Failure Prediction for Helical Coils under a Magnetic Pulse

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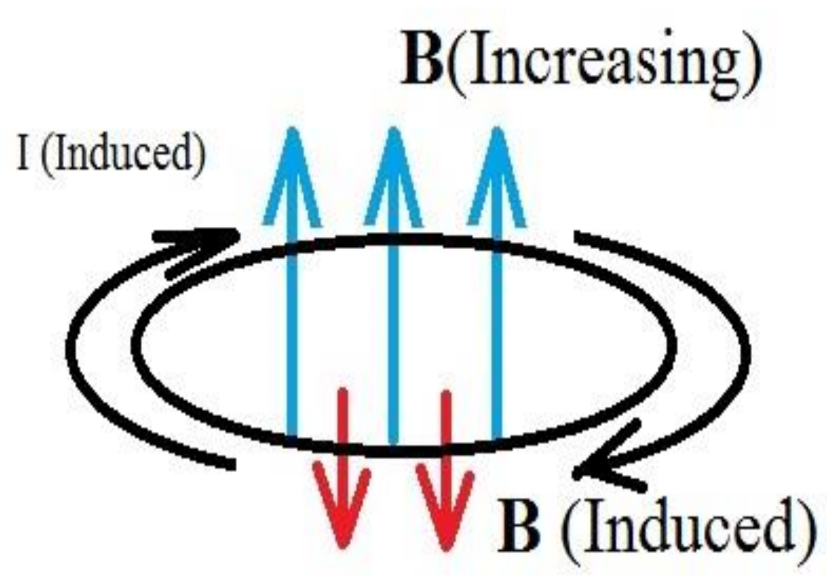
Abstract

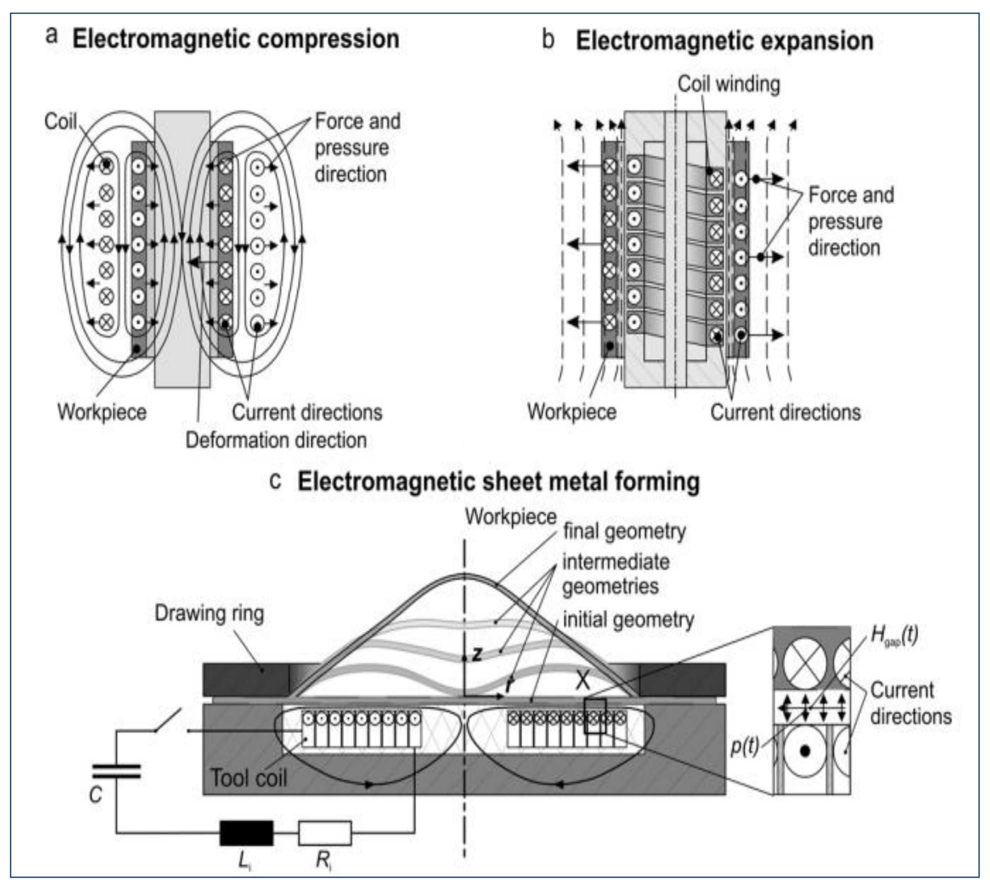
Electromagnetic formation (EMF) is a high velocity metal forming process that involves sending a current pulse through a coil of wire. This process has been applied to sheet metal formation as well as tube expansion and compression. The coil generates a magnetic field, causing a field of opposite polarization in the workpiece from eddy currents. This results in a mutual repulsion of the coil and the workpiece, causing deformation. Past work with tube compression required energies that result in a violent explosion of our coil. We explore the magnetic pressure in the coils without a work piece to predict the minimum energy required to plastically deform a coil of a given geometry in hopes of designing coils that can survive the forming process.

