Fatigue Modeling of a Powder Metallurgy Main Bearing Cap

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Powder Metallurgy Process – Press & Sinter

Closed-Die Compaction

Final Shape and Mechanical properties are determined.

Three main steps:
1. Die Filling
2. Compaction
3. Ejection

- Load the mixture into a die or mould and apply pressure.
- This gives what is called a compact which requires only to have sufficient cohesion to enable it to be handled safely and transferred to the next stage.
- Such compacts are referred to as green, meaning unsintered: hence the terms green density and green strength.

Sintering

The thermal treatment of a powder or compact at a temperature below the melting point of the main constituent, for the purpose of increasing its strength by bonding together the particles.
Powder Metallurgy Process – Press & Sinter

- A cost-effective and superior method of forming precision net-shape metal components
- Saves valuable raw materials through recycling and elimination of costly secondary machining through net and near-net shape design.

**Scientific Approaches**

**Powder**
- (purity, size, shape, density)

**Mixing**
- (conditions, homogeneity, segregation, packing, flow)

**Compaction**
- (discrete flow, friction, compaction, lubrication)

**Sintering**
- (temperature, time, heat rate, atmosphere, mass loss, densification, warpage)

**Heat Treatment**
- (homogeneity, heat, size change)

- Variations in input size powders
- Discrete element analysis
- Constitutive equations, tooling, lubrication, friction, work hardening
- Heat transfer, densification, mass change, phases
- Phase changes, diffusion, heat transfer

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Current PM Parts in Automotive Industry

- **Gears**
  - Phased teeth sprocket for General Motors 4T40/45 transmission.

- Main-bearing powder metal caps for 3.8 and 3.1 liter General Motors automotive engines.

*Courtesy of Cincinnati, Inc. (1995)*
Objective and Benefit of PM Modeling

Objective

- Shorten the lead-time needed from concept to implementation for new components
- Optimize current component for increasing performance and reduced weight
- Use modeling tool to evaluate (lightweight) material substitution in components
- Cost reductions
  - eliminating tooling iterations
  - eliminating prototype components (right-the-first-time)
  - improve material efficiency
  - significantly reducing warranty cost
- Improve our scientific understanding of powder metallurgy

Performance & Design Optimization

- Eliminating prototype components (right-the-first-time)
- Improving material efficiency
- Significantly reducing warranty cost
- Improving our scientific understanding of powder metallurgy
Outline

I – Compaction
- Material Modeling
- Material Characterization
- Closed-die Compaction of a Multi-Column part
- Closed-die Compaction of a Main Bearing Cap (MBC)

II – Sintering
- Material Modeling
- Material Characterization – Dilatometer Tests/Dimensional Changes
- Sintering of a Main Bearing Cap
- Density Comparison FEA & Experiments

III – Fatigue Analysis of Main Bearing Cap (MBC)
- MBC Supplier Fatigue Fixture
- Multi-Stage Fatigue Model (MSF)
- Fatigue Curve and Initial Conditions
- FEA results
- Comparison Fatigue Tests Results and FEA Predictions

IV – Summary
The yield surface is composed of:
- a failure envelope
- a movable cap surface

Three different types of behavior are possible:
Elastic, Failure and Compaction (cap).

The **Failure** mode of behavior:
- Limit the level of shear stress that the material can support without failure.
- Non-associated flow rule.
- The plastic strain is composed of an irreversible deviatoric (shear) component.

The **Cap** mode of behavior:
- The motion of the cap is related to the plastic volumetric strain through the use of a hardening rule (cap hardening).
- Associated flow rule.
- The plastic strain is composed of a shear component together with a negative volumetric component, which represents permanent compaction of the material.
- The Cap surface does not move during purely elastic deformation or when the stress point lies on the failure envelope alone.
I – Compaction
Material Modeling – Drucker/Prager Cap Model (VUMAT User Material subroutine in Abaqus/Explicit)

\[ F^*(p_s) = d + \frac{p_s - p_d}{2} \tan \beta \]

\[ q = s - \alpha \]

Shear Failure Surface \( F_s \)

Cap Surface \( F_c \)

\[ F^*(p_s) = d + \kappa + \frac{p_s - p_d}{2} \tan \beta \]

Mises Surface \( F_p \)

\[ \sigma_1, \sigma_2, \sigma_3 \]

\[ p \]
I – Compaction
Material Characterization – FC-0205 Steel Powder with 0.6% and 1.0% Acrawax

– All compaction tests are performed on cylindrical compacts
– Young’s Modulus measured from green compacts at different densities

