Universidade de Coimbra

Centro de Engenharia Mecânica
da Universidade de Coimbra

A staggered coupling strategy for the finite element analysis of warm deep drawing process

**J.M.P. Martins[1] • P.M. Cunha[1] • D.M. Neto[1] • J.L. Alves[2] • M.C. Oliveira[1] •
H. Laurent[3] • L.F. Menezes[1]**

[1]CEMUC, Department of Mechanical Engineering, University of Coimbra, Portugal
[2]CMEMS, Department of Mechanical Engineering, University of Minho, Portugal
[3]Université Bretagne Sud, IRDL, F-56100 Lorient, France

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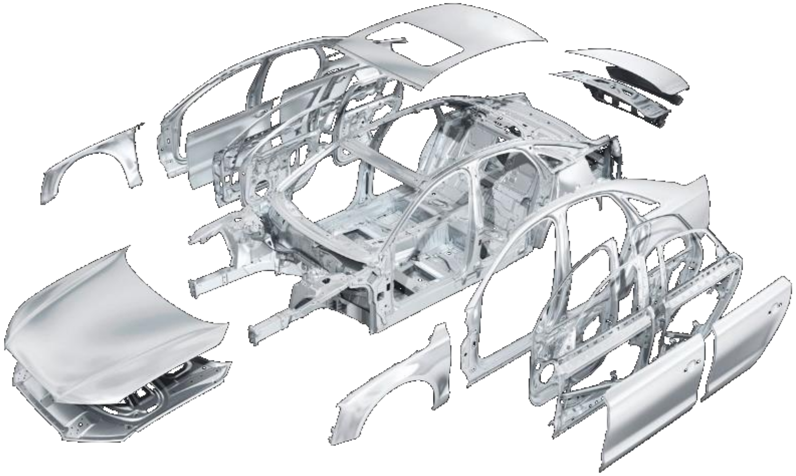
Introduction



AUTOMOTIVE INDUSTRY

Environment protection

- Reduce fuel consumption
- Reduce CO_2 emissions

Safety specifications

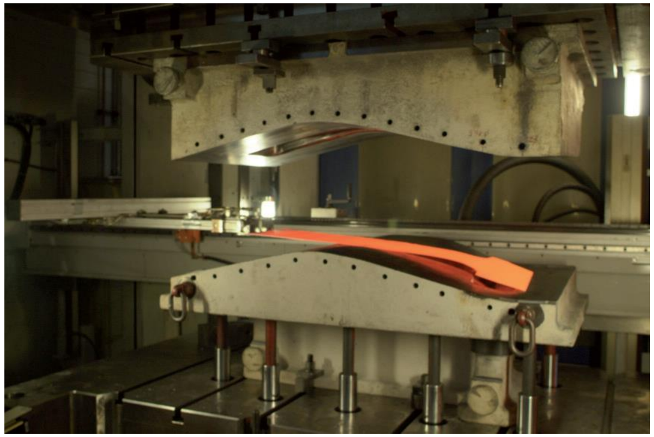
- Increase crashworthiness
- Improve passengers' safety

Recent challenges of the sheet metal forming processes

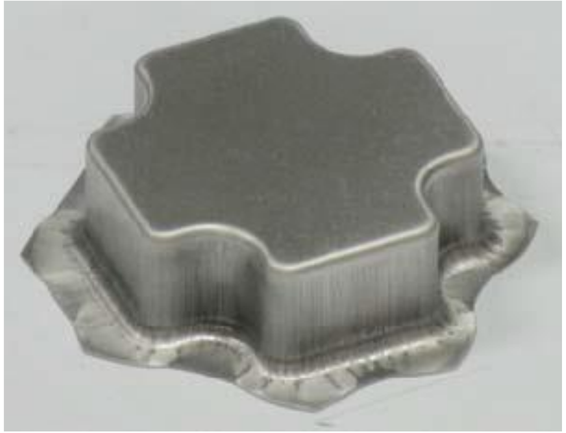
- Adoption of new materials and innovative manufacturing processes
- Hot stamping process of ultra high strength steels
- Warm stamping process of aluminum alloys

Warm and hot stamping processes

- Allows to **improve the formability** and **reduce the springback** effect
- Ideal for complex automotive structural components such as B-pillars
- Thinner parts with better mechanical properties
- Reduce the vehicle weight while increases the safety standard