Background

- Application of Faraday's Law of Electromagnetic Induction: $\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$
- Utilizes pulsed magnetic fields to form sheet metal, compress or expand cylindrical tubes



A conducting loop experiences an increase in magnetic flux through its surface. Lenz's Law states that the a current is induced in the loop as to oppose the change in magnetic flux.



Pysk et al. 2011

In process (a) above, the workpiece is placed inside of the coil, where the magnetic applied magnetic field is concentrated, and the repulsion causes the tube to compress. Similarly in process (b), the coil is placed inside the workpiece of interest in order to expand it. Process (c) uses a tool coil to generate eddy currents in a sheet of metal causing it to deform. (See Ethan Thibaudeau's graduate research for more on this process)

Defining the Magnetic Field

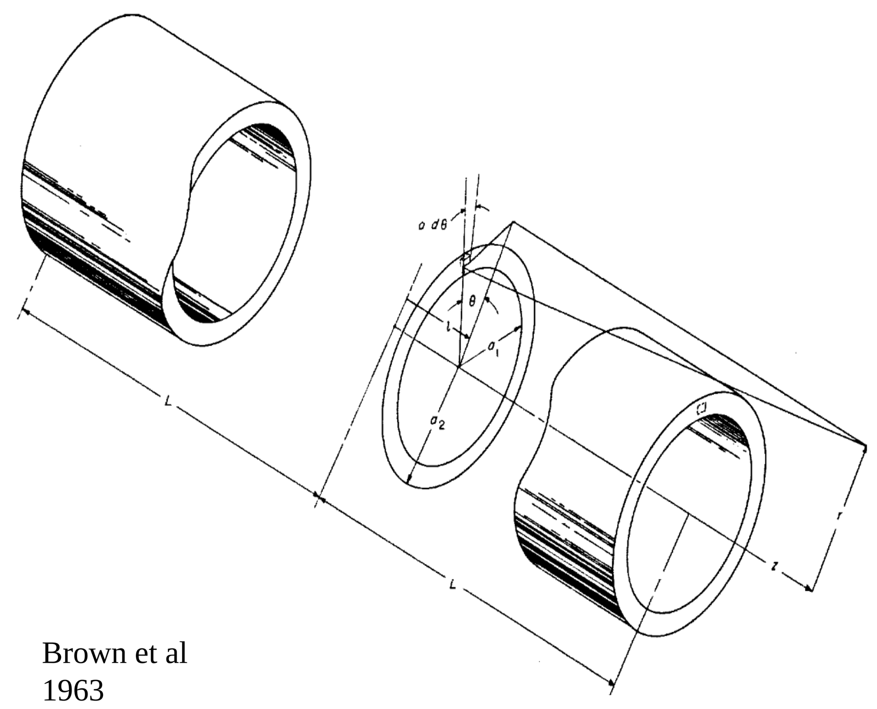
In order to determine the stress in our coils, we need to determine the forces acting on them. The magnetic field of the coil, **B**, is determined numerically from Brown et al (1963) under the following conditions:

Restrictions:

- No workpiece
  - avoids complexities such as mutual inductance and induced magnetic field
  - is a situation of extreme loading, creating an upper load limit for practical use [1].

Assumptions:

- Tightly wound coil
- Azimuthal current
- Symmetric about z=0
- Evaluated at r=a1, z=0
- Coil treated as a thin walled pressure vessel



Brown et al 1963

Coil geometry from [2]. Note they treat their coil as a long, solid conducting tube, however since our coils are tightly wound this is a sufficient approximation.

