Residual Stresses in Injection Molding

Basic understanding and measurement
1. Injection Molding
2. Simple stress model
3. Residual Stress measurements
4. Conclusions

1. Injection molding
Residual stresses in finished products
• Due to crystallization, thermal shrinkage and pressure
• Invisible
• Affects product performance
• More sensitive to stress cracking
• Warpage, tolerance problems
• Undesired optical effects (birefringence)

2. Simple stress model
With equations
• Solidification pressure: $p_f(z) = \frac{1 - 2\alpha}{2} [L(z) - \bar{L}]$
• Hydrostatic strain: $e_s = \frac{1 - 2\alpha}{2} [L(z) - \bar{L}]$
• Expansion upon ejection: $e_{e} = \frac{1 - 2\alpha}{2} [L(z) - \bar{L}]$
• Stress after ejection: $\sigma_z = \sigma_y = -\frac{1 - 2\alpha}{2} [L(z) - \bar{L}]$

Note: Thermal stresses vanish after ejection and cooling down
Reason: Prevention of in-mold shrinkage

2. Simple stress model
Validation studies
• Residual stresses
  $\sigma_z = \sigma_y = -\frac{1 - 2\alpha}{2} [L(z) - \bar{L}]$

• Shrinkage after molding:
  $\delta_{e} = \sigma_y = -\frac{1 - 2\alpha}{2} [L(z) - \bar{L}]$

Works amazingly well!
2. Simple stress model

Warpage due to uneven cooling

- Injection Molded plate
  - Low hold pressures warp to hot side; high to cold side
  
  \[
  \text{curvature} = -\frac{12(1-v^2)}{E} \frac{P_{\text{hot}} y}{h^3} \]

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- Model predicts correct trends, but
- Underpredicts warpage by factor 2


2. Conclusions about stress model

- Model is simple and gives a clear understanding
- For simple geometries model works as good as simulation tools
- Frozen-in cavity pressure profile determines stresses and shrinkage (not the thermal stresses!)
- Surface layer and core are in tension; sub-surface layer in compression
  
  - Shrinkage and warpage follow from same model
  - Shrinkage and warpage can be tuned with holding pressure and mold temperatures

3. Residual Stress Measurements

Overview of methods

- Birefringence
  - Sensitive to both orientation and stress (PC, PMMA more for stress, PS more for orientation)
  - Stresses relieve near cutting surface \( \rightarrow \) not useful
- Layer Removal
  - Elaborative
  - Stress relaxation due to milling heat
- Hole drilling method
  - Only "average" stress level possible \( \rightarrow \) not useful
- Environmental Stress Cracking test
  - Only "average" stress level possible \( \rightarrow \) not useful

3. Residual Stress Measurements

Outline of Layer Removal test

1. Mill top layer (50-200 \( \mu \)m)
2. Residual stresses are no longer balanced
3. Release from vacuum rig
4. Measure curvature \( \kappa \)

\[
\kappa = \frac{4}{h^2} \left( \frac{6}{h^2} - 2 \right) \left( \frac{ \Delta E}{E} \right) \]

\( \Delta E \) = deflection profiles, curvature profiles, stress distribution

(Tranting and Read, J Appl Phys 22, p.130 (1951))
3. Residual Stress Measurements

**Layer Removal method: Problems and solutions**

- Stress relaxation after production
  - Store in freezer before use
- Melting and stress release during milling
  - Use sharp tool and speed < 1500 rpm
- Creep effects after milling
  - Due to flattening in test rig! Wait 10 min (96% recovery)
- Resolution: milling <0.1 mm is difficult
  - Will give problems near surface
- Data analysis of $\kappa(z)$ curve: differentiation error
  - Do not fit a polynomial over all data points
  - but use a sliding window fit

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3. Residual Stress Measurements

**Why Excimer laser ablation**

- KrF has high energy photons (3.5-8 eV)
- direct bond breaking; no melting!
- Pulsed operation: shockwaves remove debris
- Ultra thin layers possible (< 1 µm)

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3. Residual Stress Measurements

**Comparison between standard milling and laser ablation**

- Stress levels of 5 MPa tensile to -10 MPa compression
- Typical error margin: ± 0.5 MPa
- Good consistency; differences only near surface (200 µm)
- 500-1000 rpm milling similar to laser ablation
- 2000 rpm not OK: surface stresses changed

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3. Residual Stress Measurements

**Comparison with model predictions**

- Low viscosity; high $P_h$
  - Large tensile surface stress
  - "Inversion" of stress profile
  - Low stresses in core
  - Good match with model

- High viscosity; low $P_h$
  - Large compressive surface stress
  - Almost quenching like stress profile
  - Reasonable match with model

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4. Conclusions

- Stresses in injection molding are mainly due to frozen-in pressure variations
- Warpage is due to asymmetric stress distribution
- Stress profile, warpage and shrinkage can be estimated in a relatively simple way

- **Layer Removal method** is suitable to measure stress profiles
  - but carefulness is required
- Depending on viscosity and holding pressure the frozen-in stress profiles can be tuned from compressive to tensile!