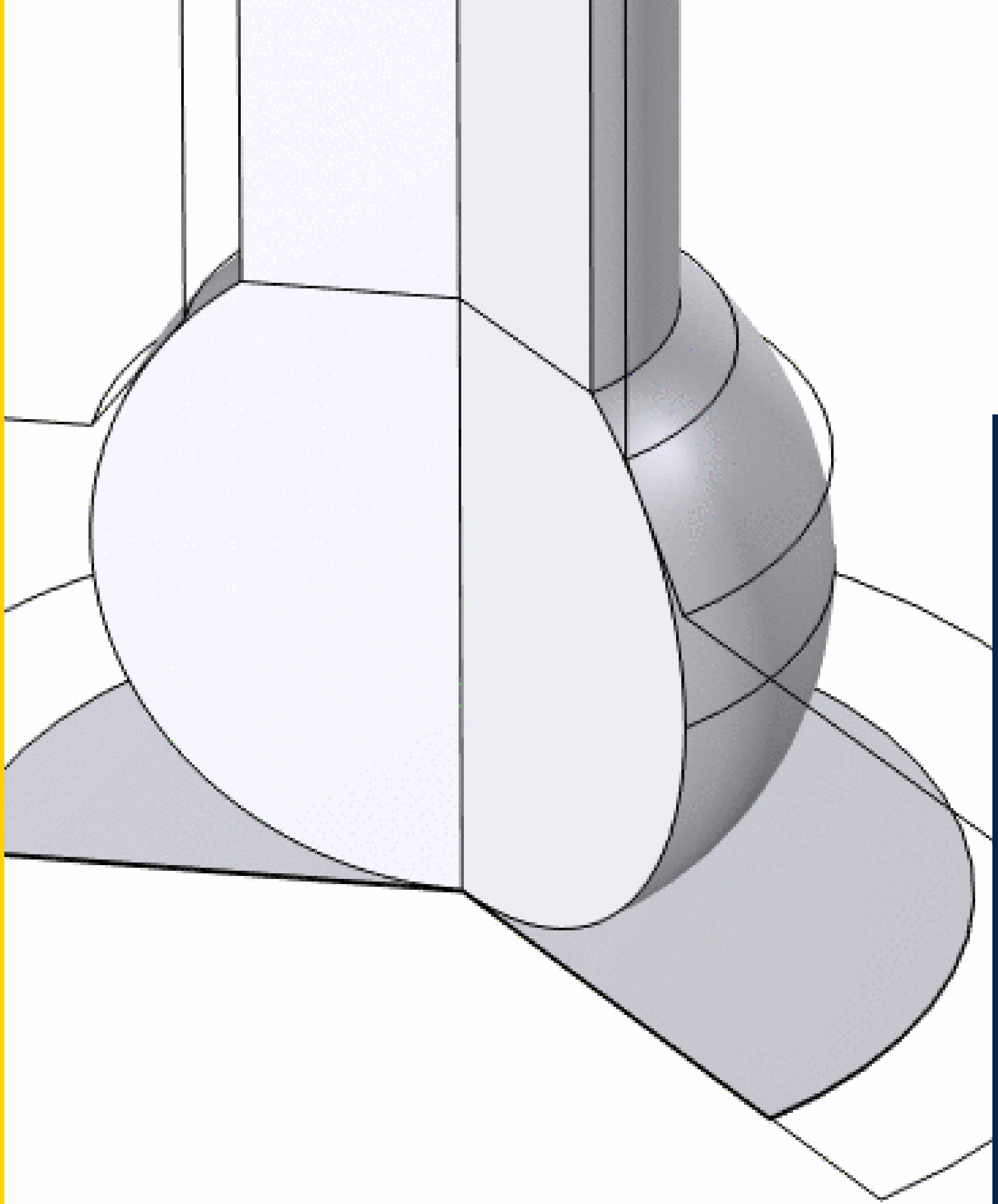

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Wire bonding: a thorough numerical methodology

Presenter

Beatrice Carasi

Authors

Beatrice Carasi, Lucrezia Guarino, Lucia Zullino, Luca Cecchetto

Agenda

- Company presentation
- Wire bonding
- Model hypothesis and set up
- Defining material properties with simulations
- Displacement and force controlled simulations
- Conclusion
- Further points of discussion

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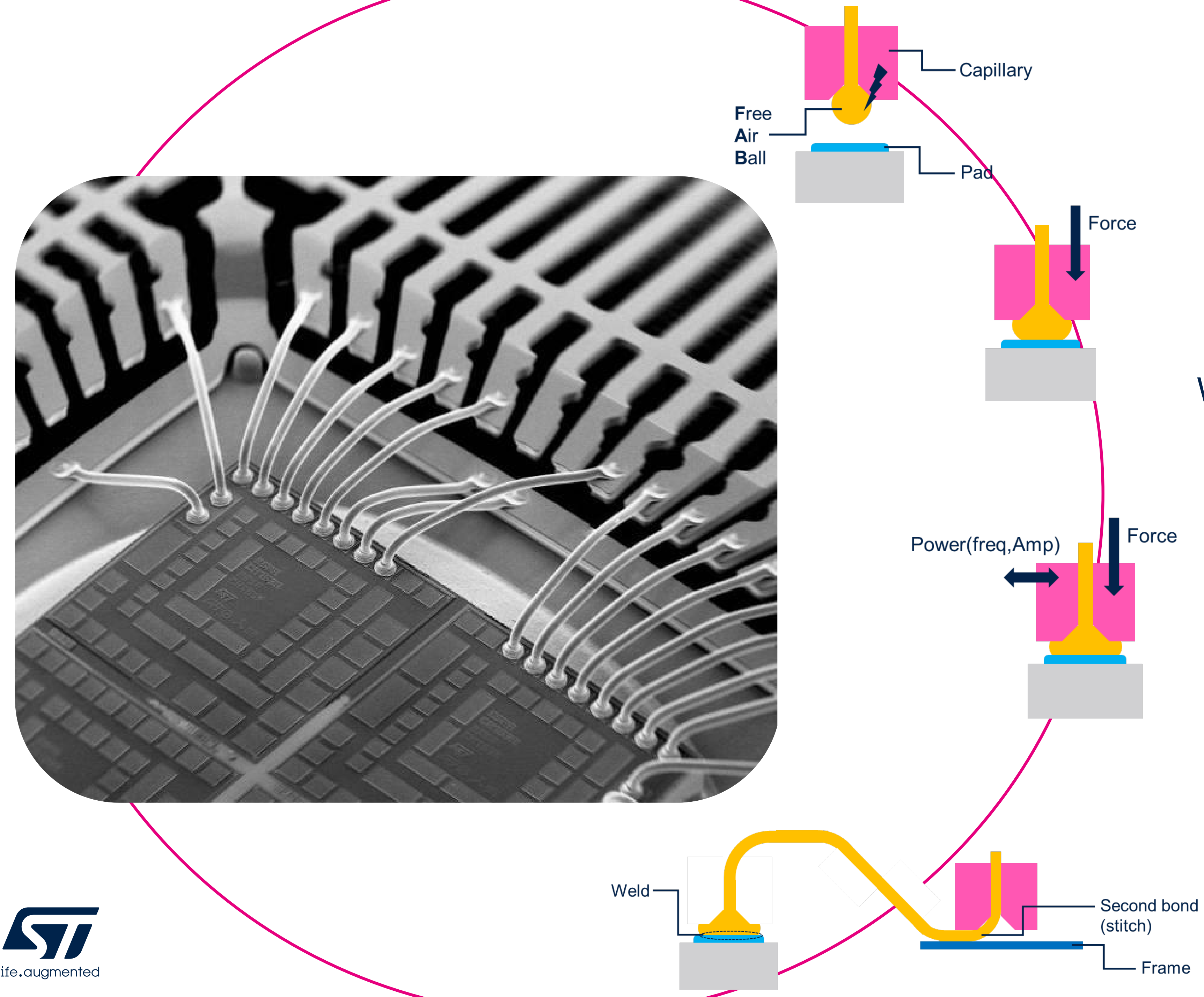
Wire bonding