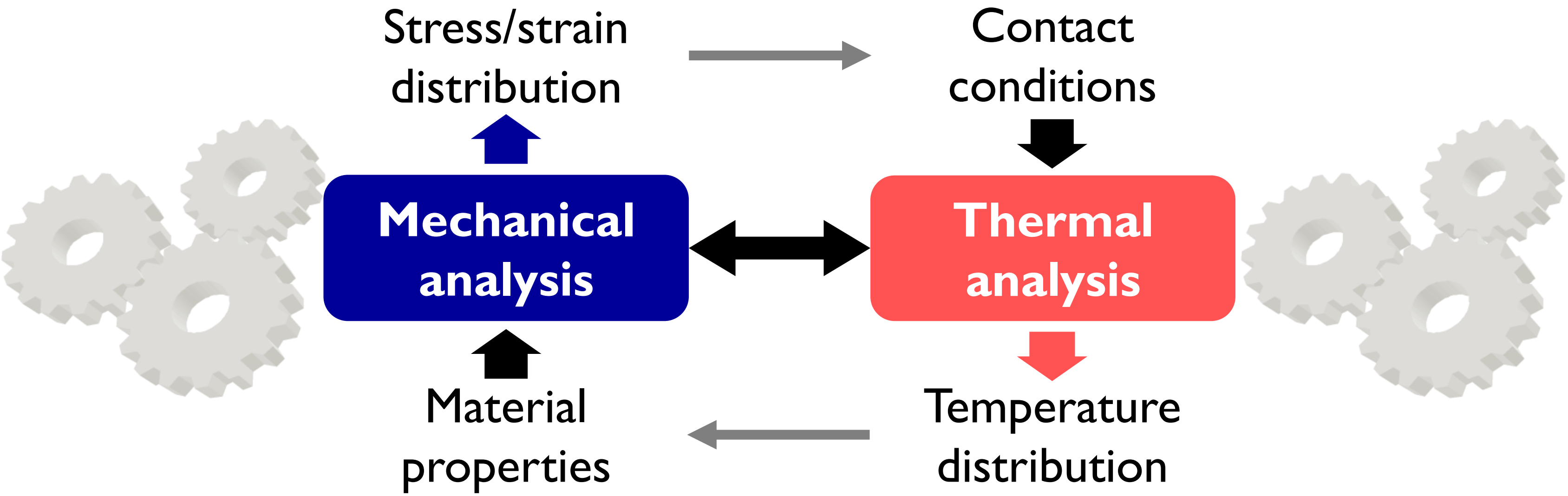
Hot stamping of a high strength steel
(Benchmark 3 - Numisheet 2008)



Warm forming of a magnesium alloy
(Benchmark 2 - Numisheet 2011)

Numerical simulation

- Numerical simulation is an **indispensable tool** in the development of new automotive components manufactured by forming
- Finite element modelling of hot/warm forming processes is **very complex** due to the highly non-linear material behavior, thermo-mechanically coupled characteristics and frictional contact conditions



Stress/strain distribution

Contact conditions

Mechanical analysis

Thermal analysis

Material properties

Temperature distribution

D.M. Neto
diogo.neto@dem.uc.pt

Thermo-mechanical coupling

Coupling strategies currently used in the finite element method simulation of thermo-mechanical problems:

- Monolithic strategy
  - Mechanical and thermal problems solved simultaneously
  - Single system of equations (displacements and temperatures)
  - Complex implementation
- Staggered strategy
  - Mechanical and thermal problems solved sequentially
  - Two systems of equations (strategy to exchange information between thermal and mechanical solutions)
  - Allow to use FE codes already developed (simple implementation)

DD3IMP finite element code

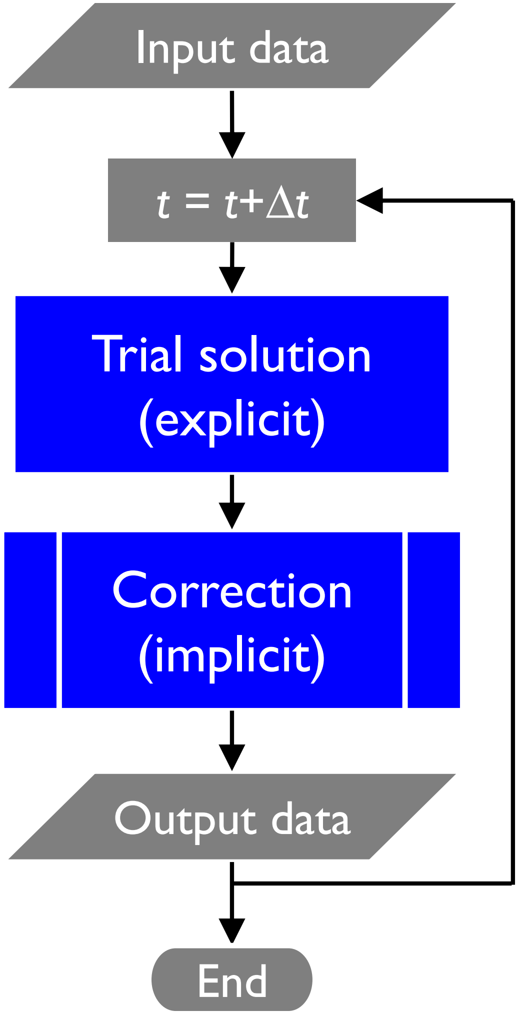
Finite element code specifically developed to simulate (cold) sheet metal forming processes