Compressibility – Cap Hardening

Young’s Modulus $E$

Material Cohesion $d$

Cap Eccentricity $R$

Interparticle Friction $\beta$

$F_t$ Brazilian
$\sigma_t = \frac{2F_t}{\pi DT}$
$p_t = \frac{2\sigma_t}{3}$
$q_t = \sqrt{13}\sigma_t$

$F_C$ Compression
$\sigma_c = \frac{F_C}{A}$
$p_c = \frac{\sigma_c}{3}$
$q_c = \sigma_c$

Strain gages to measure hoop strains

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I – Compaction
Material Characterization – PQ-Plots: Iso-Densities Lines in PQ Stress Space

Evolution of Yield Surfaces during densification

Theoretical Density
FC-0205 0.6% & FC-0208: 7.44 g/cc
FC-0205 1.0%: 7.25 g/cc

Tap Density: 3.29 g/cc
Apparent Density: 3.02 g/cc
I – Compaction
Closed-Die Compaction of a Multi-Column part (Abaqus/Explicit)

- Abaqus/Explicit with CAX4R elements
- Axisymmetric model with swept display

Experiment
characterized by X-ray and Archimedes’ density measurements

Density values from Archimedes’ Method

<table>
<thead>
<tr>
<th>Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
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</thead>
<tbody>
<tr>
<td>Immersion Density (g/cc)</td>
<td>6.07</td>
<td>6.41</td>
<td>6.50</td>
<td>6.56</td>
<td>5.50</td>
<td>6.60</td>
<td>6.36</td>
<td>6.36</td>
<td>6.53</td>
<td>6.41</td>
<td>6.50</td>
<td>6.53</td>
</tr>
<tr>
<td>FEA (g/cc)</td>
<td>5.99</td>
<td>6.49</td>
<td>6.46</td>
<td>6.45</td>
<td>5.51</td>
<td>6.48</td>
<td>6.65</td>
<td>6.35</td>
<td>6.20</td>
<td>6.11</td>
<td>6.10</td>
<td>6.04</td>
</tr>
<tr>
<td>Difference (g/cc)</td>
<td>-0.08</td>
<td>0.08</td>
<td>-0.04</td>
<td>-0.11</td>
<td>0.01</td>
<td>-0.05</td>
<td>0.05</td>
<td>-0.01</td>
<td>-0.16</td>
<td>-0.32</td>
<td>-0.20</td>
<td>-0.31</td>
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<tr>
<td>Percent Error</td>
<td>-1.36</td>
<td>1.20</td>
<td>-0.61</td>
<td>-1.64</td>
<td>0.16</td>
<td>-0.77</td>
<td>0.69</td>
<td>-0.15</td>
<td>-2.59</td>
<td>-4.93</td>
<td>-3.20</td>
<td>-4.84</td>
</tr>
</tbody>
</table>

2D X-Ray CT attenuation distribution
(sample thickness: 0.25 inch)

Finite Element Analysis
Immersion Density

Average Densities (g/cc)

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I – Compaction
Closed-Die Compaction of Main Bearing Cap (Abaqus/Explicit)

C3D8R Elements in Abaqus/Explicit
No Separation Relationship
Non Uniform Apparent density
I – Compaction
Closed-Die Compaction of a Main Bearing Cap – Springback (Abaqus/Standard)

Geometry and Material Solution imported from Abaqus/Explicit to Abaqus/Standard for Elastic Springback Analysis

Boundary Conditions

- Point with x = 0
- Points with y = 0
- Points with z = 0

Volume grows 0.6% after springback

Geometry of MBC before (with mesh) and after (without mesh) springback. (Deformation Scale Factor = 100)
To study the creep of powder due to diffusional mass transport on the interparticle contacts, McMeeking and Kuhn [1992] proposed a macroscopic diffusional creep law.

To obtain the diffusional deformation rate as defined by McMeeking and Kuhn [1992], we introduce the following sintering dissipation potential [Kwon et al., 2004]:

$$ F_{di} = -\frac{1}{2K_d} (p + \sigma_s)^2 + \frac{q^2}{6\mu_d} $$

$K_d(p, p_0, T, G, Q_b, R)$ is the bulk viscosity

$\mu_d(p, p_0, T, G, Q_b, R)$ is the shear viscosity

$\sigma_s(p, p_0, G, \gamma)$ is the macroscopic manifestation of the driving forces for the processes of sintering.

