Predicting mechanical behavior of over-molded thermoplastic composites

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"Calling for a sustainable world"

Brightlands
Materials Center

M2i Meeting materials 2018.12.11
Noordijkerhout

Brightlands Materials Center

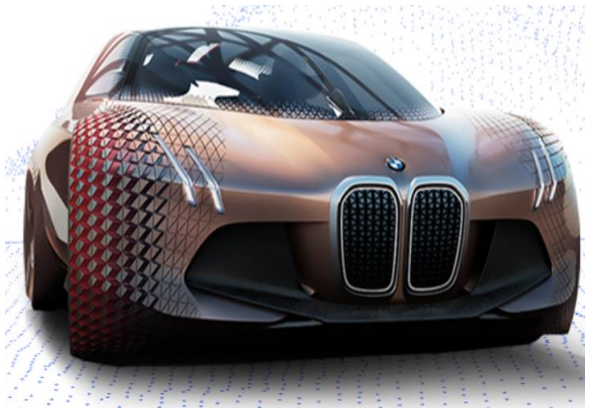
- Public-private partnership initiative founded March 19, 2015 by TNO and the Province of Limburg
- Focusing on sustainable innovations in polymeric materials
- Programmatic R&D along the chain of knowledge driven by application challenges
- R&D programs supported by fundamental academic knowledge
- Collaboration of industrial partners in shared R&D leading to shorter time-to-technology
- Network of partners around physical location at the Brightlands Chemelot Campus

- Three programs initiated:
  - Sustainable Buildings
  - Additive Manufacturing
  - Lightweight Automotive

Our Programs

Sustainable Buildings

Infrared regulating (IRR) window coatings and functional nanocomposite foils



Lightweight Automotive

Material technologies in fiber reinforced thermoplastics and hybrid materials for lightweight applications

Additive Manufacturing

Polymeric materials for additive manufacturing with improved quality, durability, and new functionality

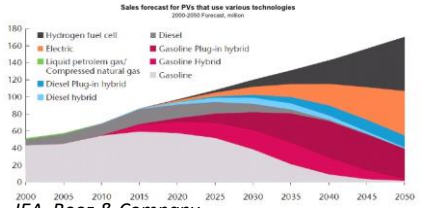
Automotive & Thermoplastic composites

- Automotive
  - Emissions
  - Energy
  - Mobility
  - Safety

  Electrification & Lightweight

  Autonomous driving

Continental



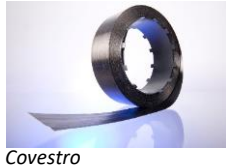
IEA, Booz & Company

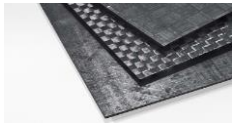
Hyundai Ioniq

IBM Olli

Volvo concept

- Thermoplastic Composites
  - Production capacity & capability
  - Automated part processing & equipment
  - Education & knowledge transfer


Covestro


SGL

Automated Dynamics

ENGEL

Composite World

Thermoplastic composites parts

- Common features
  - Hybrid materials: Metals & thermoplastics
  - Continuous fibers as basis, others to add functionalities
  - Processes: Forming, over-molding, tape placement

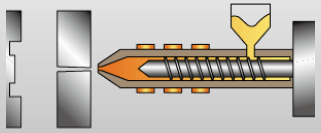
- Common challenges
  - Prediction of long term behavior in service
  - Known behavior in combined loadings (fatigue, aging, impact)
  - Integration and adhesion of dissimilar materials
  - Design and processing know-how TPC

Source: Demonstrator parts at various institutes & industry

What is Injection over-molding and Why it is Important

- Thermoplastic injection molding and composites fabrication share the same foundation material which is polymer. However, in the past, they were separated by process differences.

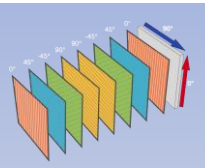
Injection molding



- highly automated
- machine-dependent
- volume-driven and cycle time-focused
- Randomized quality inspection of the products
- ….

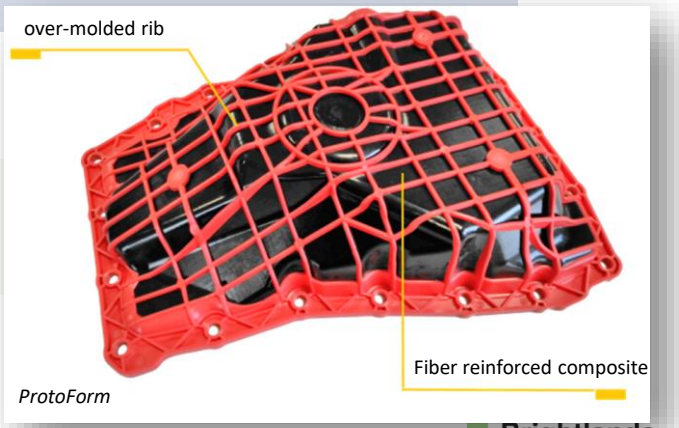
Injection over-molding

Composites



- Not highly automated
- Hand work is not uncommon
- Cycle times are measured in hours, or at best, minutes
- Quality via process control is rare
- …

over-molding technique combines the great potential of the fiber reinforced composites with the well developed and established injection molding process.



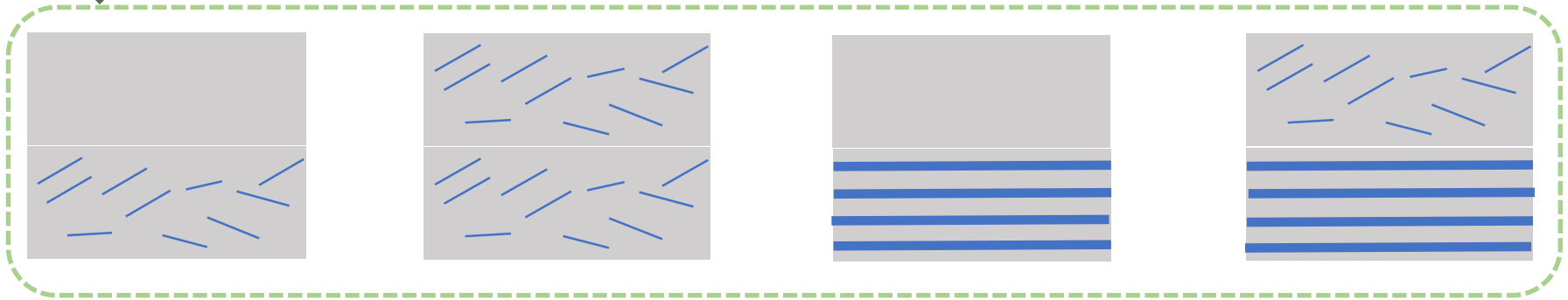
Predicting mechanical behavior of over-molded thermoplastic composites