Main features:

- *Quasi*-static nonlinear analysis with implicit time integration (Newton−Raphson)
- Elasto-plastic behavior (large strains)

Objective:

Incorporate thermo-mechanical effects, such as thermal conduction, heat generation by plastic deformation, thermal expansion and thermal softening



Staggered strategy

Isothermal split methodology: the mechanical problem is solved at constant temperature while the thermal problem is solved for a fixed configuration

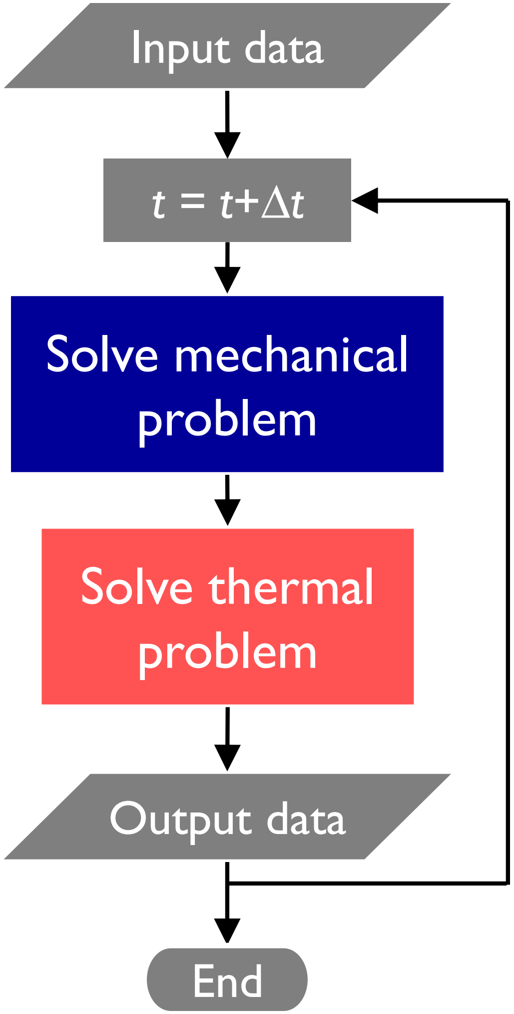
- Explicit coupling algorithm
  - The mechanical problem is solved using the temperature field obtained in the previous increment

- Implicit coupling algorithm
  - In each time increment, an iterative procedure between mechanical and thermal problems is adopted until attaining a convergence criterion

D.M. Neto
diogo.neto@dem.uc.pt

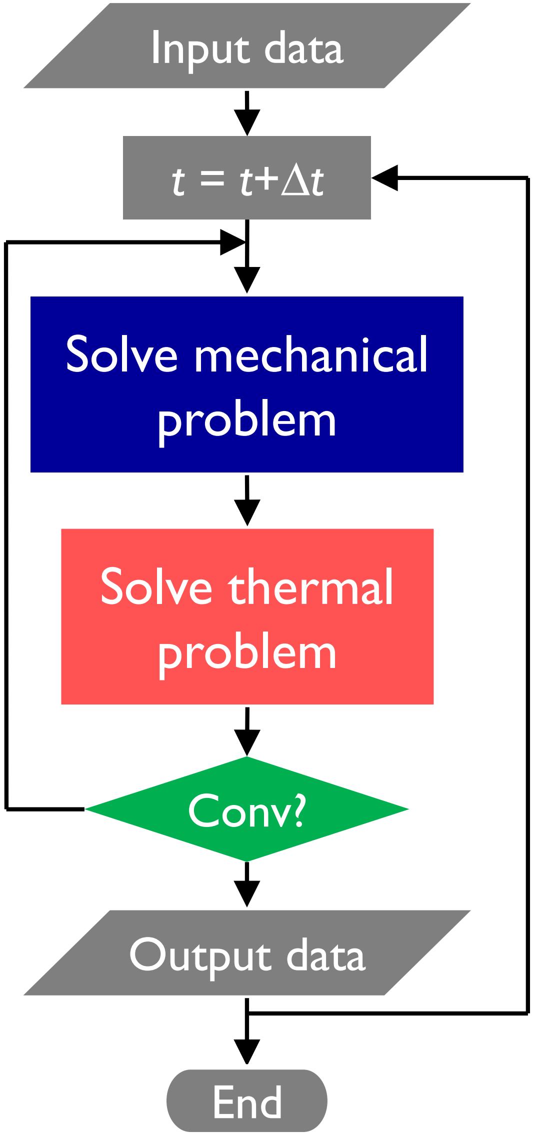
Explicit coupling algorithm

- Mechanical problem solved using the temperature field of the previous increment
- Delay between mechanical and thermal problems
- Exchange of information between mechanical and thermal problems only once in each increment
- Low computational cost



