Overmolding: An Integrated Design Approach for Dimensional Accuracy and Strength of Structural Parts

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AGENDA

Interface strength of overmolded thermoplastic composites

- Introduction
  - Overmolding process
  - COMPeTE Project

- Interface strength
  - Modelling
  - Experimental validation
  - Conclusions
  - Simulation examples

- Shape distortions
  - Introduction and approach
  - Results and conclusions
OVERMOLDING

Process overview

Overmolding = stamp forming + injection molding

- Short cycle times
- Net shape manufacturing
- Integration of reinforcing ribs / functionality

One-step process: forming and injection molding combined
Two-step process: forming and injection molding separated
OVERMOLDING
COMPeTE Project: Composites OverMolding Production TElchnology

- **Background:**
  - Combination between stamp forming and injection molding
    - Series production & Function integration
  - Knowledge gap
    - Interface strength
    - Shape distortions

- **Objective: reduce development time**
  - Develop models and simulation tools, provide guidelines
    - Interface strength
    - Shape distortions

- **Polymers of interest:**
  - PA6, PEEK
Interface strength
OVERMOLDING
COMPeTE Project: Interface strength

Objective:

- Develop models and simulation tools
  - Autodesk Moldflow for injection molding / thermal simulation
  - Predict the interface strength with relatively simple models
    - Input data easily obtained

- Characterize the interface strength using small research geometries
  - Tensile / shear loading

V-notched (Iosipescu) geometry:

Rib-on-plate geometry:
OVERMOLDING PROCESS

Process overview

Interface between:
- Insert
  - Woven fabric / UD laminate
  - Preheated shell / molten blank
- Flow
  - Short fiber reinforced polymer

Limited time for bonding:
- High cooling rates
  - Low mold temperature
- Heat transfer from flow to insert

Process parameters → Interface strength?

Moldflow simulation for $T_{\text{insert}} = T_{\text{mold}}$
INTERFACE STRENGTH
Development of the bond strength

Time required for intimate contact:
\[ t_{ic} \propto \frac{\eta_0}{P} \rightarrow \text{neglect} \]

Degree of healing: strength with respect to a fully healed surface

Time required for healing:
\[ D_h(t) = \frac{\sigma(t)}{\sigma_\infty} = \left[ \int_0^t \frac{1}{t_r(T(t))} \, dt \right]^{1/4} \]

Temperature profile
Polymer reptation time

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INTERFACE STRENGTH
Polymer reptation time

Reptation time:
- Required time to complete healing
- Temperature dependent
- Highly influenced by crystallites

Boundary conditions for healing:
- $T_g$

Reptation time

Healing of amorphous polymers

TPRC proprietary
INTERFACE STRENGTH
Polymer reptation time

Reptation time:
- Required time to complete healing
- Temperature dependent
- Highly influenced by crystallites

Boundary conditions for healing:
- $T_g$
- $T_m$ (heating)
- Crystallization temperature (cooling)
**INTERFACE STRENGTH**

Temperature profile

Insert heats up during overmolding
- Approaches average between $T_{\text{inj}}$ and $T_{\text{insert}}$
- For constant $c_p$ and no melting enthalpy

![Temperature profile diagram](image)

What happens if:
- $T_{\text{insert}} < T_m$
- $T_{\text{insert}} > T_m$

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Semi-crystalline PA6
- $T_m = 220 \, ^\circ\text{C}$
- $T_{\text{inj}} = 300 \, ^\circ\text{C}$
- $T_{\text{mold}} = T_{\text{insert}} = 160 \, ^\circ\text{C}$

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**Moldflow simulation**

![Moldflow simulation graph](image)
**INTERFACE STRENGTH**

Temperature profile and boundary conditions

**Boundary conditions:**
- **$T < T_m$**
  - No healing
- **$T > T_m$**
  - Healing according to model
  - $t_{rep}$ is very short above $T_m$
    - For PA6 and PEEK
    - ‘Instantaneous’ healing
- Simulation is very sensitive:
  - $T_{\text{insert}}$ (thermal simulation)
  - Onset for healing ($T_m$)
    - Melting trajectory