- Main objective:
  - Characterizing the mechanical behavior of the adhesion bond in the over-molded thermoplastic composites

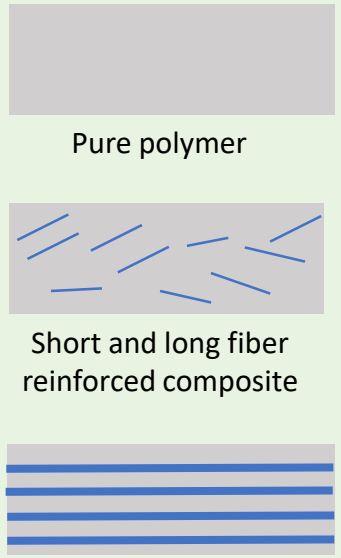
- Research approach: Numerical & Experimental
  - Numerical simulations
    - Developing a multiscale numerical modeling framework for the interface simulation of over-molded TPCs.
    - Developing the relevant phenomenological models if required
    - Predictive simulation of the real scale over-molded thermoplastic composites
  - Experimental study
    - Developing the required testing tools for the injection over-molded TPCs
    - Study of the over-molding process
    - Study of the mechanical behavior of the injection over-molded TPCs

Possible bonding configurations in the TPCs injection over-molded components

Demonstrator parts of over-molded composites

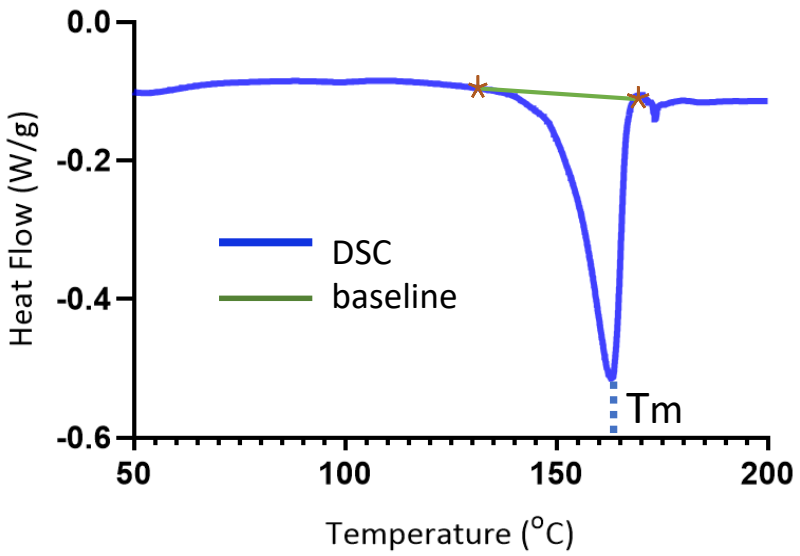


Different adhesion bond configurations

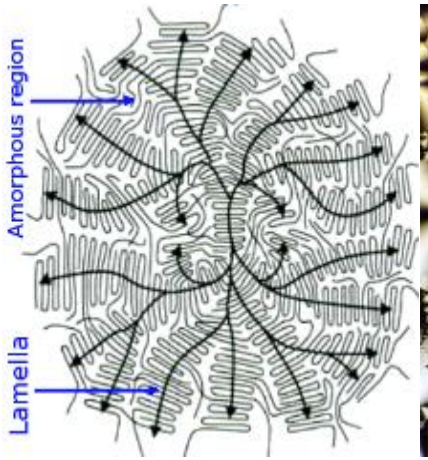


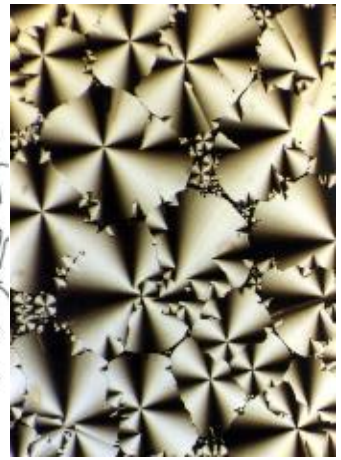
Interfacial Adhesion in Over-Molding of Semi-Crystalline polymers

- Crystallization dominates the interfacial strength in over-molding process (~1-10s).
- For PP, various crystalline phases are as:
  - α-phase: ambient pressure, low/moderate cooling rate
  - β-phase: specific nucleating agents or from oriented α-crystals by moderately strong flow
  - γ-phase: elevated pressure and high crystallization temperature
  - Mesomorphic: high cooling rate

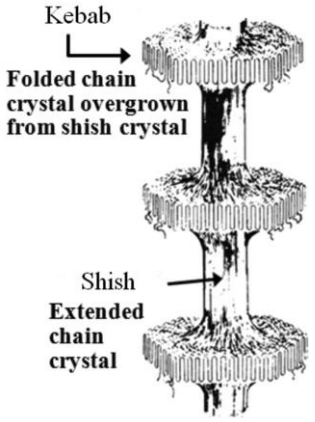


Spherulites





(a)