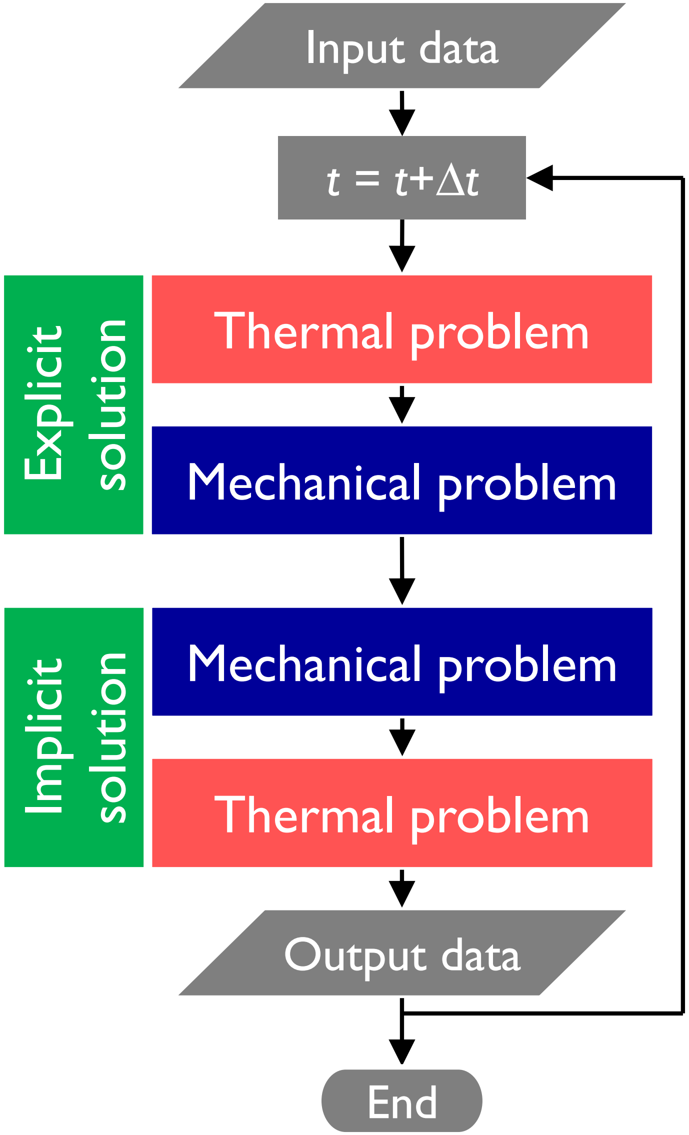
Implicit coupling algorithm

- Exchange of information between mechanical and thermal problems within an iterative procedure (several times in each increment)
- Guarantee the thermo-mechanical equilibrium (higher accuracy in the solution)
- High computational cost due to the iterative procedure (mechanical ↔ thermal) within each increment



