ENERGY-BASED MODELING OF AN ELECTRICALLY-ASSISTED FORGING PROCESS

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ABSTRACT
A new approach to improving formability of metals using electrical current field application has been recently studied, and found to not only greatly improve achievable elongation, but also has a beneficial effect on residual stress levels and reduces elastic springback magnitude. The effect has been shown to be somewhat attributable to thermal softening, but there are also unaccounted electrical effects. This paper presents a formal quantification of the electrical field effect using an energy balance approach. A physical model incorporating the electrical field and mechanical energy input is derived, and a new electroplastic effect coefficient is introduced to account for the direct contribution of the current on material flow. The derived model is compared against experimental results and predicts the electroplastic behavior.

INTRODUCTION
Leading automotive manufacturers are constantly striving to increase fuel economy while enhancing vehicle performance. From lightweight engineering, using materials such as aluminum alloys with superior strength-to-weight properties, auto makers are able to significantly decrease vehicle weight without compromising performance. Consequently, manufacturing challenges must be overcome when implementing Al alloys into production. These challenges include: poor formability, high yield strength, and a low strain hardening coefficient compared to more malleable carbon steels. This reduces the complexity of the components that can be formed from Al alloys without preheating or annealing, and also requires complex components to be joined or assembled from simpler parts.

Production plants utilize many manufacturing techniques in an attempt to meet these challenges: hot working, incremental forming (IF), and the use of tailor welded blanks (TWB’s). Hot working lowers a metal’s yield strength and increases ductility by working the metal above its recrystallization temperature. However, reduced die strength and lubrication effectiveness will occur, due to the high temperatures of the process. Additionally, thermal gradients may produce dimensionality variations. IF helps to achieve greater part ductility by deforming a blank in steps with a small heat treatment performed in between steps (Golovashchenko,
2005). Increased production times and reduced accuracy, due to constant refixturing, are disadvantages of this technique. Recently, the use of TWB’s has become popular, where multiple blanks are welded together before forming, such to position certain materials with desired properties, in given areas of a component when formed (Kinsey, 2003). As a result, excess time and personnel are needed, increasing production costs and times.

Electrically-Assisted Manufacturing (EAM) is an emerging manufacturing technique where electricity is applied to a homogeneous metallic workpiece during deformation. This technique has been proven capable of reducing required die forces, increasing achievable part displacement, and reducing or even eliminating springback effects. In this technique, electricity is applied during deformation. Unlike IF and hot working, no heater or furnace is needed, and contrary to TWBs, it does not require any preforming or joining procedures. Hence, EAM is a financially-viable alternative to many traditional manufacturing techniques.

ELECTRICAL THEORY AND PRIOR WORK

Beginning in the 1950’s, researchers began examining electricity’s effects on different materials. Machlin, in 1959, concluded that electricity significantly affected the flow stress, ductility, and yield strength of group 1A NaCl salts (Machlin, 1959). Years later, Nabarro discussed electricity’s effect on crystals in his book (Nabarro, 1967). In 1969, Troitskii found that tensile and compressive flow stress in zinc, tin, lead, and indium alloys could be lowered from electricity (Troitskii, 1969). Years later, Klimov et al. described that, other than Joule heating, electric current may have a specific effect on a metal’s structure (Klimov, 1982). From a microstructure analysis performed by Xu et al. in 1988, electric current caused the recrystallization rate and grain size of given materials to increase (Xu, 1988).

Moving forward, in 1998, Chen et al. formulated a relationship between intermetallic compounds and electrical flow (Chen, 1998). In 2000, Conrad published research showing that very short duration/high current density pulses were successful in altering the plasticity and phase transformations of numerous metals and ceramics (Conrad, 2000). In 2007, Perkins et al. examined the effects of a continuously applied current on many metals (aluminum-, copper-, iron-, and titanium-based alloys) while undergoing an upsetting process (Perkins, 2007). Findings from this research proved that continuous electricity applied during the deformation process reduced the flow stress, minimized springback, and increased forgeability, which led to greater deformations prior to cracking. More recent work by Jones et al. shows extreme compressive formability improvements in Mg AZ31B-O specimens by using EAM (up to 400% improvement compared to non-pulsed baseline tests) (Jones, 2009).