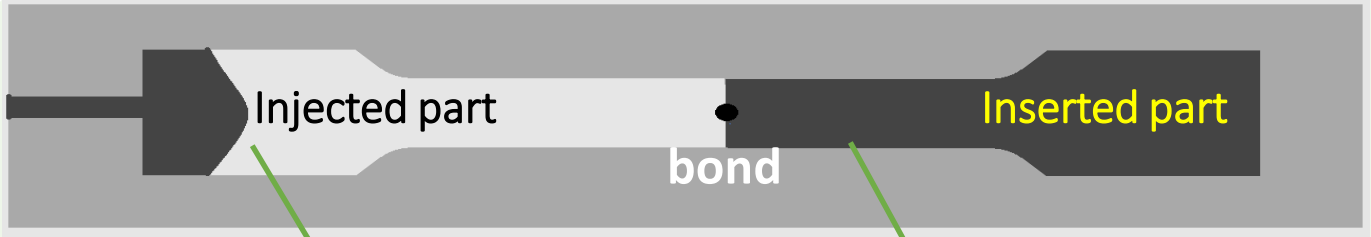
(b)

Shish-kebab: Pennings et al. (1970)

- Understanding the crystallization in the over-molding process and its influence on the adhesion bond properties.
- optimizing the over-molding process to obtain the best adhesion quality

Designed and prepared experiments

over-molding on fiber filled TP



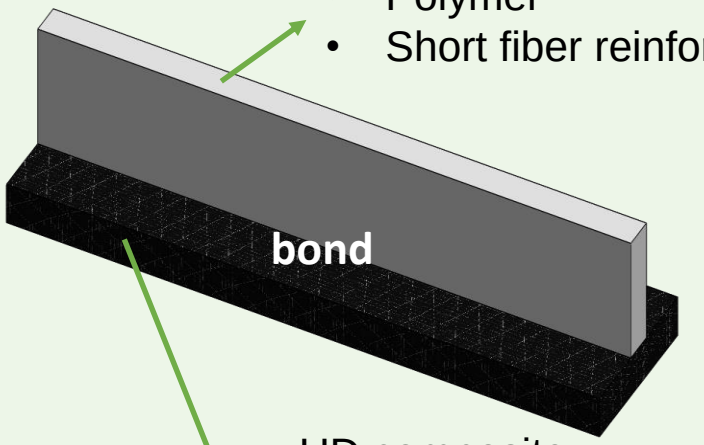
- Polymer
- Short fiber reinforced

- Polymer
- Short fiber reinforced

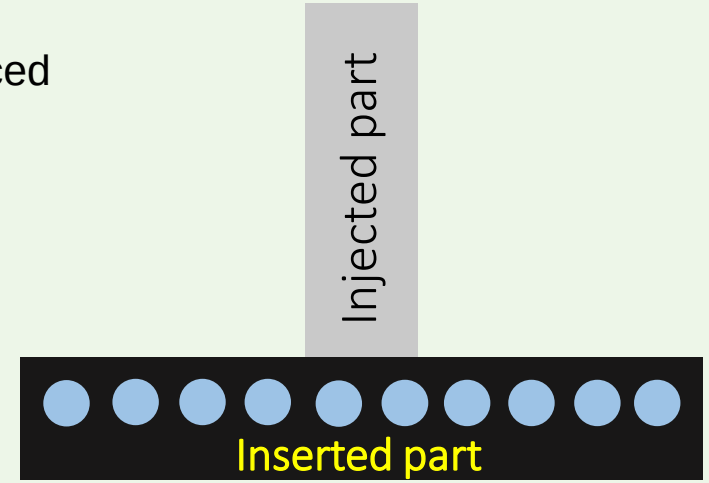
Based on the defined bond configurations