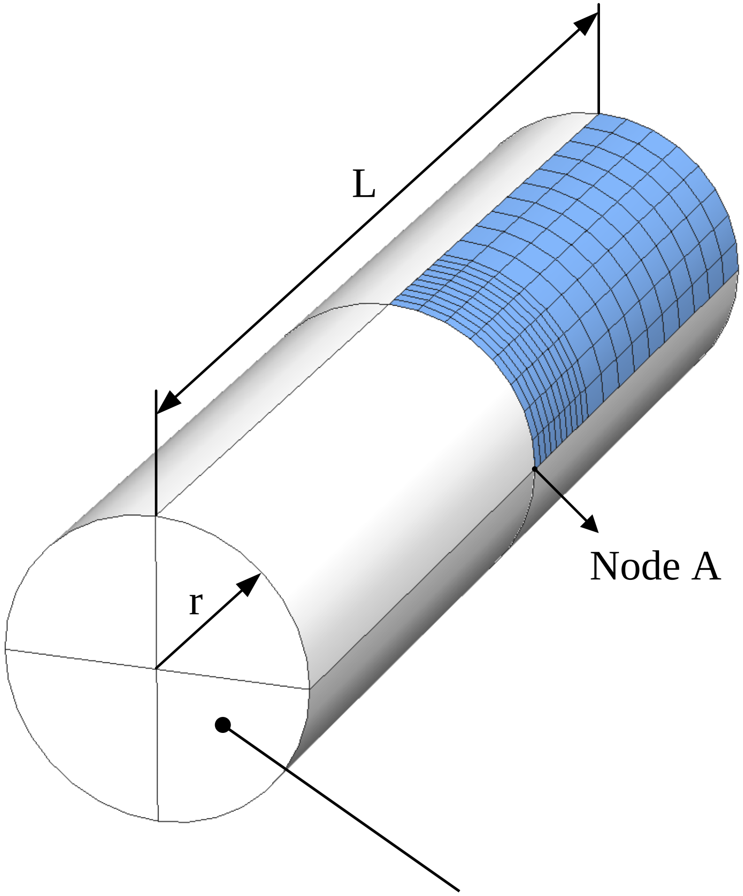
Proposed coupling algorithm

- Split each increment in **2 phases**: prediction phase (explicit solution) and correction phase (implicit solution)
- Prediction phase: solve the thermal problem (plastic and frictional power from the previous increment) before the mechanical problem
- Correction phase: solve the mechanical problem (using trial temperature field) before the thermal problem



Tensile test of a cylindrical bar

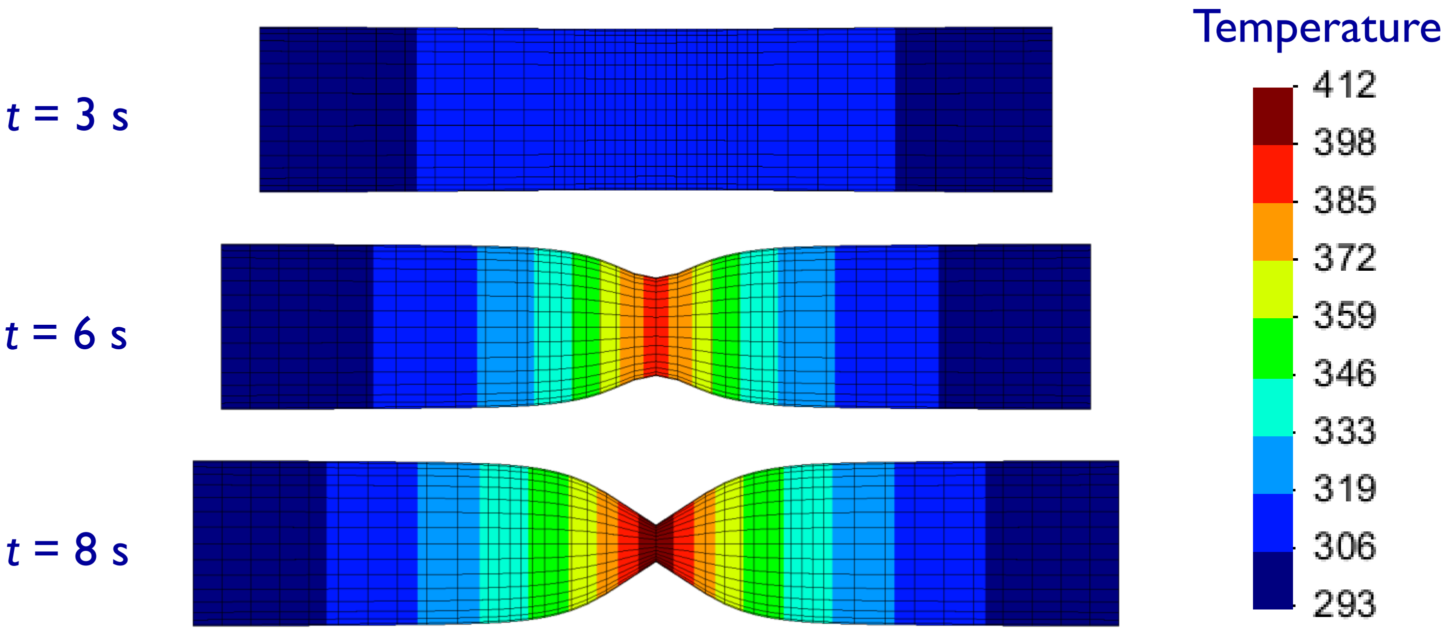
- Prescribed displacement (8 mm) using constant velocity (1 mm/s)
- 1/8 of the model (symmetry conditions)
- 960 hexahedral finite elements (SRI in mechanical problem and FI in thermal problem)
- Initial temperature: 293 K
- Thermal isolated bar (heat generated by plastic deformation)
- Thermal softening (decrease of the flow stress)