Much work has been done, both theoretical, and experimental, attempting to model or characterize electricity’s ability to improve a metal’s formability (i.e. the “electroplastic effect”). Kronenberger et al. produced and tested a FE model representative of EAM-compression on Al6061-T6511 slugs, the same Al alloy of interest in this study (Kronenberger, 2009). The model was able to accurately account for the temperature rise due to electricity. Additionally, it correctly predicted true stress vs. strain curves for a room temperature test and isothermal test at 142°C. However, when tested on predicting the stress vs. strain curvature for an EAM test at 60A/mm², the model, which accurately accounted for resistive heating, did not show nearly the level of flow stress reduction as produced from the actual EAM test, as seen in Figure 1.

As part of their research on EAM compression testing of Ti 6AL-4V specimens, Ross et al. conducted isothermal tests to distinguish between the effects of electricity and those caused solely by temperature increase (Ross, ...
Specifically, isothermal tests were run at temperatures about 20°C hotter than the hottest temperature reached during EAM testing. Worth mentioning, is that this temperature was only reached for a brief time during EAM testing. After comparing the results, shown in Figure 2, one can see that the isothermal test only accounted for about 10% of the formability enhancement produced by the EAM test.

FIGURE 2. DISTINCTION BETWEEN THERMAL EFFECTS AND EAM (ROSS, 2009).

Both initial works were important in determining that temperature was not the sole reason for formability enhancement during EAM. However, neither work was able to correctly model electricity’s influence on plasticity. The present work introduces an energy-based analytical model for electrically-assisted forging. This model includes the effects of the electrical current applied on the deformation mechanism.

OBJECTIVE AND APPROACH

The objective of this paper is to establish a closed-form solution describing the flow stress of a material which is plastically deformed under a compressive load while direct electric current is applied through the dies. Energy-based derivation equations are aimed at predicting the effective stresses and strains, and the forming load for different parameters of the applied current. It is expected that this model may be beneficial in preliminary determination of the feasibility of electrically-assisted forging a part based on formability improvement. The analytical model will bring better understanding of the electroplastic deformation mechanism and will open new avenues for derivation of analytical solutions for more complicated processes.

The derivation begins by establishing expressions for the effective stresses and strains acting on a plastically deformed billet without current in the classical cylindrical upsetting test, by employing upper bound analysis. The material is assumed to follow the power law, \( \bar{\sigma} = K \bar{\varepsilon}^n \), where \( \bar{\sigma} \) is the flow stress, \( K \) is the strength coefficient, \( \bar{\varepsilon} \) is the effective strain, and \( n \) is the strain hardening exponent. After the equations for stress-strain are established, the next step is to include the effect of the electrical current applied to the part. Two aspects are considered: (a) the applied electrical energy, and (b) the electroplastic effects on the material’s behavior and on the efficiency of the process. The analytical model is verified with results (force and position data) from EAM compression tests run on Al6061-T6511 specimens, by Perkins et al. (Perkins, 2007). Finally, the potential applications of the developed analytical model are discussed.

ANALYSIS OF AN ELECTRICALLY-ASSISTED COMPRESSION PROCESS

An experimental schematic of an electrically-assisted compression test is shown in Figure 3. A power source provides electricity and a variable resistor controls the magnitude of current flowing through the dies. Insulation is placed between the dies and the machinery, thus to ensure all electricity flows through the workpiece. Electrons flow through the workpiece from anode to cathode; material flow is shown schematically in Figure 3. Friction is present at the workpiece/die interfaces, thus causing the part to bulge into a specific barrel shape. This barreling effect is neglected in the initial analysis.

FIGURE 3. EAM COMPRESSION TEST SCHEMATIC.

Assumptions of the Model

The following major simplifications and assumptions are used throughout the derivations in this study:

- The material is homogeneous and isotropic.
The elastic deformation is negligible and the power law is used for the flow stress of the material.
- The von Mises yield criterion is applied.
- The friction of the workpiece/die interfaces follows Coulomb’s friction law. Sliding friction conditions assumed and barreling is ignored.
- The specific heat/resistivity of the material are assumed independent from temperature.
- The strain rate sensitivity is neglected since previous experimental investigations found that the temperature rise is not high enough for the process to be considered hot forming.
- Volume constancy is valid throughout the deformation process.
- The lubrication regime is assumed unaffected by the presence of electricity.