over-molding on continuous TPCs

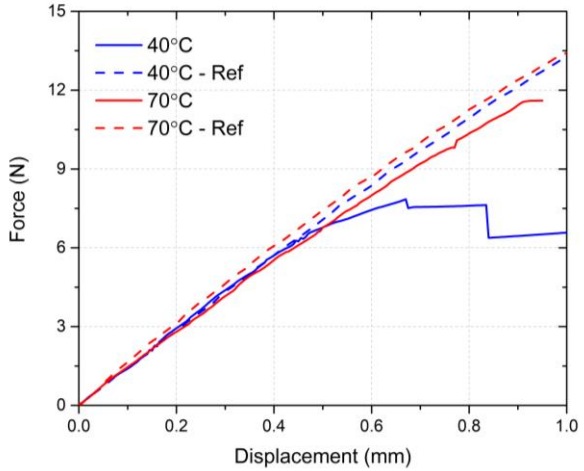
- Polymer
- Short fiber reinforced

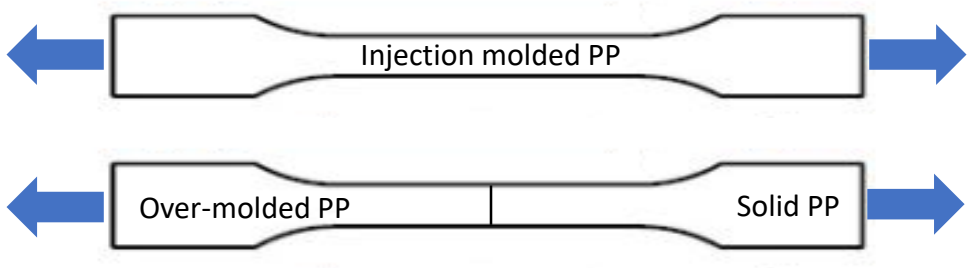


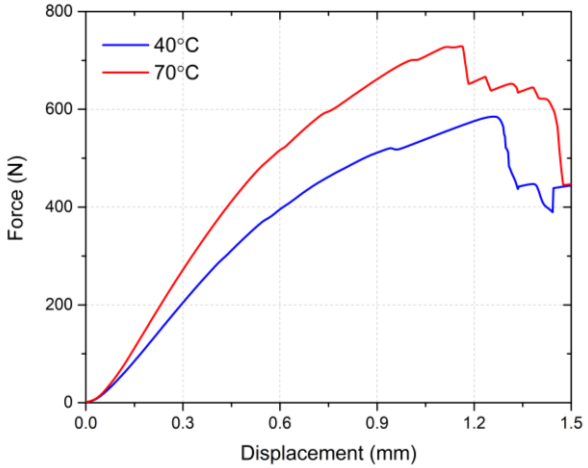
- UD composite
- Cross-ply

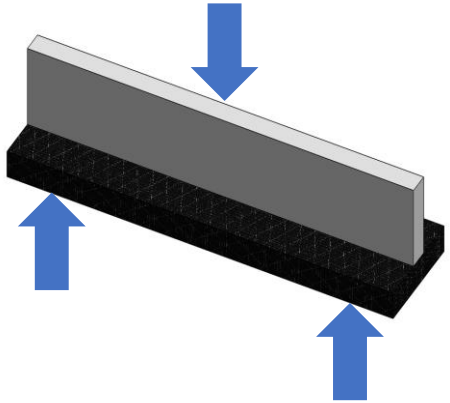


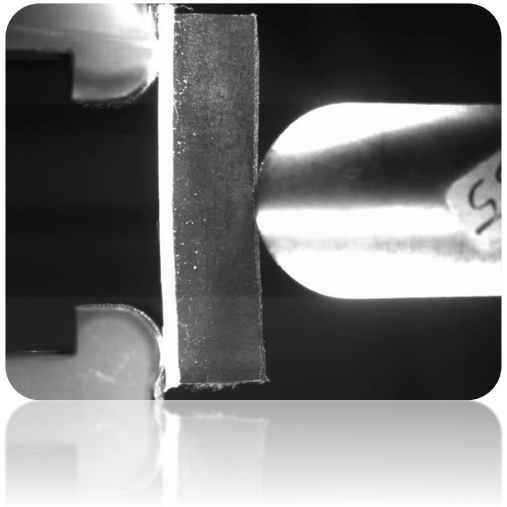
Experiments study of the over-molded PP











Preliminary study

Influence of the insert temperature on the mechanical behavior of the injection over-molded PP samples.

- Over-molded samples are compared with the injection-molded ones.
- The over-molded samples are weaker than the injection-molded ones.
- 70°C samples with the initial insert temperature of 70°C are stronger than the samples with the insert temperature of 40°C ones.

Simulation road-map

- Experimental verification
- Modifications & Improvements

Process Simulation

- Material flow
- Thermal history
- Fiber orientation
- Fiber distribution
- Fiber volume fraction

Multi-phases crystallization kinetics

Micromechanical simulations

- Homogenization of the different phases behavior. Interface, insert and over-molded area