(also called the sintering potential)

The grain growth evolution under pressureless sintering can be written as [Kwon et al., 2004]:

$$ \dot{G} = k' \frac{G}{G^2} $$

$k'(T, Q_G, R)$ is a material constant

The deformation rate is given by:

$$ D_{di} = \frac{1}{3} \frac{\partial F_{di}}{\partial p} I + \frac{\partial F_{di}}{\partial q} n = -\frac{1}{3} \frac{p + \sigma_s}{K_d} I + \frac{q}{3\mu_d} n $$
Dimensional Changes for FC-0205 0.6% Acrawax
Heating Rate: 10°C/min – Green density: 0.61%
II – Sintering

Sintering Analysis of a Main Bearing Cap – Dimensional changes (Abaqus/Standard)

- C3D8R Elements in Abaqus/Standard
- Density mapping from Springback solution
- MBC supplier temperature profile applied to every node

Density distribution and shrinkage of the MBC after sintering with a deformation scale factor of 100 (mesh of green part is shown as transparent).
II – Sintering
Density Comparison FEA & Measurements

- Highest percent error in zones 6, 7, 8 and 9 where the particle flow is the most important during compaction.
III – Fatigue Analysis of Main Bearing Cap

MBC Fatigue Fixture

**Fixture description:**

The load is applied at an angle of 10° vertical axis of the bearing cap and it is distributed at an arc length relative a 52.5° angle. A preloading torque of 60 ft-lbs was applied to each of vertical bolts.
– The microstructure-based multi-stage fatigue (MSF) model incorporates different microstructural discontinuities (pores, inclusions, etc.) on physical damage progression.
– The fatigue life is partitioned into three stages based on the fatigue damage formation and propagation mechanisms:

\[ N_{Total} = N_{Inc} + N_{MSC} + N_{PSC} + N_{LC} = N_{Inc} + N_{MSC/PSC} + N_{LC} \]

• Crack incubation (INC) as a function of local plastic deformation (modified Coffin–Manson law),

\[ C_{inc} N_{inc}^\alpha = \beta = \frac{\Delta \gamma_{max}^p}{2} \]

• Microstructurally small crack (MSC) and physically small crack (PSC) growth [Gall et al., 2000]:

\[
\left( \frac{da}{dN} \right)_{MSC} = \chi (\Delta CTD - \Delta CTD_{th}) \\
\Delta CTD = aC_1 \left( \frac{GS}{GS_0} \right)^{\sigma_0} \left( \frac{GO}{GO_0} \right)^{\varepsilon} \left[ \frac{U\Delta\sigma}{S_{ut}} \right]^{\xi} + C_1 \left( \frac{GS}{GS_0} \right)^{\sigma_0'} \left( \frac{GO}{GO_0} \right)^{\varepsilon'} \left[ \frac{U\Delta\gamma_{max}^p}{2} \right]^{2}_{macro} 
\]

• Long crack (LC) growth (Paris law):

\[
\log \left( \frac{da}{dN} \right) = \log \left( A(\Delta K)^m \right) \quad \Delta K = Y\Delta\sigma \sqrt{\pi a}
\]
III – Fatigue Analysis of Main Bearing Cap
Fatigue curve and Initial Conditions (Abaqus/Standard)

- Fatigue tests performed on samples of low and high densities
- Interpolation of fatigue life for other density values.

Density Distribution from Compaction/Sintering Analyses

Young’s Modulus distribution (MPa)

Shaft is represented by a rigid surface

Strain Amplitude vs. Cycle to failure curves for the lower and higher bounds.

- Low Porosity Fatigue Data
- High Porosity Fatigue Data
- MSF Low Porosity Fatigue Life
- MSF High Porosity Fatigue Life

Strain Amplitude

Cycles to Failure

0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
0.0040
0.0045

10^2 10^3 10^4 10^5 10^6 10^7

0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
0.0040
0.0045

10^2 10^3 10^4 10^5 10^6 10^7

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III – Fatigue Analysis of Main Bearing Cap
FEA Results – Mises Stress Distribution at Shaft Maximum Load (Abaqus/Standard)

– Three step analysis:
  • Bolt load of 60 ft-lbs
  • Minimum Shaft Load of 1,000 lbs
  • Maximum Shaft Load of 23,000 lbs

Mises stress distribution [MPa] at a shaft load of 23,000 lbs.

\[ \Delta \sigma_{eq} = \sigma_{eq\text{Max Load}} - \sigma_{eq1,000 \text{ lbs}} \]

Mises stress amplitude distribution [MPa] at a shaft load of 23,000 lbs.

Deformation Scale Factor of 25
III – Fatigue Analysis of Main Bearing Cap
FEA Results – Fatigue Life for Incubation and Long Crack (Abaqus/Standard)

Number of Cycles $N_{INC}$ for incubation at a shaft load of 23,000 lbs.

Number of Cycles $N_{LC}$ for long crack at a shaft load of 23,000 lbs.