Prescribed temperature
T=293 K

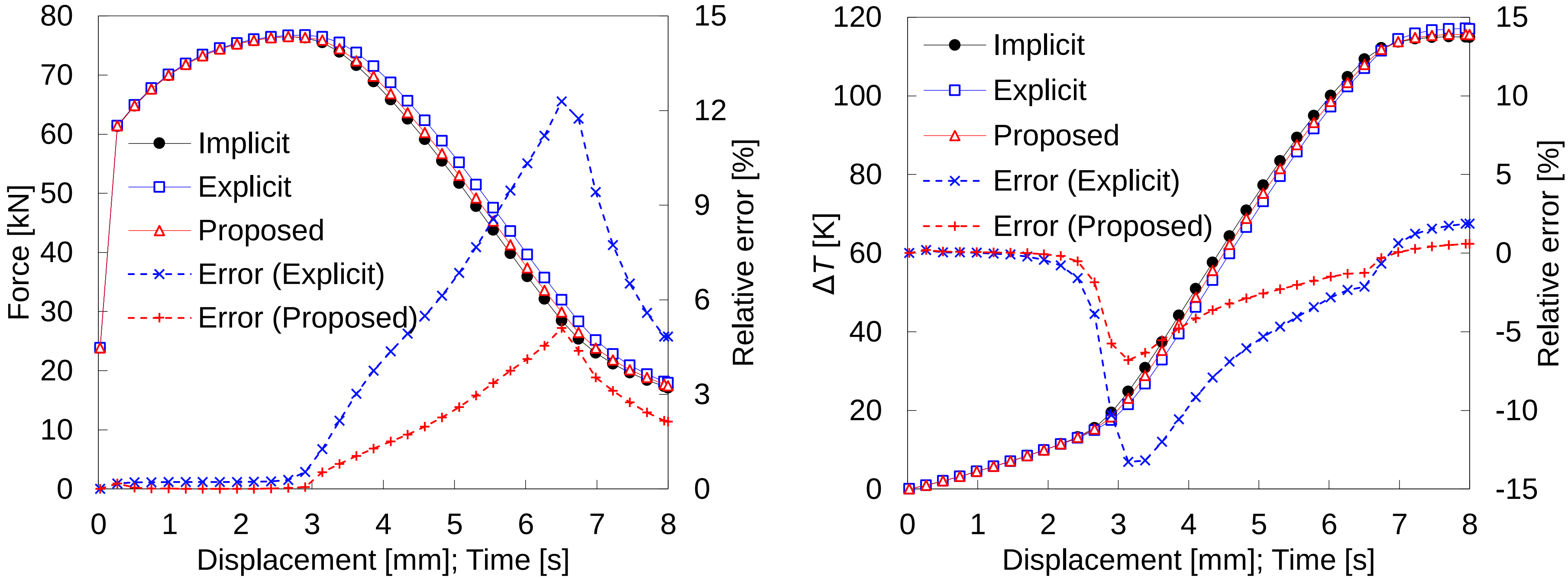
Tensile test of a cylindrical bar

- Decrease of the flow stress in the middle of the bar induced by the heat generated by plastic deformation (thermal softening)
- Occurrence of necking due to the temperature gradient
- Higher temperature in the middle of the bar



Tensile test of a cylindrical bar

- Comparison between coupling algorithms (Implicit, Explicit and Proposed)
- The relative error (considering the implicit coupling strategy as reference) is approximately two times lower using the proposed algorithm than the explicit coupling algorithm



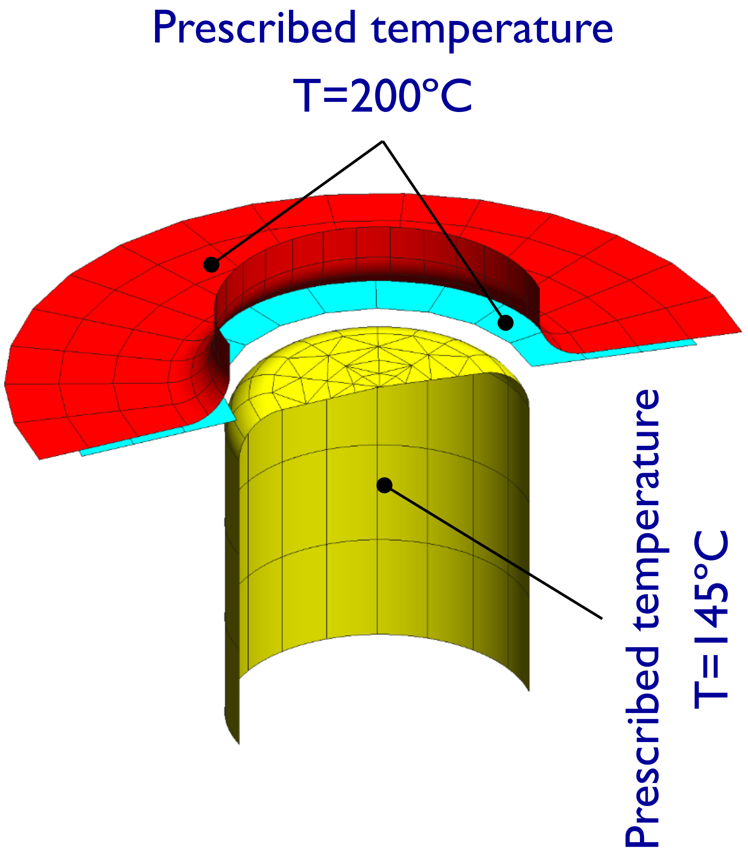
Tensile test of a cylindrical bar

- The computational time required by the proposed algorithm is only slightly large one required by the explicit coupling algorithm
- The computational cost of the implicit coupling algorithm is twice the time required by the proposed algorithm

