Use of FEA to Optimise Cure Cycles of Rubber Components

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Rubber In Engineering Group
Afternoon Technical Discussion: Design and Manufacture with Elastomers
University of Nottingham, Friday 1st July 2016
How do we optimise the cure procedure for
• Large items
• Small items cured at high temperature?
Einstein diffusion equation: \( \bar{x} = \sqrt{2\kappa t} \)

- \( \kappa \) - thermal diffusivity
- \( \bar{x} \) - RMS distance
- \( t \) - time

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Diffusion Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>20 seconds</td>
</tr>
<tr>
<td>10</td>
<td>8 minutes</td>
</tr>
<tr>
<td>50</td>
<td>3.5 hours</td>
</tr>
<tr>
<td>100</td>
<td>14 hours</td>
</tr>
</tbody>
</table>

\( \kappa = 10^{-7} \text{ m}^2\text{s}^{-1} \)
Theoretical Background
Heat Diffusion

Diffusion equation (uniaxial heat flow):

\[ \rho c \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left( K \frac{\partial \theta}{\partial x} \right) + Q \]

\( \theta \) - temperature

\( t \) - time

\( x \) - position

\( K \) - thermal conductivity

\( c \) - specific heat capacity

\( \rho \) - density

\( Q \) - volumetric power generation

Diffusivity: \( \kappa = \frac{K}{\rho c} \)
Heat Diffusion

Diffusion equation (uniaxial heat flow):

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- \( t \) - time
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- \( K \) - thermal conductivity
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- \( Q \) - volumetric power generation

**Analytical solution:**

simple geometry and boundary conditions

\[ \theta = \theta_0 + (\theta_p - \theta_0) \left[ 1 - 4 \sum_{n=0}^{N} \frac{-1^n}{\pi} \exp \left( \frac{-\kappa(2n+1)^2 \pi^2 t}{4 \ell^2} \right) \right] \]

0 \(< t \leq t_p \)

\[ \theta = \theta_H + (\theta_0 - \theta_H) \left[ 1 - 4 \sum_{n=0}^{N} \frac{-1^n}{\pi} \exp \left( \frac{-\kappa(2n+1)^2 \pi^2 (t - t_p)}{4 \ell^2} \right) \right] \]

\( t_p < t \)

**Numerical solution:**

any geometry and boundary conditions

- In-house program
- Commercial FEA
Characterising Cure

- Rheometer torque (dNm) vs. time (minutes)
- Temperatures: 90°C, 100°C, 120°C, 140°C, 160°C
Characterising Cure

Assume
\[ \frac{t_2}{t_1} = C^{(\theta_1 - \theta_2) / \theta_c} \]

- \( t \) - cure time
- \( \theta \) - temperature
- \( C \) - coefficient of vulcanization (~2)
- Define \( \theta_c = 10^\circ C \)

Normalise rheometer torques by dividing by maximum value

![Graph showing cure times at different temperatures](image)
Characterising Cure

Assume

\[ \frac{t_2}{t_1} = C(\theta_1 - \theta_2) / \theta_c \]

- \( t \) - cure time
- \( \theta \) - temperature
- \( C \) - coefficient of vulcanization (\( \approx 2 \))

Define \( \theta_c = 10^\circ C \)

Normalise rheometer torques by dividing by maximum value
Characterising Cure

\[
\frac{t_2}{t_1} = C^{(\theta_1 - \theta_2)/\theta_c}
\]

Equivalent cure time:

\[
t_{eq}(\theta_{ref}) = \int C^{(\theta - \theta_{ref})/\theta_c} dt
\]

Representative cure temperature:

\[
\bar{\theta} = \frac{\int \theta C^{(\theta - \theta_{ref})/\theta_c} dt}{t_{eq}(\theta_{ref})} = \frac{\int \theta C^{0/\theta_c} dt}{\int C^{0/\theta_c} dt}
\]
Characterising Cure

\[ -\frac{\log C}{\theta_c} \]

fit to t70: C=1.92
Example – Cure of Laminated Bearing
# Cure of Bearing - Thermal Properties

**Rubber**
- standard engineering compound
- NR + 40pphr N550 carbon black

<table>
<thead>
<tr>
<th>Property</th>
<th>rubber</th>
<th>steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (Wm(^{-1})K(^{-1}))</td>
<td>0.24</td>
<td>63</td>
</tr>
<tr>
<td>Specific heat capacity (JK(^{-1})kg(^{-1}))</td>
<td>1530 at 0(^{\circ})C</td>
<td>420</td>
</tr>
<tr>
<td></td>
<td>2020 at 150(^{\circ})C</td>
<td>7860</td>
</tr>
<tr>
<td>Coefficient of vulcanisation</td>
<td>1.92</td>
<td></td>
</tr>
<tr>
<td>Heat of vulcanisation (Jkg(^{-1}))</td>
<td>13300</td>
<td></td>
</tr>
<tr>
<td>Density (kgm(^{-3}))</td>
<td>1096</td>
<td></td>
</tr>
</tbody>
</table>
Cure of Bearing - FEA Simulation

300 Wm$^{-2}$K$^{-1}$

3 Wm$^{-2}$K$^{-1}$
Cure of Bearing - FEA Simulation

6 Wm\(^{-2}\)K\(^{-1}\)

6 Wm\(^{-2}\)K\(^{-1}\)
Cure of Bearing - Comparison with Experiment

The diagram shows the temperature changes over time for different parts of a bearing and mould. The graphs compare experimental results with Finite Element Analysis (FEA) predictions.

- **Experiment**
  - Bearing centre
  - Bearing top
  - Mould centre
  - Mould top

- **FEA**
  - Bearing centre
  - Bearing top
  - Mould centre
  - Mould top

A dotted line represents the nominal applied temperature.
Cure of Bearing - Equivalent Cure Time

- **t_{30}** and **t_{95}**

- **Experiment - Centre**
  - FEA - Centre
  - Experiment - Edge
  - FEA - Edge

- Equivalent cure time at 110°C (hours)

- **t_{30}**: Heating
- **t_{95}**: Cooling

- **0** to **6** hours
Cure of Bearing - Equivalent Cure Time

- experiment
- FEA - realistic
- FEA - perfect mould contact
- FEA - not insulated
- FEA - perfectly insulated
- FEA - uniaxial
- FEA - no steel pin

Equivalent cure time at 110°C (hours)
- Heating
- Cooling

at centre of bearing
Optimisation of cure times for rubber pads
Optimisation of Press Time

1. Estimate press time
2. Run simulation
3. Calculate equivalent cure time
4. Check against targets:
   - \( t_{eq} > t_{50} \) everywhere when press opened
   - \( t_{eq} > t_{95} \) everywhere after cooling

If not met, re-calculate press time.

If just met, END.
Useful Tips for Large Mouldings

• Preheat the rubber or use a stepped cure
• Use a low press temperature
• Keep pressure on until centre has started to cure to avoid porosity
• Insulate the mould while heating in the press
• Cool quickly to reduce over-cure.
Acknowledgements and References


J. Gough. Optimization of times and temperatures for vulcanizing thick rubber pads. *Submitted to Rubber Chemistry and Technology*

Thanks to Mason Industries Inc. for funding and permission to publish the work on optimisation of press times of pads