Structural analysis

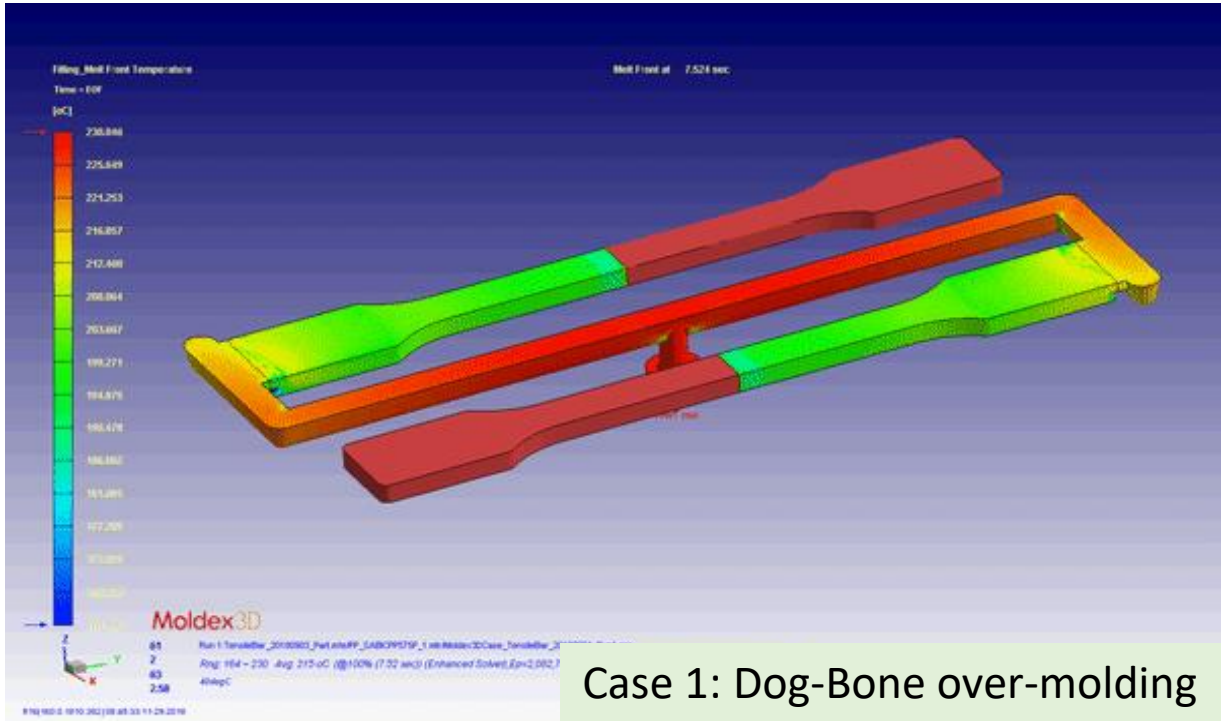
Phenomenological models

- If required

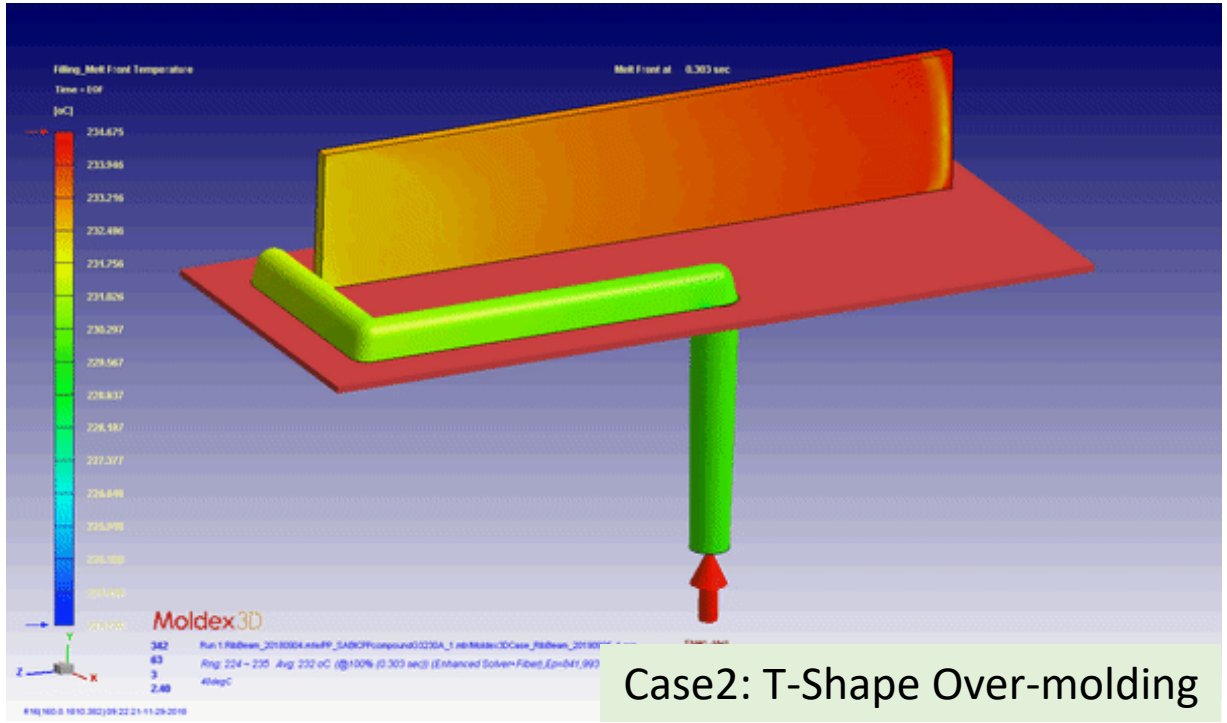
Predictive simulation of over-molded components behavior

Over-molding process simulation

- Material flow simulation of the over-molding process of T-Shape and Dog-Bone test samples.



Case 1: Dog-Bone over-molding



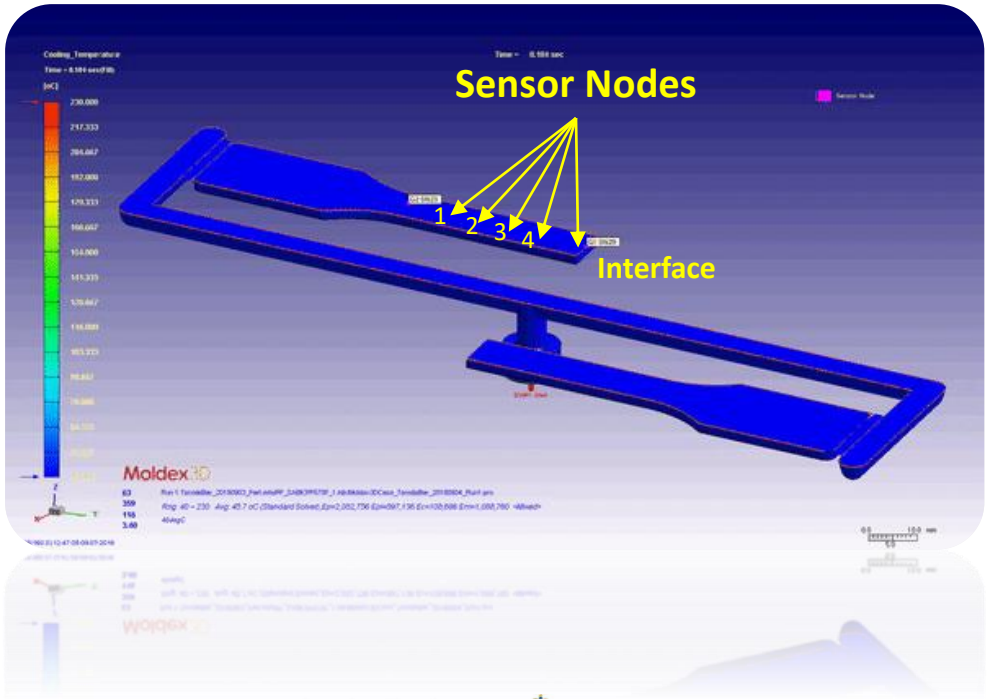
Case2: T-Shape Over-molding

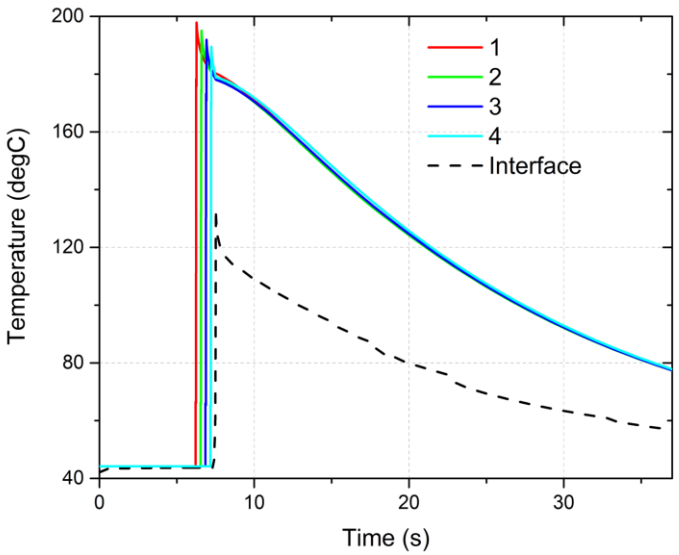
Case 1: Process History & Crystallization

- **Injection over-molding of PP material.**
  - Sensor Nodes along the flow direction are placed to monitor the process history (T,P).
  - The temperature and the pressure are processed based on the results from the sensor nodes.
  - The temperature on the interface is significantly lower due to the influence of the cold insert.
  - The final crystallinity on the interface '0.72' is a bit lower than '0,748' in Position 1.
  - However, there is much more α-phase on the interface.