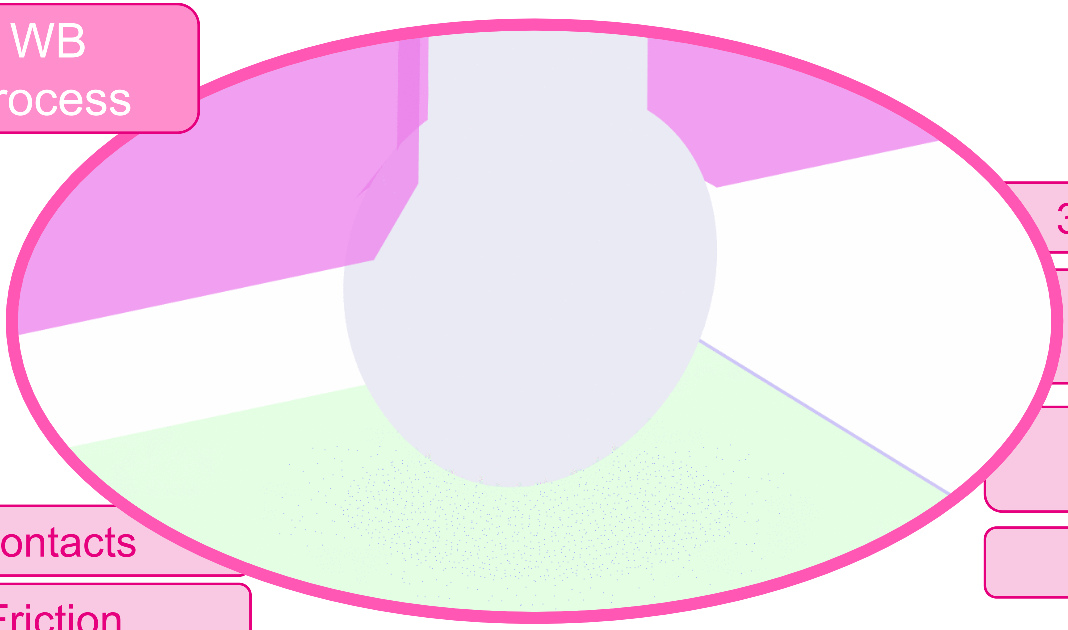


Wire bonding is a critical step in the chip packaging process since it can damage pads inducing cracks in dielectric layers.

A robust numerical model is a key factor to anticipate manufacturing risks.

