Multiphase, Dual Polymer Injection Molding & Cooling of Open Cavity
to form both distinct & graduated material properties within a complex body

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Implant Design

General Soft Tissue Mechanics

- Nonlinear, Hyper-elastic
- Anisotropic/Orthotropic
- Viscoelastic

Ideal Implant Mechanics

- Duplicate or augment the natural response of body tissue/physiological function

Ligament Replacement & Augmentation System (LARS), used for massive rotator cuff repair

R&D, FEA, CFD, Material Selection, Testing & Assessment © Continuum Blue Ltd
Novel LARS Implant

Novel elastomeric, rotator cuff LARS

a) Isometric View

Fixation holes

b) Front View
c) Side View
Material Regions

Polymer 1

Graduated Region

Generalized Force Displacement Material Region Curves

Force

Displacement

Section A-A

Section B-B

Polymer 2
Aim is to find the production & process parameters required to produce the elastomeric implant, using a single injection mold process.

- **Reduce production costs**
  - Single process
  - Reduce physical handing
  - Increased production yields
  - Reduce QC steps
- **Increase integrity & homogeneity of implant**
  - Reduces the delaminating & bonding issues found in layered production process
Model Geometry, Domains & Boundary Conditions

Initial Subdomain Phases

- Gas (Atmosphere)
- Solid (Mold)
- Fluid (Polymer Solution)

- Outlet
- Mold Walls
- Mold Cavity
- Gravity Plane
- Dual Polymer Injection Inlet
COMSOL Model Overview

• 3 Transient Modules utilized:
  • Two-Phase Flow Laminar Phase Field (*chns*)
  • Phase Field (*mmpf*)
  • Convection & Conduction (*cc*)

• Two-Phase Flow Laminar Phase Field
  • Models Fluid-Air Boundary Flow

• Phase Field
  • Models 2 dual injected polymer solutions

• Convection & Conduction
  • Models thermal changes (*Solid, Fluid & Gas*)
Density & Viscosity Functions

Change in dynamic viscosity & density vs. temperature for the two polymer solutions used in the injection mold process.
Inlet Injection Process

Mold machine polymer 1 & polymer 2 injection flow profiles vs. time.
Simplified inlet condition to equivalent condition:

- Smooth inlet flow function implemented
- Combined flow rate & volume fraction

![Graph showing Inlet Flow Volume and 2nd Polymer Blend Volume Fraction over Time Step]
Equations & Boundary Conditions

\[ \rho(T_{cc})_{\text{fluid}} = \rho(T_{cc})^{\text{poly} 1} + \left\{ \left[ \rho(T_{cc})^{\text{poly} 2} - \rho(T_{cc})^{\text{poly} 1} \right] \times Vf_{\text{mmpf}}^{\text{poly} 2} \right\} \]

\[ \rho_{cc} = \rho_{\text{chns}} \]

\[ \mu(T_{cc})_{\text{fluid}} = \mu(T_{cc})^{\text{poly} 1} + \left\{ \left[ \mu(T_{cc})^{\text{poly} 2} - \mu(T_{cc})^{\text{poly} 1} \right] \times Vf_{\text{mmpf}}^{\text{poly} 2} \right\} \]

\[ k_{cc} = A \times \phi_{\text{chns}} + B \]

\[ C_p = D \times \phi_{\text{chns}} + E \]

\[ u_{cc} = u_{\text{mmpf}} = u_{\text{chns}} \]

**Subscripts**
- Poly 1 = 1st Polymer material/solution
- Poly 2 = 2nd Polymer material/solution

**Superscripts**
- = COMSOL Multiphysics module
- = Material phase or state: solid, gas, fluid
- = Various material dependent constants
- = Thermal Conductivity
- = Heat Capacity
- = Velocity Field
Validation (Thermal Data)

Time dependent thermal response curves of validation model vs. physical data at three different & distinct locations.

**NB:** Validation data done on a different 3D Body.
Validation (Cured Sections Data)

Partial view of a cured section of a molded device, illustrating the distinct cured polymeric regions (1 & 2) and comparison to the equivalent COMSOL model.

**NB:** Validation data done on a different 3D Body
Fluid Fill & Polymer Regions

Time Steps:
17
34
40
70
88
100

Fluid-Air Boundary
2nd Polymer Volume Fraction = 0.5
2nd Polymer Volume Fraction = 1.0
Thermal Effects During Filling

Time Steps: 17, 34, 40, 70, 88, 100

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Continued Flow After Injection

Time Step: 100

Time Step: 150
(End of Polymer Injection)

Time Step: 750

Time Step: 5000
(End of Polymer Flow)
Conclusions

- COMSOL Model successfully modeled the filling & curing of an open cavity mold with a combined polymer solution at an elevated temperature through a single port to produce vary graduated and distinct materials regions.

- The COMSOL Model developed was validated against:
  - Quantitative thermal data
  - Quantitative cured sections
  - Qualitatively against captured video footage of filling process

NB: Validation data done on a different 3D Body
Future Developments

- Additional polymer solution (3rd polymer)
- Multiple inlet & outlet locations across the mold cavity
- Time dependent curing function (specifically required for 3rd polymer)
- Multi-parameter optimization of the injection flow inlet profiles, mold temperature & polymer inlet temperatures
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