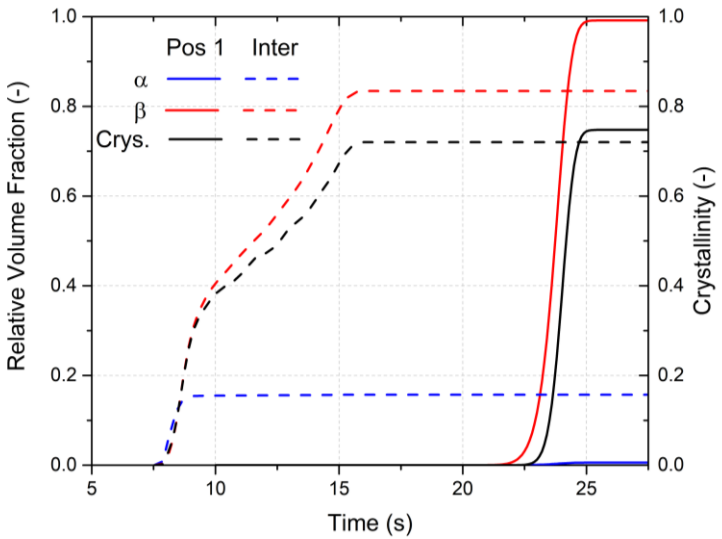
Modeling conditions

- Melt Temperature: 230 °C
- Insert temperature: 40 °C
- Filling time: 7,5s
- Packing time: 10s
- Cooling time: 20s





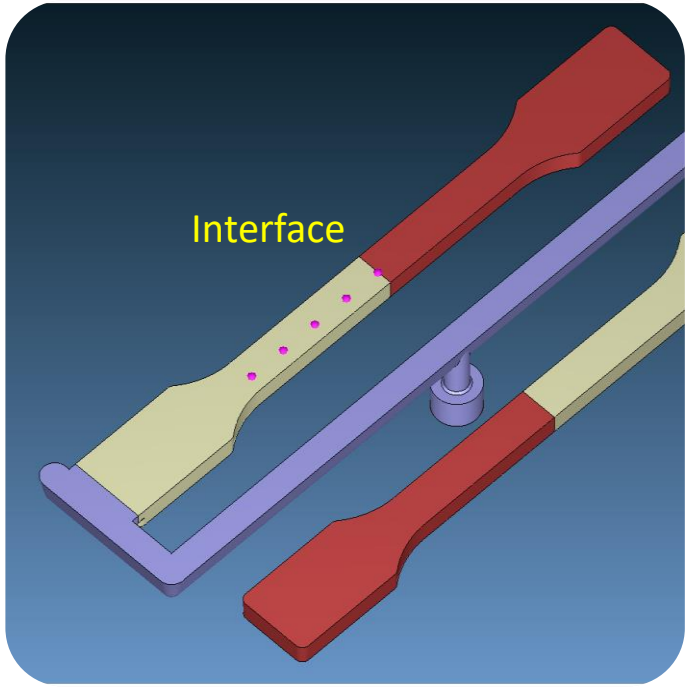
Thermal history:
Insert temperature: 40°C

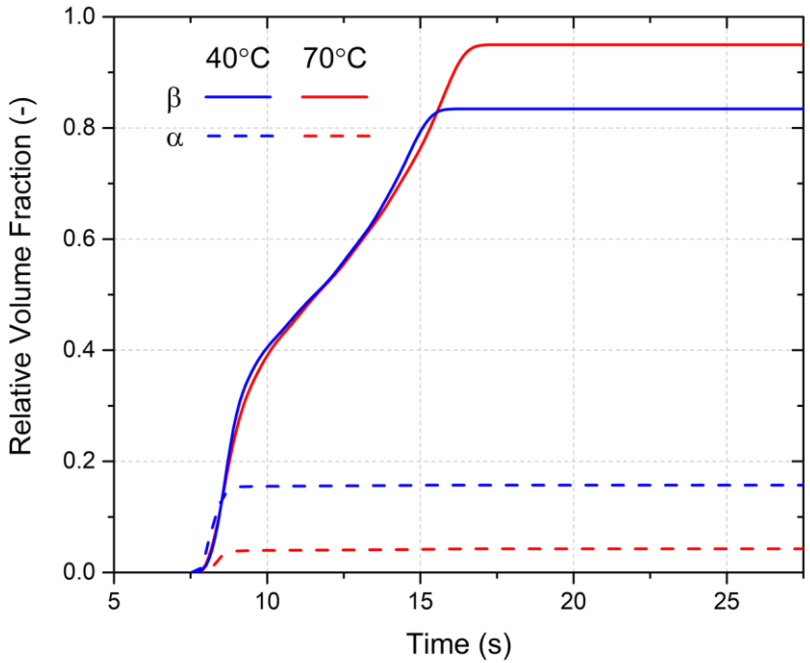


Crystallization
Insert temperature: 40°C

Case 1: Multi-phase Crystallization: Comparison

- Comparison of the crystallization of the inserts with initial temperature of 40°C & 70°C
  - β-phase on the interface is increased from 0.82 in 40°C to 0.95 in 70°C sample.
  - However, there is a significant decrease of α-phase on the interface.





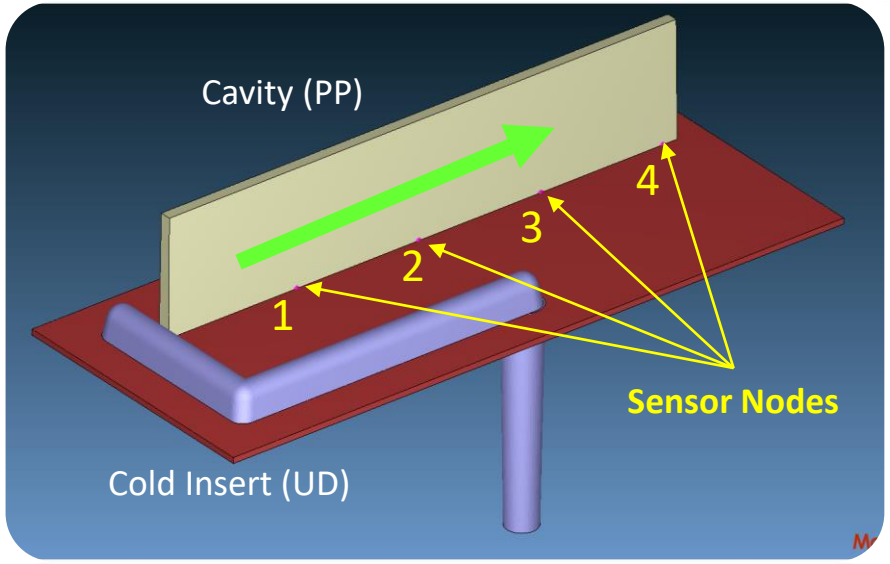
Crystallization comparison
Insert temperature: 40°C & 70°C