Coupling algorithm	Implicit	Explicit	Proposed
Computational time [s]	63	27	28

Warm forming of a cylindrical cup

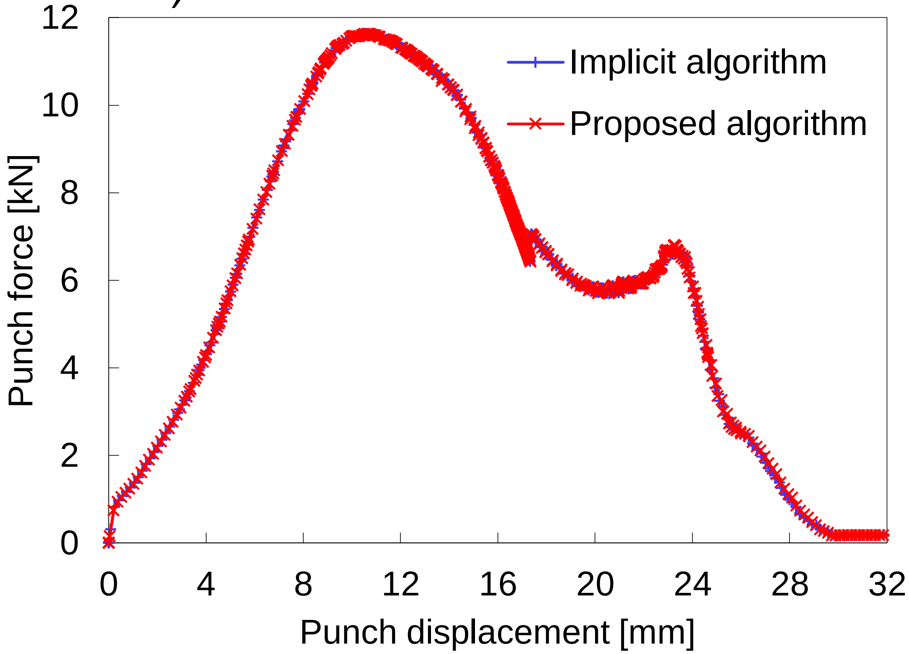
- AA5754-O aluminum alloy
- Blank with Ø60 mm and 1 mm thickness
- Constant forming velocity (1 mm/s)
- 1/4 of the model (symmetry conditions)
- 9068 hexahedral finite elements (SRI in mechanical problem and FI in thermal problem)
- Hockett-Sherby hardening law and the Hill'48 anisotropic yield criterion
- Initial blank temperature: 200°C
- Forming tools at constant temperature

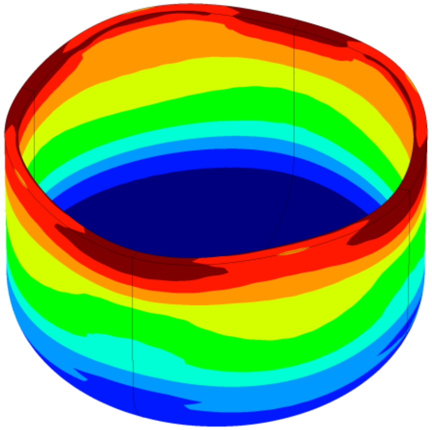


- ✓ Heat generated by friction and by plastic deformation
- ✓ Thermal contact conductance

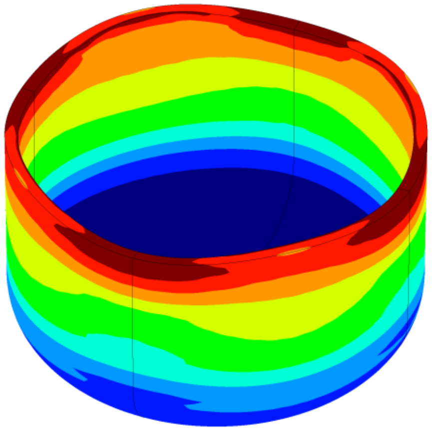
Warm forming of a cylindrical cup

- Comparison between implicit and proposed coupling algorithms (identical results)
- Required about 500 increments (large strains, thermo-elasto-plastic behavior and frictional contact)