III – Fatigue Analysis of Main Bearing Cap
Comparison Fatigue Test Results and FEA Predictions

<table>
<thead>
<tr>
<th>Shaft Load (lbs)</th>
<th>Recent FC-0208 Test Results</th>
<th>Previous FC-0208 Test Result</th>
<th>MPP – Ilia et al., 2003</th>
<th>Fatigue FEA Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>18,000</td>
<td>N/A</td>
<td>N/A</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>19,000</td>
<td>Pass</td>
<td>N/A</td>
<td>Pass/Fail</td>
<td>Pass</td>
</tr>
<tr>
<td>20,000</td>
<td>Pass/Fail</td>
<td>Pass</td>
<td>Pass/Fail</td>
<td>Pass</td>
</tr>
<tr>
<td>21,000</td>
<td>Pass/Fail</td>
<td>Pass/Fail</td>
<td>Pass/Fail</td>
<td>Pass</td>
</tr>
<tr>
<td>22,000</td>
<td>Fail</td>
<td>Pass/Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>23,000</td>
<td>N/A</td>
<td>Fail</td>
<td>N/A</td>
<td>Fail</td>
</tr>
</tbody>
</table>

The FEA Compaction and Sintering modeling is a good methodology to predict the density in Powder Metallurgy automotive components.

The Multi-Stage Fatigue Model provides a good life prediction of the Main Bearing Cap automotive component based on the density distribution.

Design Optimization for better performance and lower mass & cost.

Material substitution with Al-MMC (Metal Matrix Composites).

Initial density remains an uncertainty especially in large PM components.

Powder flow can be difficult to simulate especially in complex geometries and multi-level parts.

New numerical functionalities such as Coupling Eulerian-Lagrangian (CEL) or Discrete/Finite Elements may improve the prediction of powder flow.
I – Compaction
Material Characterization – Cap Hardening / Compressibility Curve

The $p_b-\varepsilon_{vp}$ curve describes how the cap section of the yield surface evolves while the volumetric strain $\varepsilon_{vp}$ increases. The curve can be established using the data from:
- uniaxial die compaction, or
- isostatic compaction experiments.

From the sensitivity analysis, it is found that the $p_b-\varepsilon_{vp}$ curve has a great effect on the compaction pressure $p_b$.

$$\bar{\varepsilon}_{vol}^p = W \left(1 - \exp\left[-c_1(p_b - p_{b\|0})^{c_2}\right]\right)$$

$$\rho = \rho_0 \exp\left(\frac{\bar{\varepsilon}_{vol}^p}{\rho}\right)$$

(from Conservation of Mass)

$\rho_0$ initial density
$\rho$ density
$W, c_1, c_2$ shape parameters

I – Compaction
Material Characterization – Failure Stress for Brazilian and Compression Tests

\( \sigma_t = \frac{2F_t}{\pi DT} \)
\( p_t = \frac{2\sigma_t}{3} \)
\( q_t = \sqrt{13}\sigma_t \)

\( \sigma_c = \frac{F_C}{A} \)
\( p_c = \frac{\sigma_c}{3} \)
\( q_c = \sigma_c \)

\( (p_c, q_c) \) points
\( (p_t, q_t) \) points

Drucker-Prager Failure line intersect iso-density points \( (p_t, q_t) \) and \( (p_c, q_c) \)

The material cohesion $d$ measures the cohesive strength of the material. The increase in material cohesion $d$ plays a dominant role in flow dynamics as it directly impacts the bulk flowability of solid material.

$$d = \begin{cases} 
0 & \text{if } \rho \leq \rho_d \\
\rho \exp[\rho_d - \rho_d] - d_1 & \text{if } \rho > \rho_d
\end{cases}$$
The interparticle friction $\beta$ defines the slope of the failure envelope. It is also called the internal friction angle.

The equation of the interparticle friction is given by:

$$\tan \beta = \begin{cases} b_1 - b_2 \rho_d & \text{if } \rho \leq \rho_d \\ b_1 - b_2 \rho & \text{if } \rho > \rho_d \end{cases}$$
The cap eccentricity $R$ is a material parameter that controls the ellipsoidal shape of the cap surface [Coube and Riedel, 2000].

$$R = \frac{R_1 - R_2}{1 + (\rho / \rho_c)^k} + R_2$$

$$p = \frac{1}{3} (\Sigma_a + 2\Sigma_r)$$

$$q = \Sigma_a - \Sigma_r$$

The Young's Modulus $E$ is a function of the relative density $\rho$.

$$E = (E_0 + E_1\rho) \exp\left(\frac{\rho}{\rho_E}\right)^\gamma$$