Model hypothesis and set up:
Informed Simplification is Key

WB process

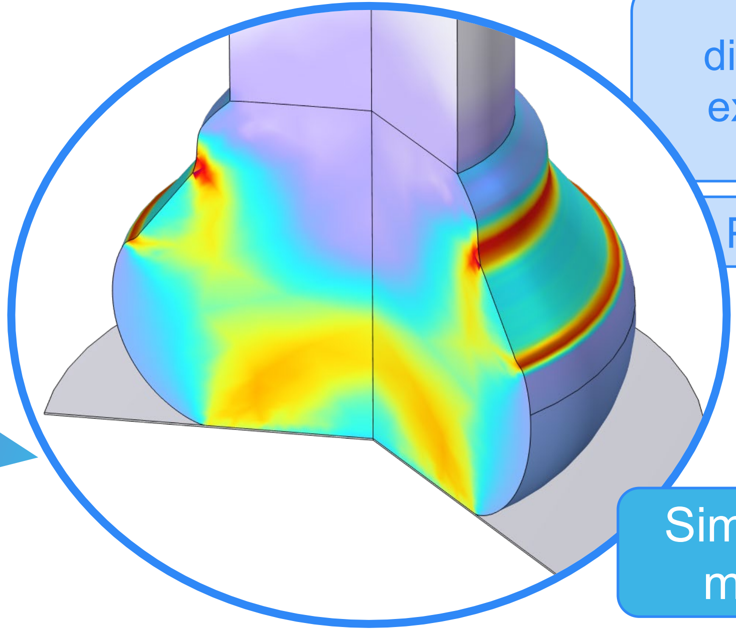


- Contacts
- Friction
- Welding
- Plasticity
- Acoustic Softening

- 3D Geometry
- Thermal Gradients
- Capillary Kinematics
- Transient

Negligible & Unknow phenomena

Experiments focused on FAB:
Hard pad structure
No Ultrasonic power

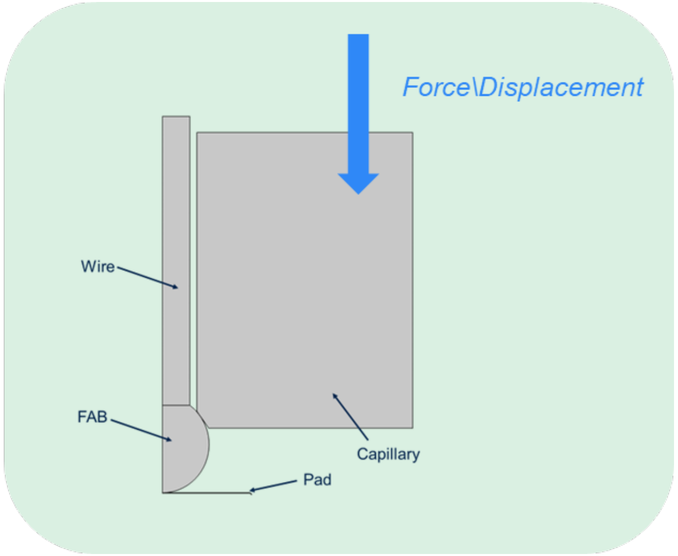


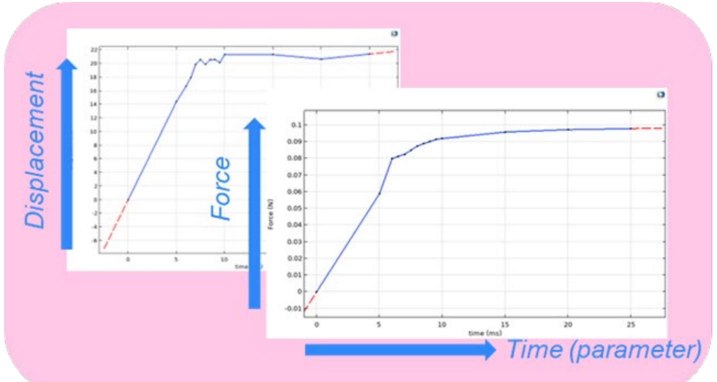
- 2D axi geometry
- Contacts
- Plasticity
- Force and displacement experimental curves
- Parametric

Simplified model

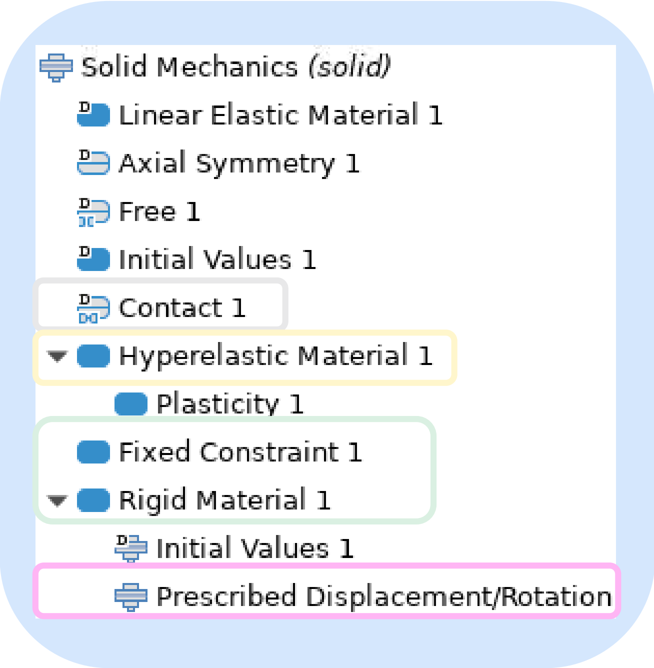
Simplified model is reliable, fast & robust

Model hypothesis and set up: The simplified model



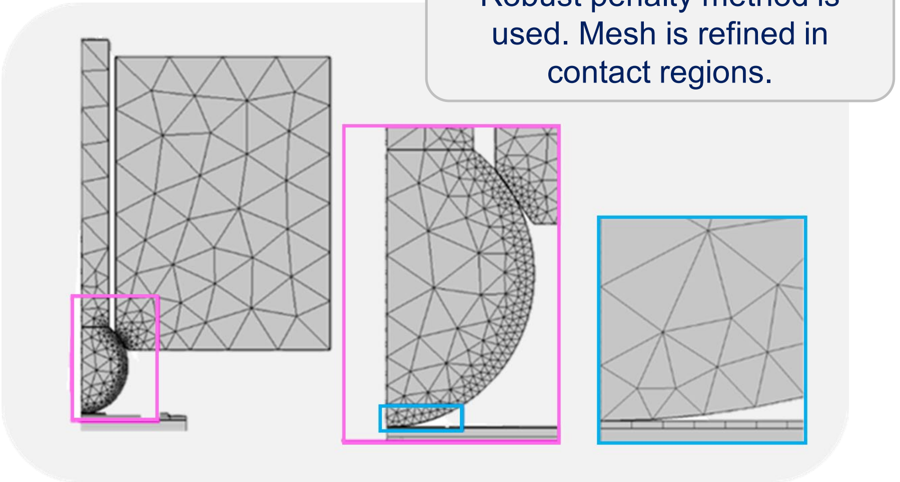


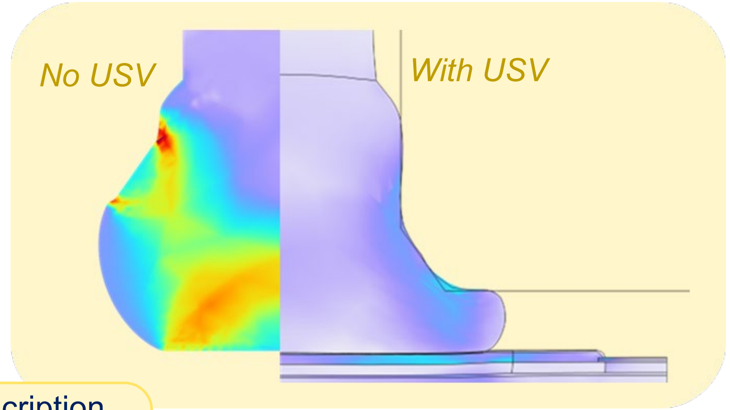
Experimental curves imposed on the capillary



- Solid Mechanics *(solid)*
  - Linear Elastic Material 1
  - Axial Symmetry 1
  - Free 1
  - Initial Values 1
  - Contact 1
  - Hyperelastic Material 1
    - Plasticity 1
  - Fixed Constraint 1
  - Rigid Material 1
    - Initial Values 1
    - Prescribed Displacement/Rotation

Robust penalty method is used. Mesh is refined in contact regions.