**Effective Stress and Effective Strain – Classical Compression Test**

The energy, and therefore the power needed to plastically deform a cylindrical billet is found by employing the upper bound analysis method as presented by (Avitzur, 1980). The objective of this method is to determine the strain rate field that minimizes the following relation:

\[ J^* = \pi r^2 \bar{\sigma} \dot{u} \left( 1 + \frac{2\mu \sigma_0}{3h} \right) = F \dot{u}, \]  

(2)

where \( r \) and \( h \) are the instantaneous radius and height of the workpiece, \( \bar{\sigma} \) is the flow stress of the material, \( \dot{u} \) is the velocity of the compressive die, \( r_0 \) is the initial radius of the billet, and \( F \) is the forming load. When the applied load and die velocity are known, the pressure exerted by the die is determined as follows:

\[ p = \frac{F}{\pi r^2} = \bar{\sigma} \left( 1 + \frac{2\mu \sigma_0}{3h} \right). \]  

(3)

The power law will be used to formulate the relation between the effective stress and strain, thus the pressure will be given by:

\[ p = K \bar{\varepsilon}^n \left( 1 + \frac{2\mu \sigma_0}{3h} \right). \]  

(4)

By employing the slab analysis method and simple balance of forces in the axial direction, along with the von Mises criterion, the compressive and effective stresses are determined:

\[ \sigma_z = p, \sigma_\theta = \sigma_r = p - \bar{\sigma}, \]
\[ \varepsilon_z = -2\varepsilon_\theta = -2\varepsilon_r, \]  

(5)

where \( \sigma_z, \sigma_\theta, \sigma_r \) and \( \varepsilon_z, \varepsilon_\theta, \varepsilon_r \) are the principal stresses and strains in axial, hoop, and radial direction, respectively, and \( h_0 \) is the initial height of the billet.

**Effective Stress and Effective Strain – Electrically-Assisted Compression Test**

The required flow stress to deform a specimen to a desired strain is lowered by applying electric current during the process. In this section, the effective electrical energy utilized in reducing stress is formulated.
**Energy effect.** When electricity is applied during deformation, a part of the electrical energy is imparted into the mechanical deformation process. Thus the total power consumed by the process will be given by:

\[
J^* = J_m^* + J_e^*,
\]

where \( J_m^* \) is the mechanical component given by the product of the forming load and the die velocity, and \( J_e^* \) is the effective (usable) electrical power, as follows:

\[
J_e^* = \xi \cdot P_e,
\]

where \( \xi \) is defined as the electroplastic effect coefficient, and \( P_e \) is the power of the electrical current passing through the workpiece. The electroplastic effect coefficient is a new material property coefficient introduced here, and it reflects the ratio of the electrical power that contributes towards plastic deformation to the total input electrical power. As seen in Figure 4, this ratio represents the difference between the power required for a non-pulsed baseline test and the power required for each EAM test using a different current density. This fraction of power is assumed to be converted into mechanical power and work towards aiding the deformation (i.e. imparting energy on the dislocations and facilitating their movement by providing enough energy to overcome lattice obstacles). The electroplastic effect coefficient, \( \xi \), depends on the material, applied current density and time, and can be determined through the tests defined below. Electric current will also increase part temperature, thereby lowering the flow stress of the material and contributing to decreased required work.

**Temperature rise effect.** Through resistive heating, the electric current results in thermal softening of the material, thereby decreasing flow stress as represented by the strength coefficient \( K \) in (4). In our analysis, a stepwise approach is used, whereby the material is strained by \( d\varepsilon \), the contribution of electrical energy to the deformation work calculated, the remaining electrical energy converted to heat, then the material workpiece temperature rise and subsequent effect on strength coefficient derived. The process is repeated to final desired strain.

When the electric current passes through the metallic workpiece, heat is generated and the temperature of the part rises. The temperature rise can be determined from an energy balance conforming to the following equality:

\[
\frac{\partial \rho U}{\partial t} + \frac{\partial}{\partial x_j} (\dot{Q}_{\text{conv}} + \dot{Q}_{\text{cond}}) = Q_{\text{rad}} + (1 - \xi)P_e,
\]

where \( \frac{\partial \rho U}{\partial t} \) is the rate of change of the internal energy of the part, \( \frac{\partial}{\partial x_j} (\dot{Q}_{\text{conv}} + \dot{Q}_{\text{cond}}) \) are the convective and conduction components of the heat flux, \( Q_{\text{rad}} \) is the radiation heat, and \( (1 - \xi)P_e \) is heat generated in the part from the electric energy dissipated. Using constitutive equations for each component, the heat equation to be solved for, that determines the temperature rise for particular electric parameters is:

\[
\rho V_v C_p \frac{\partial T}{\partial t} = -A_s [h (T - T_\infty)] - 2kA_x \frac{\partial^2 T}{\partial x_j^2} - A_c \varepsilon \sigma_{SB} (T^4 - T_{\infty}^4) + (1 - \xi)VI,
\]

where \( \rho \) is the density of the material, \( V_v \) is the volume of the part, \( C_p \) is the specific heat of the material, \( T \) is the temperature, \( t \) is time, \( A_s \) is the lateral surface of the part, \( h \) is the convection heat transfer coefficient, \( T_\infty \) is the surrounding temperature, \( k \) is thermal conductivity of the die material, \( A_c \) is the cross-sectional area, \( x_j \) are coordinates, \( \varepsilon \) is radiative emissivity for the part, \( \sigma_{SB} \) is the Stefan-

![Figure 4. Determination of the Electroplastic Effect Coefficient](image-url)
Boltzmann constant, $V$ is the electric voltage, and $I$ is the intensity of the current, given by the product of the current density and cross-sectional area.

The local heating of the workpiece influences the flow of the material. At room temperature, the flow is given by the power law presented earlier, but as the temperature rises, the flow curve depends strongly on the temperature. If the temperature is higher than the temperature at which recovery and recrystallization take place, then the flow depends also on the strain rate of the process, conforming to following equation:

$$
\bar{\sigma} = C \bar{\varepsilon}^m \bar{\varepsilon}^m,
$$

(10)

where $C$ is the strength of the material, $\bar{\varepsilon}$ is the effective strain rate, and $m$ is the strain rate sensitivity. The investigations conducted by previous researchers indicated a maximum temperature of the part between 100 and 200ºC, thus the strain rate dependency may be neglected, but the influence of the temperature on the strength of the material is still significant, since the higher temperatures favor the climbing of the dislocations, thus the deformation process.

**Strain and Temperature Effect on Resistance and Current.** By virtue of strain and material heating, the resistance of the sample and ultimately the induced current is affected. Referring to Figure 3, the DC source is a voltage source; the current is set through adjustment of the voltage and a variable resistor as shown. During deformation, the resistance is affected by workpiece geometry and material resistivity according to

$$
R[\Omega] = \rho \frac{L}{A}.
$$

(11)

For 6061-T6 Al, the resistivity is given by

$$
\rho = 4 \cdot 10^{-8} (1 + 0.0039T) [\Omega - m].
$$

(12)

For specimens at different nominal applied current densities, the reduction in resistance of the specimens is plotted in Figure 5. We observe that the geometric effects dominate, and that the specimen resistance decreases up to 87% in the test data. However, the overall system resistance is dominated by the variable resistor, so this effect is negligible.

![Normalized Resistance](image)

**FIGURE 5. SAMPLE RESISTANCE CHANGE WITH STRAIN AND TEMPERATURE.**

**Analytical model for electrically-assisted compression.** The proposed analytical model is based on the stress-strain equations presented for the classical test, but adapted to take into consideration the various effects of the electrical energy on the deformation mechanism. Thus, the amount of electrical energy contributing to the deformation, as presented in Eqns. (6) and (7), is introduced in Eqns. (2-5).

$$
J^* = F \ddot{u} + \xi \cdot P_v = \sigma \left(1 + \frac{2 \mu_0}{3h}\right) \pi r^2,
$$

(13)

where the effective stress will be given by Eqn. (10). Thus the equation can be written as follows:

$$
F \ddot{u} + \xi VI = C \bar{\varepsilon}^m \bar{\varepsilon}^m \left(1 + \frac{2 \mu_0}{3h}\right) \pi r^2,
$$

(14)

where $V$ and $I$ are the voltage and current intensity. The current is given by:

$$
I = \pi r^2 C_d,
$$

(15)

with $C_d$ being the current density on surface unit. Eqns. (9), (14), and (15) constitute the analytical model for an electrically-assisted compression test.