Magnetic Pressure and Yield Stress

With the magnetic field, we define the magnetic pressure as

$$P_r = \frac{B_r}{2\mu_0}$$

where P_r and B_r are the radial components of the magnetic pressure and magnetic field, respectively. The radial pressure is defined similarly.

We then determine the stress on the coil by treating it as pressure vessel with radial and axial stress given by

$$\sigma_r = P_r \frac{a1}{d}$$

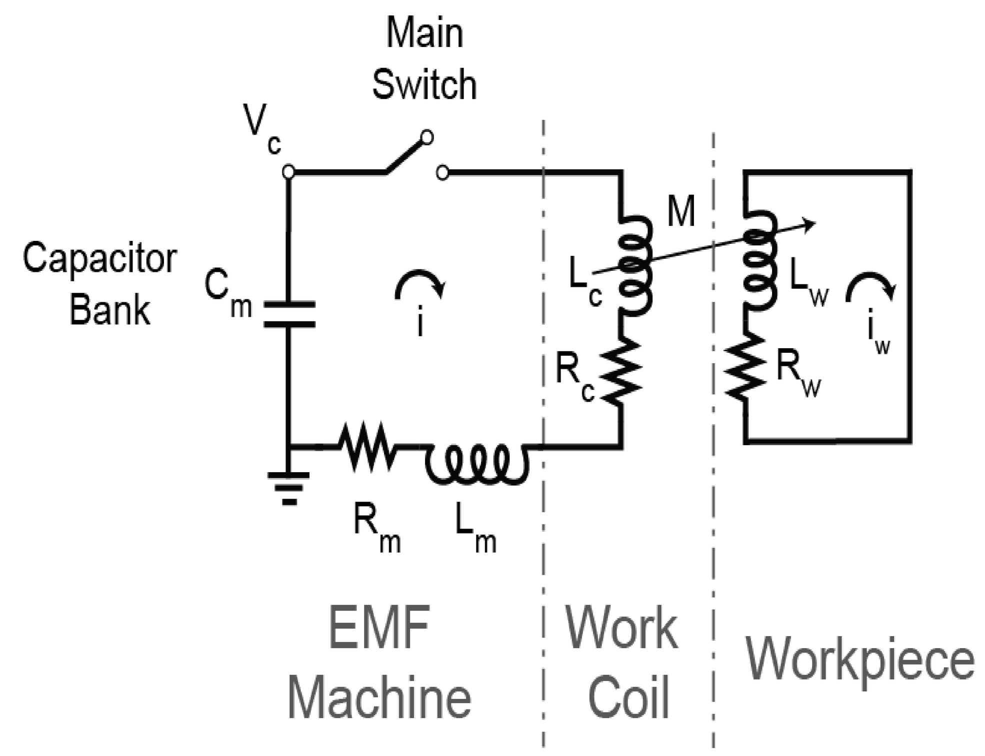
and

$$\sigma_z = P_z \frac{a1}{2d}$$

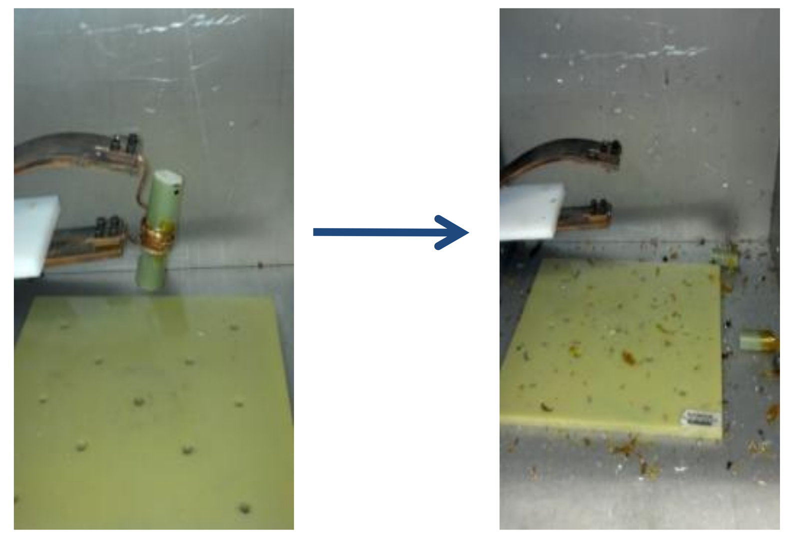
where d is the diameter of the wire used for the coil. From this we compare the stress to the yield stress by using Von Mises criteria

$$\sigma_{VM} = \sqrt{\frac{(\sigma_r - \sigma_z)^2 + \sigma_r^2 + \sigma_z^2}{2}}$$