Hyperelastic description more robust with high mesh deformations (important with USV)

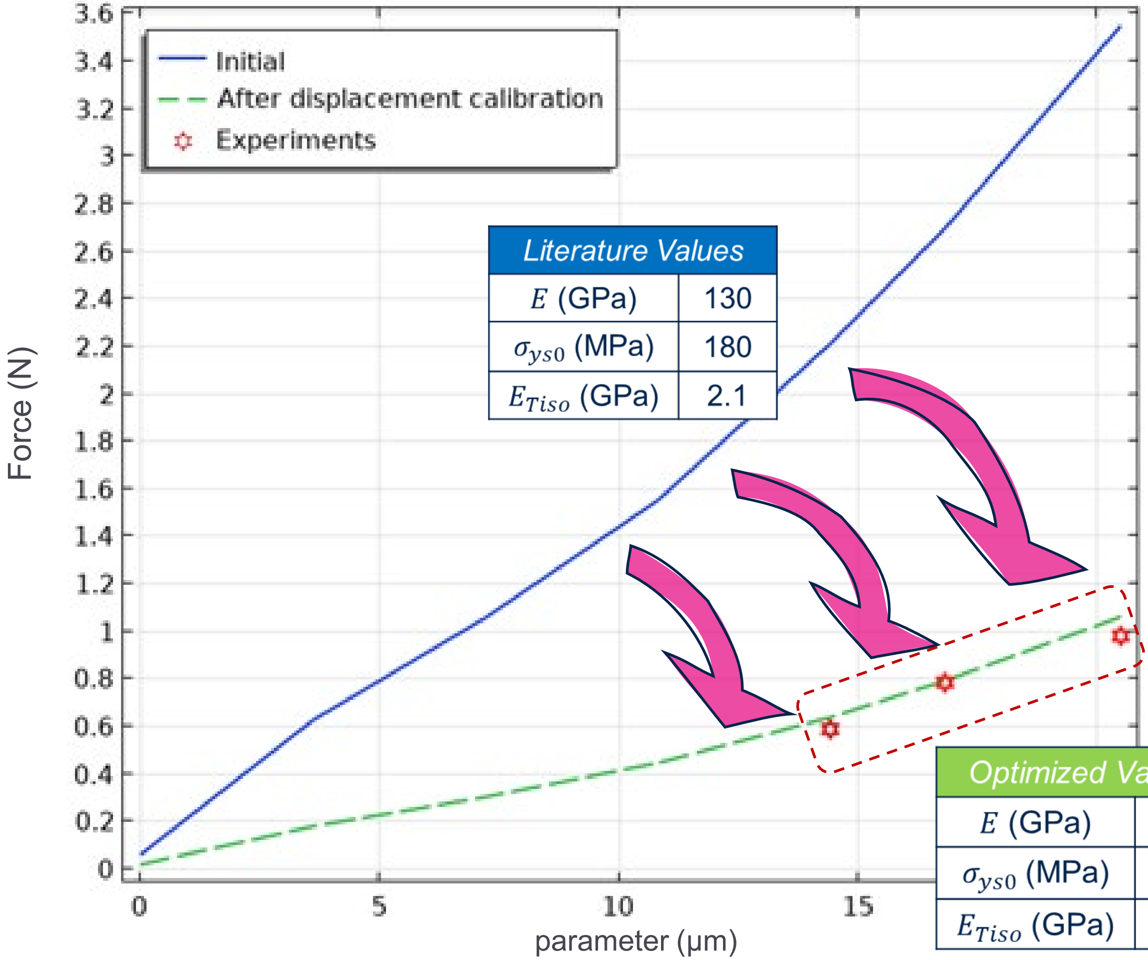
Defining material properties with simulations

Material properties of the FAB are not available and not easily to obtain experimentally.

Experimental TD (touch down, displacement) and force on the capillary are available.

The constitutive law is captured correctly when both experimental displacement and force are matched. Material properties are scanned parametrically until this condition is reached.

This approach is valid not only for solid mechanics



Literature Values	
E (GPa)	130
σ_{ys0} (MPa)	180
E_{Tiso} (GPa)	2.1

Optimized Values	
E (GPa)	80
σ_{ys0} (MPa)	50
E_{Tiso} (GPa)	0.6

Final displacement for 3 different forces is recorded in the experiments. Displacement controlled simulations. E *is the Young's modulus,* σ_{ys0} *is the Initial yield stress and* E_{Tiso} *the isotropic tangent modulus*