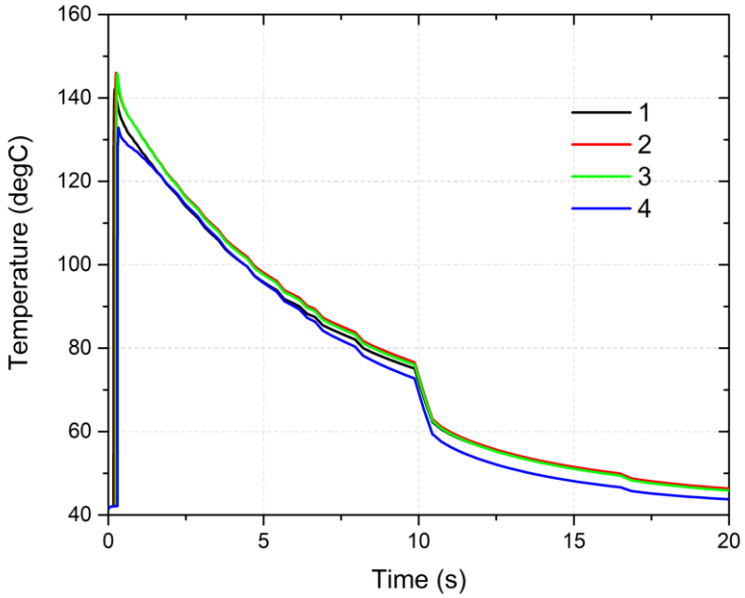
Case 2: Process History and Crystallization

- **Injection over-molding of glass fiber filled PP on UD composite.**
  - The highest temperature on the interface is about 150°C.
  - There is more mesomorphic phase in Position 4 because it has a higher cooling rate.

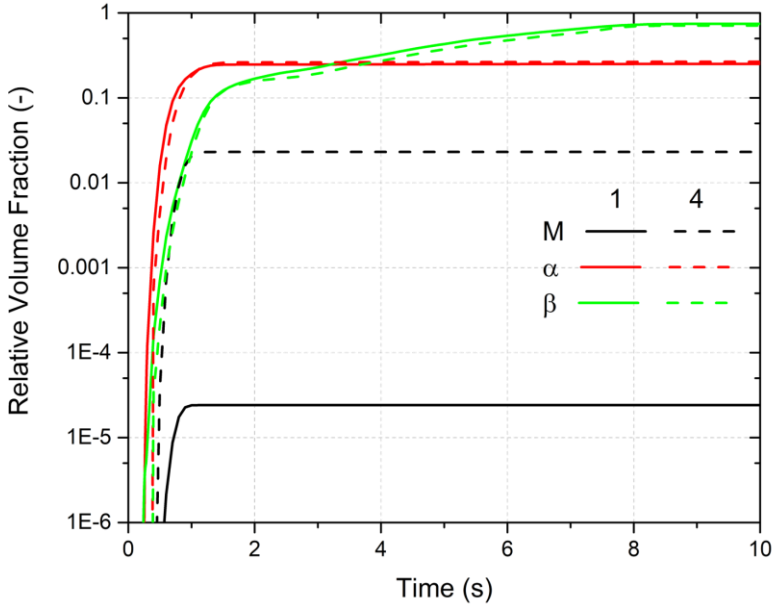
Modeling conditions

- Melt Temperature: 230 °C
- Insert temperature: 40 °C
- Filling time: 0,3s
- Packing time: 4,7s
- Cooling time: 15s