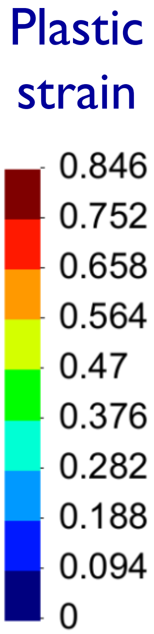




Implicit algorithm

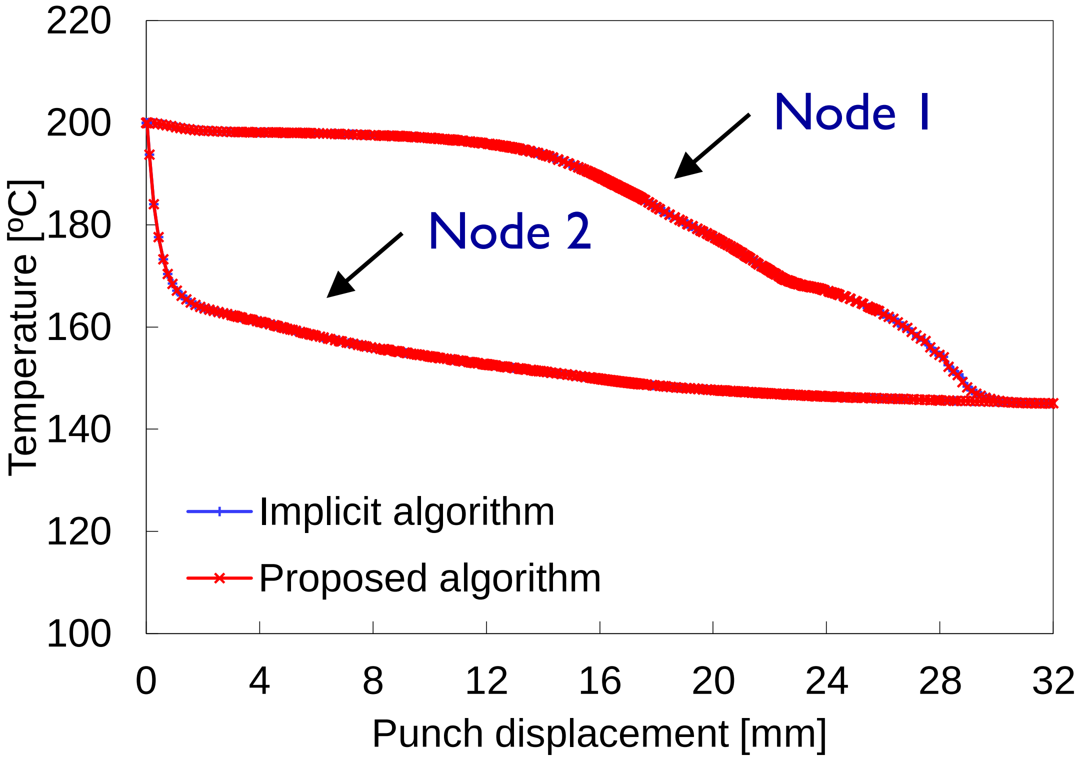


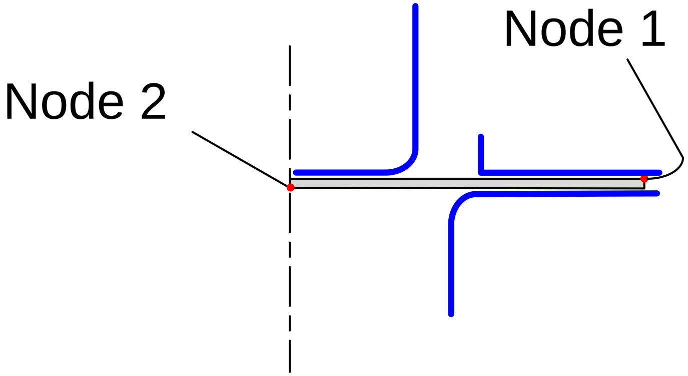
Proposed algorithm



Warm forming of a cylindrical cup

- Evolution of the temperature in the blank: rim (Node 1) and center (Node 2)





Global cooling of the blank, converging to the punch temperature (140°C)

Coupling algorithm	Implicit	Proposed
Computational time [h]	2.4	1.6

Conclusions

- A new staggered algorithm for thermo-mechanical coupling is presented, which was implemented in DD3IMP finite element code (static implicit)
- Split each increment in 2 phases: prediction phase (explicit solution) and correction phase (implicit solution)
- The computational cost of the proposed algorithm is identical to the explicit coupling algorithm, while the accuracy is significantly higher
- Validation of the proposed algorithm using a warm forming example, where the temperature distribution presents a strong effect on the mechanical behavior

Acknowledgements

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Thank you for your attention!