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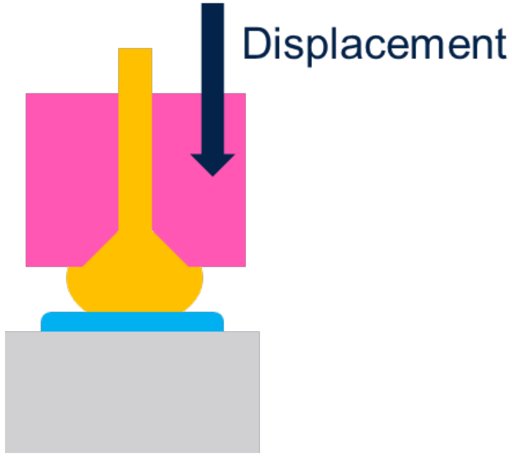
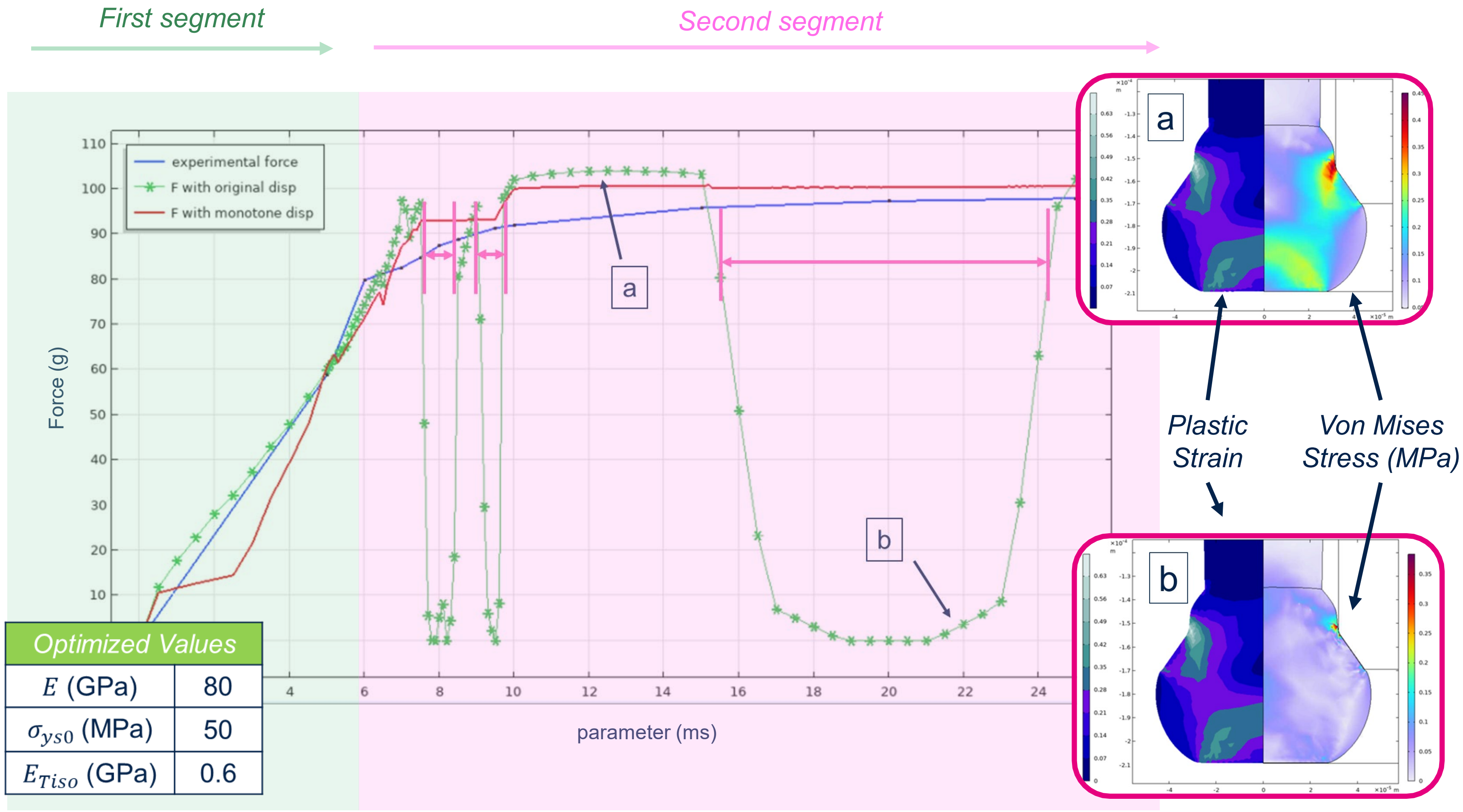
Displacement controlled simulations



A two segments bond is simulated.

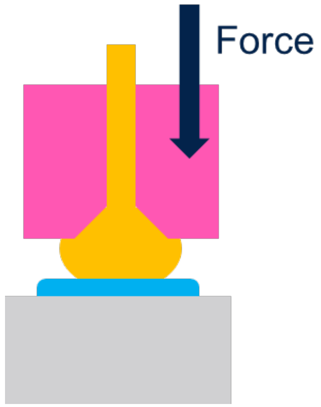
Force matching is good, this proves the correctness of the approach for identifying material properties.



Optimized Values	
E (GPa)	80
σ_{ys0} (MPa)	50
E_{Tiso} (GPa)	0.6

The force drops to zero when the capillary is lifted from the plasticized ball.