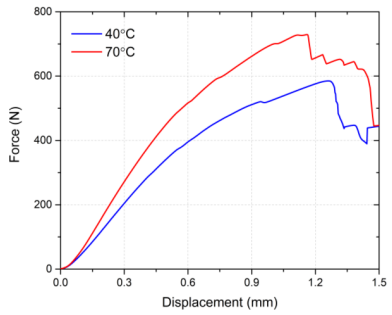


Thermal history:
Insert temperature: 40°C

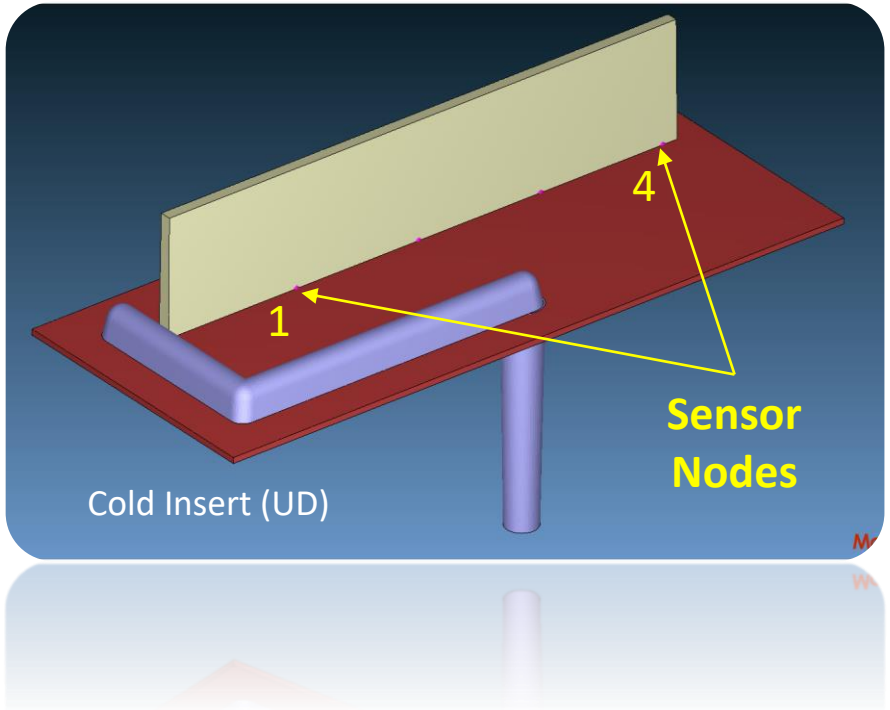


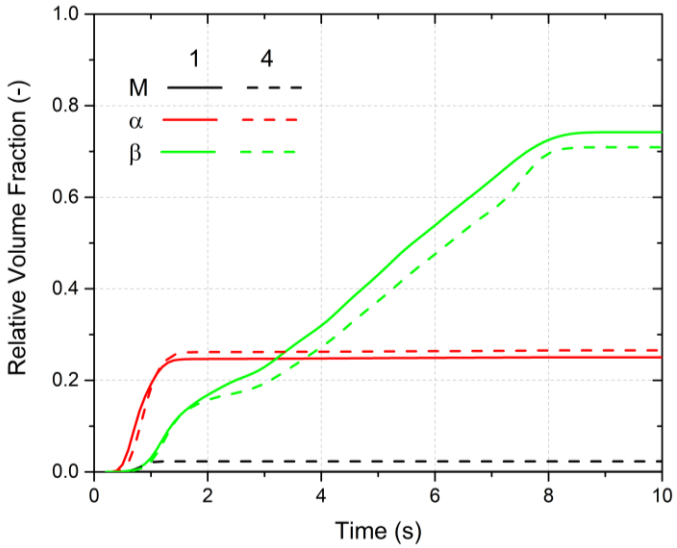
Crystallization
Insert temperature: 40°C

Case 2: Multi-phase Crystallization: Comparison

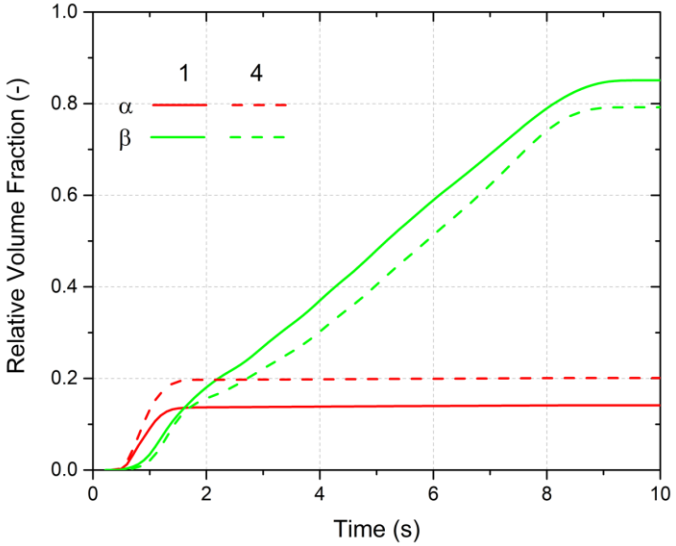


- **Comparison of the crystallization of the inserts with initial temperature of 40°C & 70°C**
  - There is more β-phase on the interface for the insert temperature of 70°C.
  - However, there is less α-phase on the interface for the insert temperature of 70°C.
  - Because of a low cooling rate no mesomorphic phase is observed in the insert of 70°C.





Insert temperature: 40°C



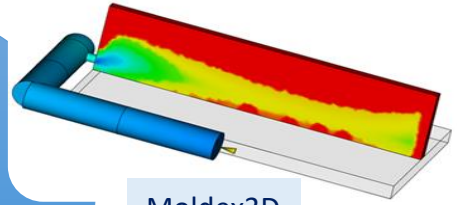
Insert temperature: 70°C

Preliminary multiscale simulations

- Experimental verification
- Modifications & Improvements

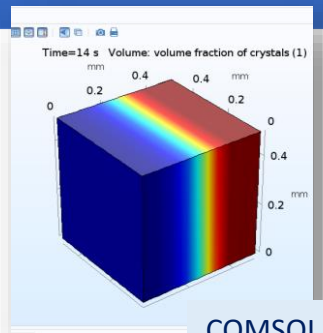
Process Simulation

- Material flow
- Thermal history
- Fiber orientation
- Fiber distribution
- Fiber volume fraction
- …



Moldex3D

Multi-phase crystallization kinetics

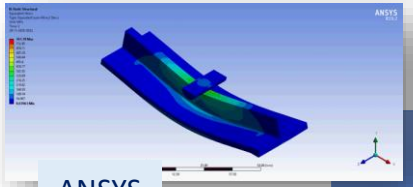


COMSOL

Micromechanical simulations

DIGIMAT

- Homogenization of the different phases behavior. Interface, insert and over-molded area
- …



ANSYS

Structural analysis

Phenomenological models

- If required

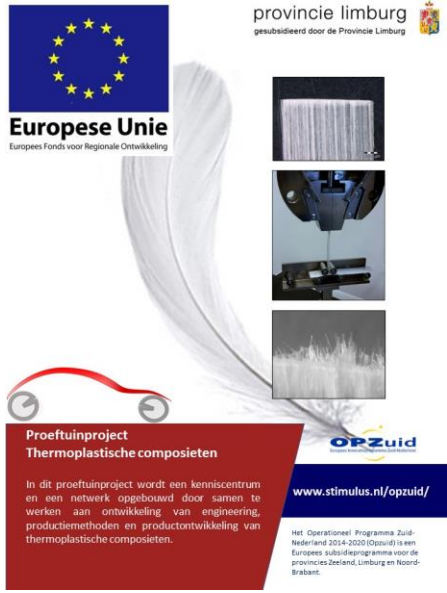
Predictive simulation of over-molded components behavior

Conclusions

- Experimental study:
  - The required experimental facilities and infrastructure have been setup.
    - Injection molding machine, Molding tools, test samples, mechanical testing apparatuses, microscopy facilities, etc.
  - The preliminary experimental studies show that at cold tooling temperature for fast cycling, insufficient adhesion happens between the over-molded and inserted PP.

- Numerical simulations:
  - Preliminary multiscale simulations have been designed and performed.
  - The numerical simulations show that crystallinity and microstructure of the interface are inhomogeneous due to thermal history of an over-molded part. This influences the interface property.

- Outlook: Identification and prediction of processing conditions for optimized adhesion



Thank you very much