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Alternative approach?
INTERFACE STRENGTH
Degree of melting for semi-crystallines

Heat flow [J/s] vs. Temperature [°C]

Degree of healing $D_h$ vs. Degree of melting $D_m$

Degree of melting $D_m$ vs. Temperature [°C]

Degree of healing $D_h$ vs. Maximum temperature [°C]

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MODELLING
Numerical implementation

Moldflow analysis:

- Injected polymer
- Insert
- Gate
- Interface

No healing below $T_m$:

$T_{inj} = 300$ °C
$T_{mold} = T_{insert} = 160$ °C

GUI for healing analysis:

- Mesh data
- Temperature data

$D_m$ approach:
EXPERIMENTAL VALIDATION
Iosipescu geometry: Tensile test

Overmolding B3K on B3K, $T_{\text{mold}} = T_{\text{insert}} = 90$ °C, $T_{\text{inj}}$ varied

**Typical force-displacement diagram**

- Fully IM
- $T_{\text{inj}} = 260$ °C
- $T_{\text{inj}} = 280$ °C
- $T_{\text{inj}} = 300$ °C

**Tensile test for B3K on B3K insert**

- Fully injection molded specimen

$T_{m} = 220$ °C, Average temperature: 175 °C, 185 °C, 195 °C
EXPERIMENTAL VALIDATION

PA6 – Tensile. $T_{\text{inj}} = 280^\circ C$, $T_{\text{mold}} = 90^\circ C$

B3ZG6 on CETEX TC912 laminate. $T_{\text{mold}} = 90^\circ C$, $T_{\text{inj}} = 280^\circ C$

$T_m = 220^\circ C$  
Average temperature:  
Degree of healing (model):

<table>
<thead>
<tr>
<th>Insert temperature</th>
<th>90°C</th>
<th>180°C</th>
<th>230°C</th>
<th>270°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile stress [MPa]</td>
<td>185°C</td>
<td>230°C</td>
<td>255°C</td>
<td>275°C</td>
</tr>
<tr>
<td>Degree of healing</td>
<td>2%</td>
<td>50%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>
EXPERIMENTAL VALIDATION

PA6 – Tensile. $T_{\text{inj}} = 280^\circ\text{C}$, $T_{\text{mold}} = 90^\circ\text{C}$

B3ZG6 on CETEX TC912 laminate. $T_{\text{mold}} = 90^\circ\text{C}$, $T_{\text{inj}} = 280^\circ\text{C}$

$T_m = 220^\circ\text{C}$  Average temperature: 185 °C  230 °C  255 °C  275 °C
Degree of healing (model): 2%  50%  100%  100%
EXPERIMENTAL VALIDATION

PA6 – Tensile. \( T_{\text{inj}} = 280^\circ \text{C}, T_{\text{mold}} = 90^\circ \text{C} \)

B3ZG6 on CETEX TC912 laminate. \( T_{\text{mold}} = 90^\circ \text{C}, T_{\text{inj}} = 280^\circ \text{C} \)

\[ T_m = 220^\circ \text{C} \quad \text{Average temperature:} \quad 185^\circ \text{C}, 230^\circ \text{C}, 255^\circ \text{C}, 275^\circ \text{C} \]

\[ \text{Degree of healing (model):} \quad 2\%, 50\%, 100\%, 100\% \]
EXPERIMENTAL VALIDATION

PA6 – Tensile. $T_{\text{inj}} = 280^\circ\text{C}$, $T_{\text{mold}} = 90^\circ\text{C}$

B3ZG6 on CETEX TC912 laminate. $T_{\text{mold}} = 90^\circ\text{C}$, $T_{\text{inj}} = 280^\circ\text{C}$

5 mm

$T_m = 220^\circ\text{C}$

Average temperature:

Degree of healing (model):

- 185 °C: 2%
- 230 °C: 50%
- 255 °C: 100%
- 275 °C: 100%
EXPERIMENTAL VALIDATION

PA6 – Tensile. $T_{\text{inj}} = 280^\circ\text{C}$, $T_{\text{mold}} = 90^\circ\text{C}$