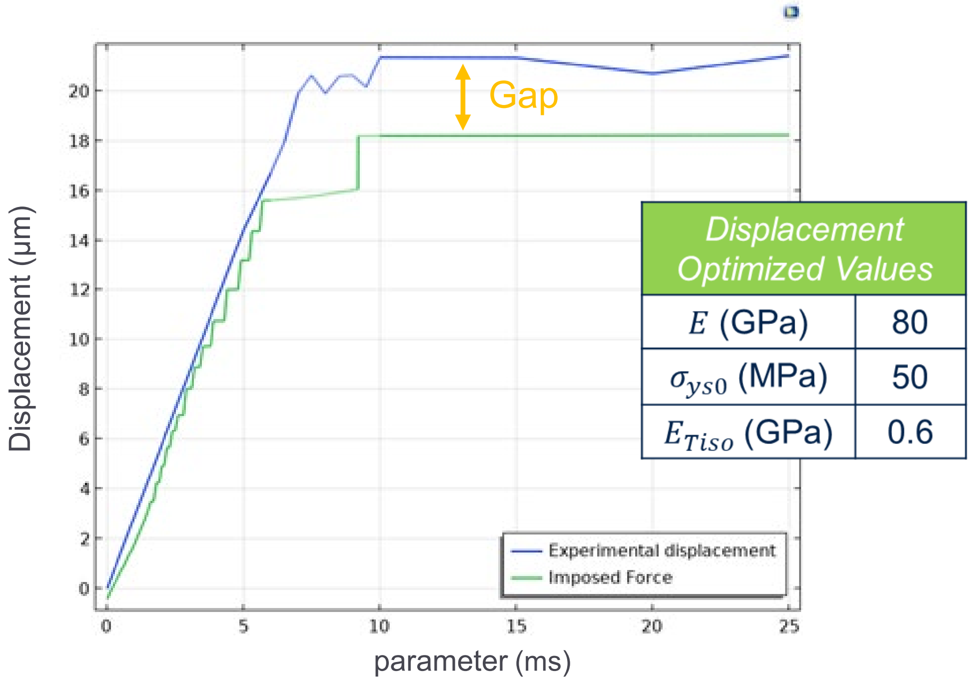
Force controlled simulations



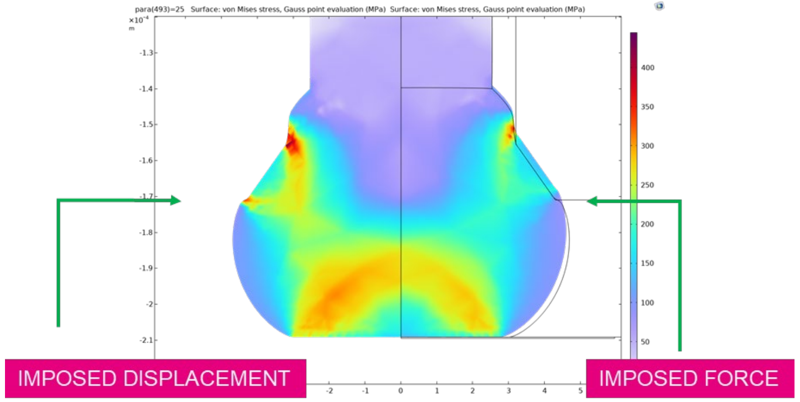
With the same material data that properly match the force imposing the TD, underestimation of the TD is observed imposing the force.

Both strategies should provide the same results, but this is true only if the physics of the system is fully understood*.