Experimental Setup



Experimental setup consists of a 12 kJ pulse generator. Once energy is charged in the capacitors C_m, current pulse runs through coil. In the presence of a workpiece a current is induced, contributing to the circuit through its mutual inductance with the work coil.



Example of EMF process from "shrunken quarter" experiments. As you can see the during the process the coil explodes violently. The coil is connected to the leads which are connected to our pulse generator (not shown).

Machine Parameters :

- C_m = 360 μF
- R_m = 5.2 mΩ
- L_m = 0.6 μH

The inductance, L_c, and resistance, R_c, of the coil vary and can be determined by the following expressions:

$$L_c = \frac{\Phi}{I} = \frac{\bar{B} \cdot A_{coil}}{I}$$

and

$$R_c = \frac{\rho l}{A_{wire}}$$

Where $\Phi = \bar{B} \cdot A_{coil}$, is the magnetic flux through the center of the coil with $\bar{B}$ being the mean magnetic field at the center of the coil (z=0).

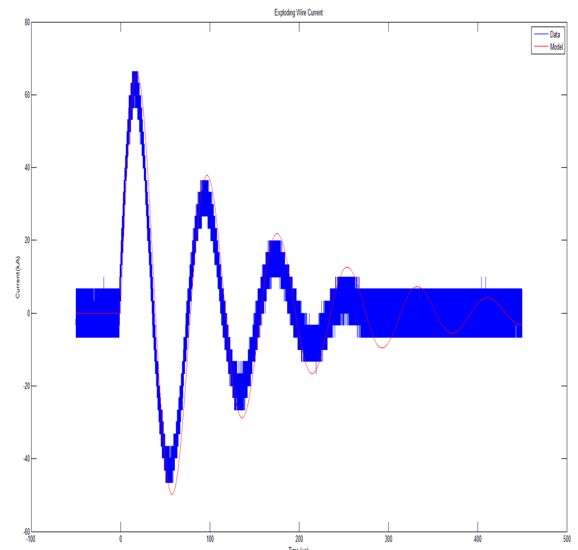
- l – unwound wire length
- $\rho = 1.54 \times 10^{-8} \Omega$ m – resistivity of Cu
- A_{coil} – coil cross-section
- A_{wire} – wire cross-section

Results

Several tests were run on coils made from 10 AWG magnet wire. The tests were designed to corroborate the theoretical model for yield stress. The coils had a diameter of $2a_1 \approx 16$mm with varying wire lengths.

Number of turns	Percent Energy
1.5	5.1
2.5	7.0
3.5	9.2

Results for N=1.5 strong agreement with our predictions. Results for 2.5 are within 1% energy of the model, and a single test on the 3.5 turn coil showed noticeable deformation only at 8% of our machine. The results shown did not account for σ_z, which becomes significant as the number radius to length decreases.



Current properties:
f =1.27 kHz
Rise time = 19.6 μs
β = 7000 rad/s
Rt = 6.03 mΩ
Lt=430 nH
$I_{max_{model}}$ = 65.6 kA
$I_{max_{data}}$ = 66.4 kA

However, comparing the current data (blue) to the predicted current (red) show strong agreement (see above) with only a 1.2% difference between the theoretical and actual peak current.

2.5 turn coil critical failure. Notice the remains are nearly equal in length. This demonstrates magnetic field strength is strongest at the center of the coil.

Summary

- Motivated to improve coil integrity during EMF process
- Numerical approximations of magnetic field are in good agreement with collected data
- Improving engineering analysis will improve consistency and reliability of results

References

1. Psyk, V.; "Electromagnetic Forming – A Review." Journal of Materials Processing Technology. (2011)
2. Brown, Gerald V., Flax, Lawrence, Itean, Eugene C., and Laurence, James C.: Axial and Radial Magnetic Fields of Thick, Finite-LengLh Solenoids. NASA TR R-170, 1963.