B3ZG6 on CETEX TC912 laminate. $T_{\text{mold}} = 90^\circ\text{C}$, $T_{\text{inj}} = 280^\circ\text{C}$

Average temperature: 185 °C 230 °C 255 °C 275 °C
Degree of healing (model): 2% 50% 100% 100%

Fiber migration into mold cavity $\rightarrow$ mechanical interlocking $\rightarrow$ higher strength
EXPERIMENTAL VALIDATION

PA6 – Tensile. $T_{\text{inj}} = 280^\circ\text{C}$, $T_{\text{mold}} = 90^\circ\text{C}$

B3ZG6 on CETEX TC912 laminate. $T_{\text{mold}} = 90 \ ^\circ\text{C}$, $T_{\text{inj}} = 280 \ ^\circ\text{C}$

$T_m = 220 \ ^\circ\text{C}$  
Average temperature:
Degree of healing (model):

- 185 $^\circ\text{C}$: 2%
- 230 $^\circ\text{C}$: 50%
- 255 $^\circ\text{C}$: 100%
- 275 $^\circ\text{C}$: 100%

Fiber migration into mold cavity $\rightarrow$ mechanical interlocking $\rightarrow$ higher strength
CONCLUSIONS
Modelling and experimental validation

Modelling:
- Model for bond strength prediction:
  - Moldflow
  - Non-isothermal healing model for amorphous polymers
  - Modified approach for semi-crystalline polymers
    - Melting behavior

Experimental validation:
- Small research geometries
- Migration of fibers for high $T_{\text{insert}}$
- PA6: Bond strength for $T_{\text{average}} < T_m$
  - Model is able to predict the bond strength qualitatively
    $\Rightarrow$ Identify critical area’s
SIMULATION EXAMPLES

Overmolding V-shape PEEK ($T_{\text{inj}} = 380°C$, $T_{\text{mold}} = T_{\text{insert}} = 220°C$)

Degree of healing after overmolding:

Gate locations

Possible crack-initiator

$D_h$

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SIMULATION EXAMPLES

Overmolding Demonstrator PEEK ($T_{\text{inj}} = 400^\circ\text{C}$, $T_{\text{mold}} = T_{\text{insert}} = 250^\circ\text{C}$)
SIMULATION EXAMPLES

Overmolding Demonstrator PEEK ($T_{\text{inj}} = 400^\circ\text{C}$, $T_{\text{mold}} = T_{\text{insert}} = 250^\circ\text{C}$)

Development of degree of healing during overmolding:
Shape distortions
SHAPE DISTORTIONS

Introduction

CTE mismatch

through-thickness stress distribution

warpage

material non-symmetry

warpage

laminate thickness = 0.15 mm

cavity height = 4 mm

spring-in

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SHAPE DISTORTIONS

Approach

- Conventional method (Moldflow)
  - Thermo-mechanical shrinkage without crystallization
  - Stress-free assumption
  - Uniform/nominal thickness

- Coupled approach for insert modelling (AniForm + Moldflow)
  - Temperature-dependent coefficient of thermal expansion and crystallization shrinkage
  - Shear angle-dependent properties
  - Fiber stresses from the stamp forming process
  - Thickness changes

- Model validation
  - Single curved geometry
  - Doubly curved geometry
SINGLE CURVED GEOMETRY

Results: Spring-in angle

G/PA6 laminate

C/LMPAEK laminate

Spring-in angle value with respect to 90°
SINGLE CURVED GEOMETRY

Results: Curvature

G/PA6 laminate + unfilled PA6

C/LMPAEK laminate + filled C/PEEK

Positive curvature value: midpoint of curvature on the rib side
CONCLUSIONS

Single curved geometry

- **G/PA6:**
  - **Spring-in angle** and **curvature** are more accurate using the coupled approach

- **C/LMPAEK:**
  - Improvement in predicting the **spring-in angle** and **curvature** after overmolding using the coupled approach
  - Decrease in **spring-in angle** is underestimated
    -> Possible underestimation of polymer shrinkage
DOUBLY CURVED GEOMETRY

Overview

Overmolded C/PAEK demonstrator: Simulated deformed shape (scaled):
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