**Solution Schematic.** A MATLAB program was implemented to numerically solve the equations derived for the model. The model is solved incrementally. By imposing the material and initial dimensions of the part, the model is used to determine the effective strain and stress for different current density values. The solution schematic is given in Figure 6. A step is preset for the mechanical power, $\Delta P_m$, and $P_m$ to increase incrementally. At step $i$, Eqn. (9) is
solved to determine the temperature rise, and then used to find the corresponding strength coefficient, $C$. The new value is used in Eqn. (12) and the height of the billet is calculated. The stroke, effective strain and stress, and the complete state of stress and strain can be determined if desired. The iteration continues until deformation reaches the desired value of the stroke, or a failure criterion, such as the fracture limit, is reached.

The next step is to determine the electroplastic effect coefficient. For simplicity, an average value is included in the numerical solution. To determine an average electroplastic effect coefficient, a coefficient profile was created by plotting the coefficient vs. time for each respective current density, as shown in Figure 7. Once the coefficient profile was established, an average coefficient for each current density was recognized using a flat-line approximation approach. This type of approximation is sufficient for initial model verification, and is fairly accurate except with the 60.8A/mm$^2$ test.

![Diagram](https://example.com/diagram.png)

**FIGURE 6. SOLUTION SCHEME FOR SOLVING THE ANALYTICAL MODEL.**

![Graph](https://example.com/graph.png)

**FIGURE 7. ELECTROPLASTIC EFFECT COEFFICIENT PROFILES.**

At this point, there is an unmodeled time- or strain-dependent effect of the electrical influence on deformation. Previous work has highlighted a “threshold effect” whereby electrical application benefits are negligible until a critical current density is reached. Figure 7 highlights a possible second threshold whereby the electrical effect contribution greatly increases and becomes strain-dependent at a current flux of 60.8A/mm$^2$.

Following the steps presented earlier in the solution scheme, the model was solved for three different current densities. Figure 8 compares the model predictions with the experimental results. It can be observed that the predictions agree very well for two of the cases. The differences can be attributed to the simplifications and assumptions done in the model. The next steps will be to refine the model to account for factors that were neglected, i.e., strain rate sensitivity, and also to conduct specific experiments targeting accurate measurements of material properties included in the analytical model, such as the material strength and electroplastic effect coefficient.

**RESULTS AND DISCUSSION**

**Validation of the Model via Experiments**

The analytical model developed in the previous section is able to predict the strain-stress during the compression tests assisted by electric current, or to determine the forming load needed to reach a certain strain. In this section, the strain-stress curves are compared with experimental results from EAM compression tests run on Al6061-T6511 specimens, by Perkins et al. (Perkins, 2007). The initial billet had a diameter of 6.4 mm, and a height of 9.5 mm. The compression tests deformed to a maximum stroke of 6.4 mm. Prior to solving the model, the material parameters and the friction conditions were determined by solving the model for a classical test. After fitting the data, the following values were determined: $K = 348$ MPa, $n = 0.04$, and $\mu = 0.08$. The influence of the temperature on the strength coefficient, $C$, is assumed to follow the same trend as for technical pure aluminum.

The next step is to determine the electroplastic effect coefficient. For simplicity, an average value is included in the numerical solution. To determine an average electroplastic effect coefficient, a coefficient profile was created by plotting the coefficient vs. time for each respective current density, as shown in Figure 7. Once the coefficient profile was established, an average coefficient for each current density was recognized using a flat-line approximation approach. This type of approximation is sufficient for initial model verification, and is fairly accurate except with the 60.8A/mm$^2$ test.
FIGURE 8. MODEL VERIFICATION.

**Potential Areas of Application for the Established Closed-Form Solutions**

This model is readily applicable to numerous areas of deformation processing. The noted improvement in formability can be better predicted and the result used for process planning and optimization. The electroplastic effect can now be modeled accurately through likewise derivation of the governing equations for Finite Element Analysis. Finally, the energy approach can be applied to tribological modeling of deformation under electric field conditions.

**CONCLUSION**

This paper presents an energy-based approach to analysis of electrically-assisted forming. The input electrical energy is separated into the useful energy that assists the mechanical process, and the energy that is converted to resistive heat, causing thermal softening. Future work includes identification and quantification of the localized region of thermal effects (e.g., grain boundaries), identification of the electroplastic effect coefficient for differing materials and conditions, sensitivity analysis of this parameter, and refinement of the friction assumptions.

**REFERENCES**