*capillary kinematics, material damping…. are unknow

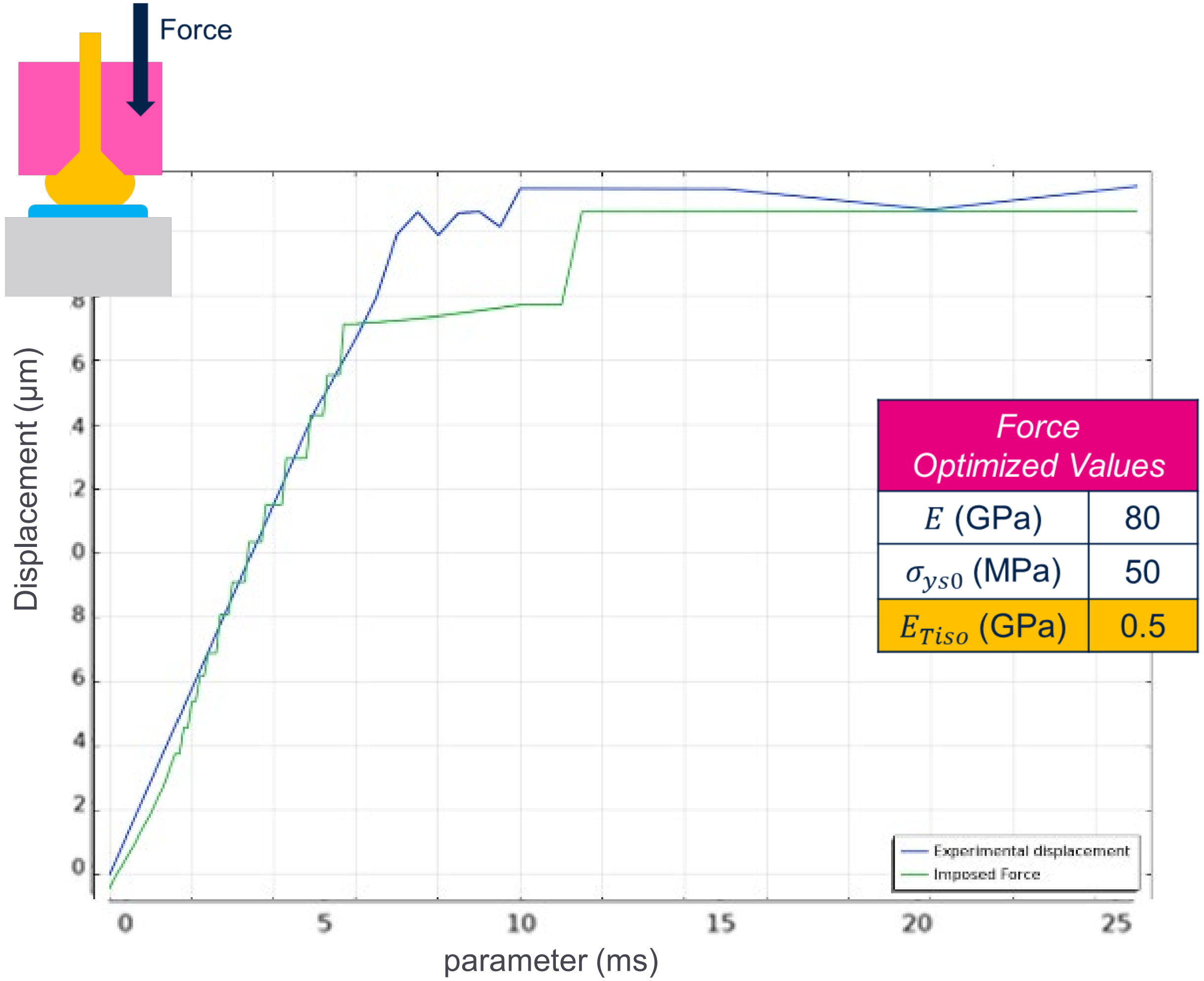


Displacement Optimized Values	
E (GPa)	80
σ_{ys0} (MPa)	50
E_{Tiso} (GPa)	0.6

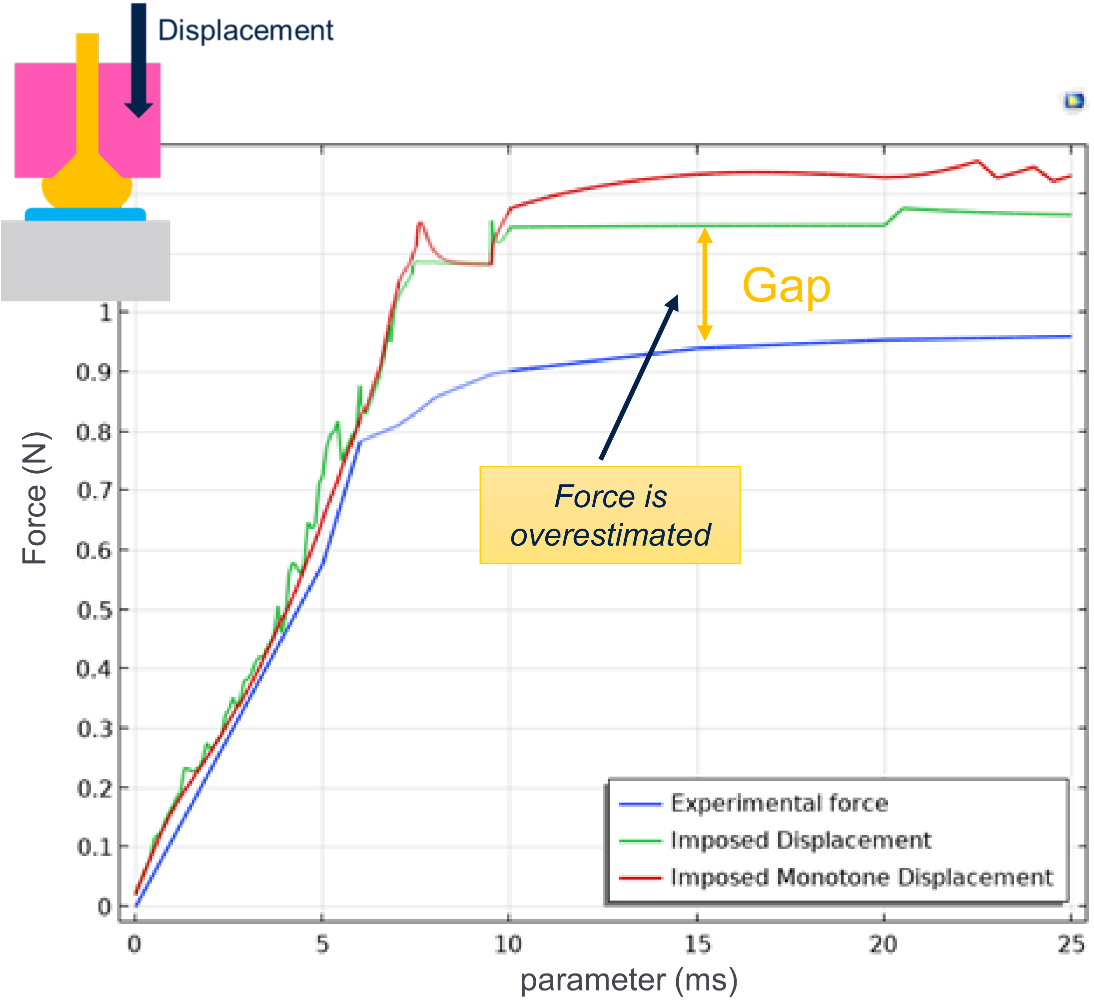


Final deformation for two segments simulation

Force controlled calibration



Force Optimized Values	
E (GPa)	80
σ_{ys0} (MPa)	50
E_{Tiso} (GPa)	0.5



Force is overestimated

Force and Displacement calibration produce slightly different optimal material parameters.

Displacement vs Force controlled simulations

We have seen that, with respect to matching experimental data, either force and displacement controlled provide good (even if different) results.

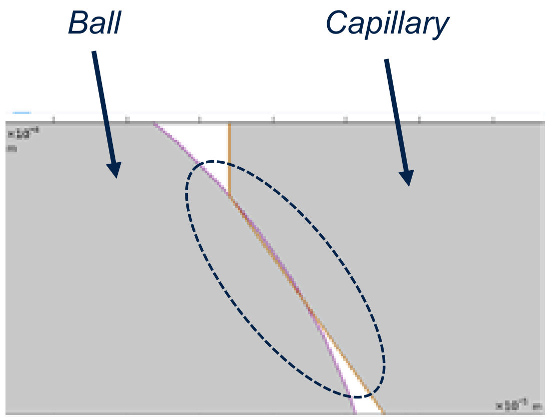
u Displacement controlled

- Easier to constrain in static simulations
- Numerically more robust (default Double Dogleg non-linear solver)

More robust and faster. Should be preferred when possible.

F Force controlled

- Strategies for a well posed\constrained numerical model are needed (spring foundations or other*)
- Non-linear solver is changed from the default to the more ‘cautious’ constant Newton, with 0.1 as damping factor.



*In 2D axi, a constraint is missing in the vertical direction if the force is imposed. An initial interference between ball and capillary is used to resolve this at t=0.

