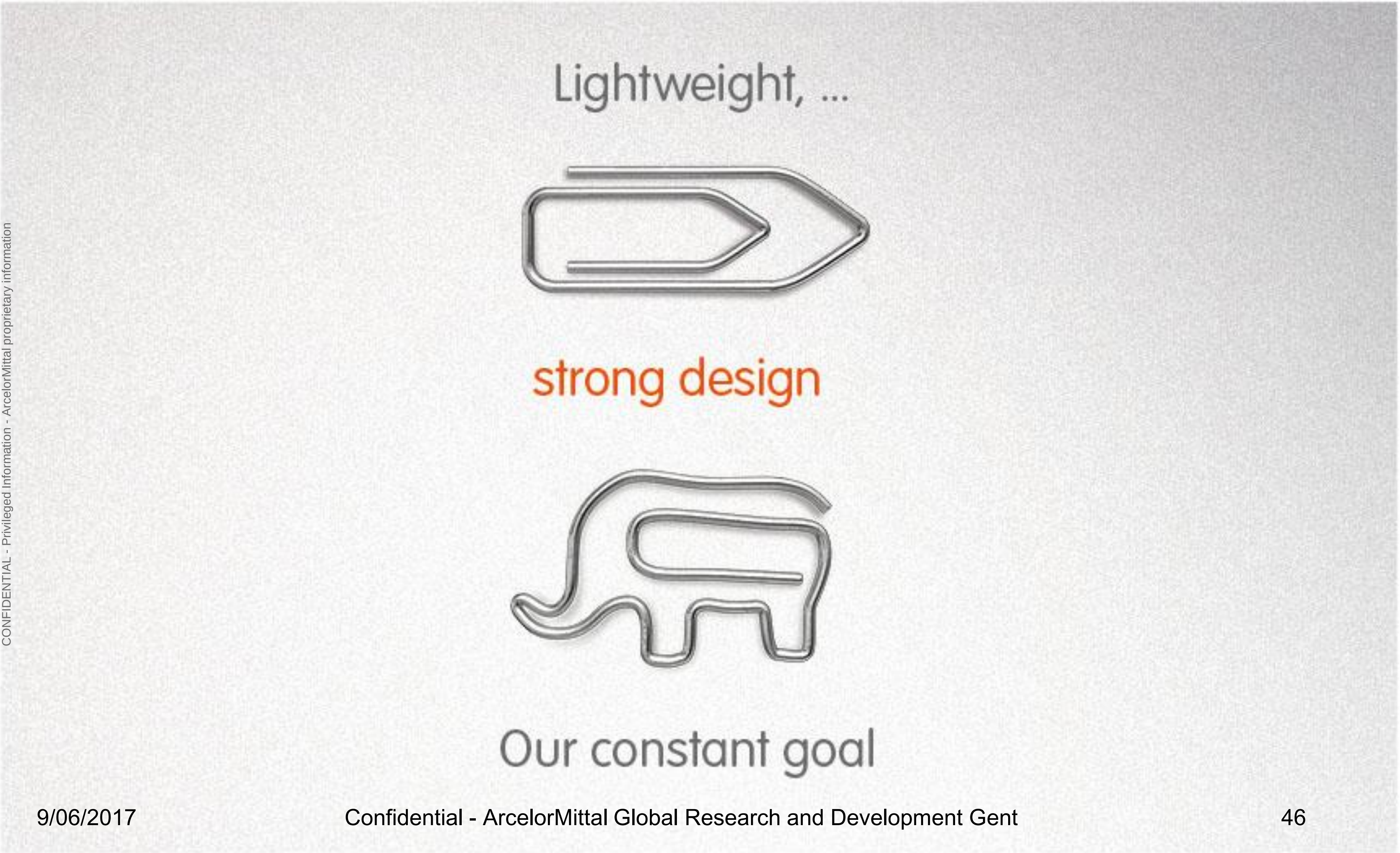
Conclusions



Conclusions

- Two linepipe applications have been presented and discussed:
  - Although induced, plastic strains are rather small, the constitutive models available in commercial FEA codes fail to predict some of the observed phenomena.
  - A more advanced constitutive model, taking into account distortional hardening, has been implemented in Abaqus/Implicit by means of the UMAT user subroutine. The first results look promising.
- Those advanced phenomenological models present several disadvantages
  - In general, not available in commercial FE codes
  - More extensive and, in general, more complex mechanical testing is required to calibrate those more advanced phenomenological models
  - Material parameter calibration → optimization problem
- Therefore there is a clear need for constitutive models with a solid physical base (e.g. crystal plasticity). Such models can for example be applied to simulate virtual experiments which can then be used to calibrate those computationally more efficient phenomenological models.