**Project 4: Fatigue Behavior of Fe-Co-2V using Experimental, Computational, and Analytical Techniques**

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Mentors

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Motivation

- Fe-Co-2V is soft, ferromagnetic material commonly used for electrical components
- Often exhibits low strength, poor ductility, and low workability due to an ordered B2 microstructure
- Limited fatigue data currently exists for Fe-Co-2V

Project Goal

Characterize the fatigue properties of Fe-Co-2V through strain-controlled fatigue testing coupled with numerical and analytical modeling

[Source: Stoloff et al., Scripta Metallurgica et Materialia, 1992]
Additively Manufactured (AM) Fe-Co-2V

- Producing Fe-Co-2V using AM could potentially improve its mechanical properties
- AM Specimens exhibited significant cracking, likely from thermal residual stresses
- Proceeded to use wrought Fe-Co-2V for the study
Quasi-Static, Monotonic Tension Tests

Average $E = 215 \text{ GPa}$
Strain-Controlled Fatigue Testing (R=-1, 1 Hz)
Strain-Controlled Fatigue Testing (R=-1, 1 Hz)

\[ \Delta \varepsilon = \frac{2\sigma_f'}{E} (2N_f)^b + 2\varepsilon_f' (2N_f)^c \]

\[ R^2 = 0.97 \]
Strain-Controlled Fatigue Testing (R=-1, 1 Hz)
SEM – 1mm Scale
SEM – 100µm Scale
SEM – 40µm Scale
Calibration – Methods

- Gradient
  - Sequential Least Squared Programming (SLQSP)
  - Nelder-Mead

- Global
  - brute
  - basinhopping

Error Metric:

\[
\text{MSE} = \frac{1}{n} \sum_{i=0}^{n} |f_i - y_i|^2
\]

- Weighted function
Calibration – Methods

Gradient
- Fast Convergence
- Susceptible to local minima vs. global

Global

\[ y = a \cdot \sin(x) \cdot \exp(bx) + cx \]
Calibration – Methods

Gradient

Global

- Guarantees minima
- Inefficient, can run into memory problems
Calibration – Data

Monotonic

Cyclic
Monotonic Calibration

$J_2$ Plasticity

- Generic Implementation of a von Mises yield surface with kinematic and isotropic hardening features

Power Law

- Describes isotropic hardening of the material

$$\bar{\sigma} = \sigma_y + A(\bar{\varepsilon}^p - \varepsilon_L)^n$$

Parameters

$E, \sigma_y, \varepsilon_L, \nu, n, A$
Plastic Hardening

Isotropic Hardening
- Uniform shift of yield surface
- Compresses at maximum of current yield stress $\sigma_y$

Kinematic Hardening
- Asymmetry between compressive and tensile yield stress
- Bauschinger’s Effect
- Max compression of initial yield stress $\sigma_{y0}$
Cyclic Calibration

BCJ_MEM

- Rate and temperature-dependent elastoviscoplasticity model with isotropic damage
- Includes effects of recrystallization and grain growth

Plastic Strain

\[ \dot{\varepsilon}_p = f(\theta) \sinh \left( \frac{\sigma}{\kappa + Y(\theta)} - 1 \right) \]

\[ \dot{\kappa}(\kappa, H, R_{d1}) \]

Parameters

\[ E, \sigma_y, \nu, H_1, h_1, R_{d1}, r_{d1} \]
Cyclic Fit – 2

Ramberg-Osgood Curve
- Based on cyclic stress and strain amplitudes from near half the fatigue life
- Used to obtain $n'$ and $H'$ for analytical model

$$\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{H'}\right)^{n'}$$

Parameter Values:
- $n' = 0.0112$
- $H' = 7.13 \cdot 10^{10}$ Pa
Multi-Stage Fatigue (MSF) Model

\[ N_{total} = N_{INC} + N_{SC} + N_{LC} \]

**Incubation Cycles, \( N_{INC} \):**

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

**Small Crack Growth Cycles, \( N_{SC} \):**

\[ \left( \frac{da}{dN} \right)_{SC} = \chi (\Delta CTOD - \Delta CTOD_{th}) \]