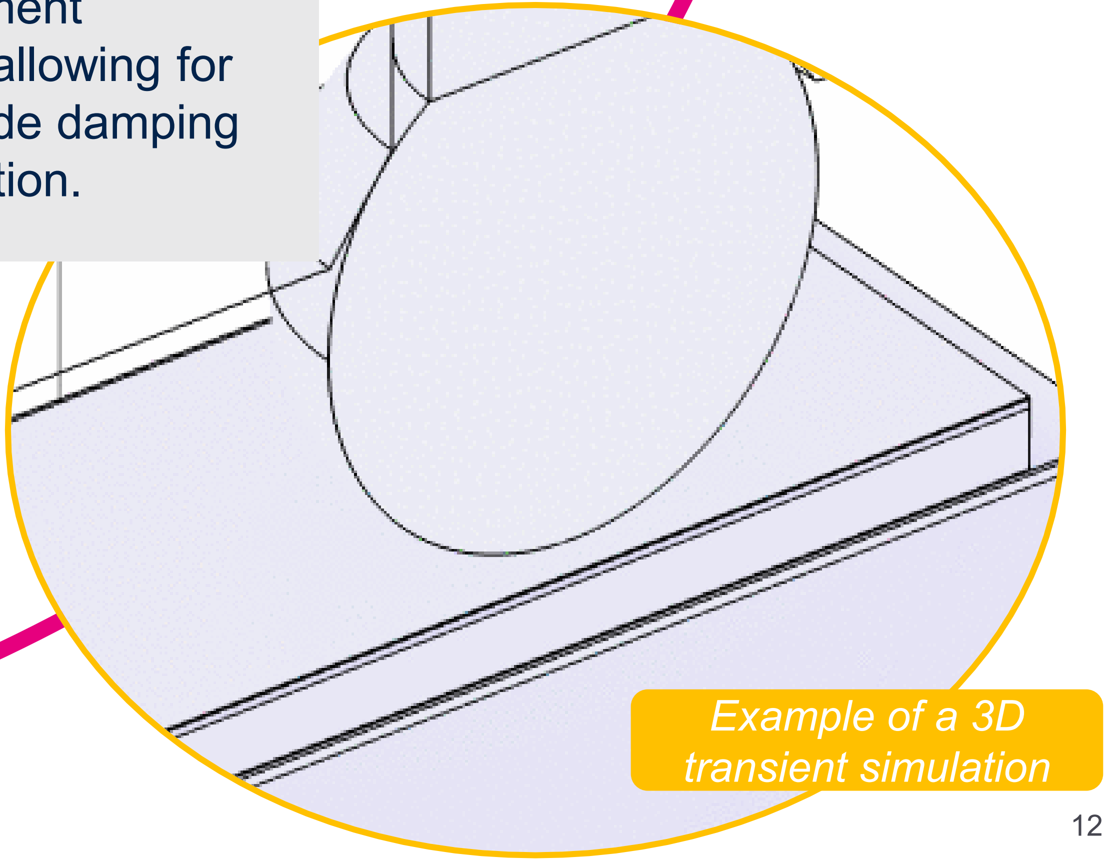
Conclusion

- Numerical simulations, combined with experimental data, can be used to infer material properties
- Displacement controlled and force controlled capillary movement produce slightly different results since kinematic of the piezoelectric actuator is unknown.
- Displacement is, as expected, to be preferred as more robust numerical input with respect to force.

Future enhancements

- model ball-pad adhesion

- when acoustic softening is present, control the horizontal capillary displacement imposing a force, allowing for oscillation amplitude damping due to weld formation.



Example of a 3D transient simulation

Further points of discussion

- 2D axisymmetric
  - transient analysis provided better match in the two segments transition zone but it is of course much slower
  - can be used as a *first* screening test for material properties characterization even in presence of USV, since most of the phenomenon is the softening of the material (lateral translation affects more ball\pad interface)
  - The Ludwik model describes better the stress-strain behavior with USV (high deformation)
- 3D are the goal since different pad structure are to be analyzed
  - Harder to constrain than 2D axisymmetric
  - Much slower (from tens of minutes to hours of computation)
  - Quadratic elements are paramount to be able to describe the shape of the ball at high TD
- …..

No temperature gradients because only the FAB is non rigid and the stress\strain curve is at that temperature

Wire bonding: a thorough numerical methodology

B. Carasi, L. Guarino, L. Zullino, L. Cecchetto
STMicroelectronics srl
via C. Olivetti, 2, 20864 Agrate Brianza (MB), Italy
Email: {beatrice.carasi|lucrezia.guarino|lucia.zullino|luca.cecchetto}@st.com

Abstract

The semiconductor industry is always looking for early anticipation of manufacturing risks, pushing the development of Computer Aided Engineering (CAE) modeling of processes. Robust Chip-Package Interaction (CPI) design requires a deep understanding of thermo-mechanical stresses imposed during the assembly process; one of the critical steps is wire bonding, which can damage pads inducing cracks in dielectric layers. Aim of this paper is the investigation of an appropriate simulation strategy, using COMSOL Multiphysics, of a 3D thermo-mechanical model of thermo-sonic wire bonding, that represents the physics accurately but also seeks numerical robustness, starting from appropriately simplified models. How numerical analysis together with experimental data can be used to obtain mechanical material characterization for thin/high temperature copper wires is also shown.

1. Introduction

1.1 The wire bonding process

CPI design is concerned with making sure that silicon die (the chip) maintains its performance when packaged. Packaging is necessary to protect the device from the environment and connect it with its application. There are many ways to achieve electrical interconnection and wire bonding (WB) is one of the alternatives (others are, for example, solder balls and direct copper interconnection). Wire bonding (see Figure 1) consists on the formation of a free air ball (FAB) at the tip of a metal wire constrained and moved by a capillary. A spark melts the wire and then the ball is pushed on the chip pad and oscillated. When the bond between ball and pad is formed the capillary lifts and translates. The wire forms a loop and then gets stitched to the package side of the connection and cut (Figure 2). This paper focuses on the first part of the process i.e. the ball-pad connection. This is the most critical one, with respect to structural assessment, since it is the die that contains functional ingredients that need to maintain their integrity during the bonding process. Also, the wire-pad interface needs to be strong enough to stay in place during operational lifetime of the chip and provide an appropriate electrical connection area. Inputs of the first bond process (and so of the numerical model) are the *temperature*, the *vertical force* on the capillary and the *ultrasonic (US) power* (combination of oscillation frequency and amplitude of the capillary tool) at each step of the process (segment). Multiple segments are possible depending on the product specifics. Many factors, including material properties of the involved surfaces [1], influence the solid state weld that is formed.

Figure 1, Wire Bonding process. 1. electrical spark, 2. vertical force application 3. ultrasonic vibration.

Figure 2 First (chip) and second (frame) bonds

1.2 The numerical model

The purpose of a numerical model for wire bonding is to provide feedback both to front end (chip) design and back end (packaging) process. With it, different material stacks, routing and bonding process parameters can be explored [2]. It will be shown that numerical models can be used to infer material characterization, provided that experimental data are available. Translation onto a mathematical model of the process described in chapter 1.1 can reach different degrees of accuracy (and numerical complexity). A somewhat complete description of WB would be a 3D, transient, structural mechanics model with contacts, non-linear materials, surface friction and stick criterion to describe welding, accounting for thermal gradients in the structure and, as it will be evident, a proper knowledge of the ultrasonic transducer kinematic behavior. It is well understood, in the simulation community, that a correctly simplified model can be of great insight and constitutes fundamental numerical foundation to build more complete ones.

1.2.1 Numerical models as characterization tools

Thermo-sonic wire bonding is a process in which the wire (here copper) is oscillated at ultrasonic frequency (50-150 kHz) inducing a softening of the metal called acoustic softening effect [3]. This, combined with a high temperature (220°C in our investigated case), softens the material during bonding. Setting up an experiment to characterize the non-linear, plastic behavior would require dedicated equipment with in-situ ultrasonic oscillation capabilities.

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