**Long Crack Growth Cycles:**

\[ \left( \frac{da}{dN} \right)_{LC} = \frac{C_i (\Delta K_{eff})^{n_i}}{\left[ 1 - \left( \frac{K_{max}}{K_{Ic}} \right)^q \right]} \]

Source: McDowell et al., Eng Fract Mech, 2003
Xue et al., Eng Fract Mech, 2007
Xue et al., Acta Materialia, 2010
Finite Element Model – 2D

\[ \mathbf{u}_{\text{app}} \]

Plane Strain

\[ \gamma_{\text{max}} \]

Number of Elements

\[ \times 10^5 \]
Average Maximum Plastic Shear Strain $\gamma_{max}^{P^*}$

$$\gamma_{max}^{P^*} = \frac{1}{A_\beta} \int_{A_\beta} \gamma_{max}^p \, dA$$

[Source: Xue et al., Eng. Fract. Mech., 2007]

$$A_\beta = 0.012D^2$$

[Source: Gall et al., Int J Fract, 2001]
\( p^* \) versus \( \varepsilon_{\alpha} \)
Finite Element Model – 3D

- Applied Displacement
- Fixed X
- Fixed Y
- Fixed Z
3D versus 2D

3D Model

2D Model
**MSF Model**

Incubation Cycles, $N_{INC}$:

$$\beta = \frac{\Delta \gamma_{max}^p}{2} = C_{INC} N_{INC}^\alpha$$

$N_{total} = N_{INC} + N_{SC} + N_{LC}$

![Graph showing relationship between incubation cycles and applied strain](image)

$\beta = 1.851 \epsilon_a + 4.028 \times 10^{-5}$
MSF Model

Incubation Cycles, $N_{INC}$:

$$N_{total} = N_{INC} + N_{SC} + N_{LC}$$

[Source: Torries et al., JOM, 2017]
Crack Propagation

- Crack propagation path determined using the eXtended Finite Element Method (XFEM)

\[ u^h(x) = \sum_{I \in N} N_I(x) \left[ u_I + H(x)a_I + \sum_{\alpha=1}^{4} F_{\alpha}b_{I}^{\alpha} \right] \]

- Initial crack: \( 0.01D = 0.542 \, \mu m \)
- Propagation modeled using LEFM
- Kink angle determined using **Maximum tangential stress criterion**:

\[ \hat{\theta} = \cos^{-1} \left( \frac{3K_{II}^2 + \sqrt{K_I^4 + 8K_I^2K_{II}^2}}{K_I^2 + 9K_{II}^2} \right) \]

[Source: Abaqus Theory Guide, v6.14, Section 2.16]

Crack Propagation

Applied Static Load
\( \varepsilon_{app} = 0.5\% \)

Linear Elastic Model
\( E = 215 \, MPa, \, \nu = 0.335 \)
MSF Model

Small Crack Growth Cycles, $N_{SC}$:

$$N_{total} = N_{INC} + N_{SC} + N_{LC}$$

Strain (mm/mm)

S, Mises (MPa) (Avg: 75%)
- 13000
- 12000
- 11000
- 10000
- 9000
- 8000
- 7000
- 6000
- 5000
- 4000
- 3000
- 2000
- 1000
- 0

CTOD

Multilinear E-Pl Model

Stress (MPa)

Crack Length (µm)

ΔCTOD (µm)

0.1% Strain
0.4% Strain
0.7% Strain
1.0% Strain
Larger discrepancy between MSF prediction and experimental data for larger strain amplitudes

⇒ Incubation life assumption
Conclusions & Future Work

Conclusions

▪ Fe-Co-2V Coffin-Manson parameters $\sigma_f^\prime$, $b$, $\varepsilon_f^\prime$, and $c$ determined for the first time

▪ Micromechanical simulations were used to compute the nonlocal maximum plastic shear strain amplitude ($\beta$) and crack tip opening displacement (CTOD)

▪ A Multi-Stage Fatigue model was used to predict fatigue life with no parameter calibration

Future Work

▪ Upper and lower defect sizes to bound MSF model prediction

▪ Analysis of AM CT imagery

▪ More fatigue tests to populate strain-life curve
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