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ALTERNATIVE CONTROL OF AN ELECTRICALLY-ASSISTED TENSILE FORMING PROCESS USING CURRENT MODULATION

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Process Control, Electrically-Assisted Forming, Tensile Deformation

ABSTRACT

Electrically-assisted forming is a technique whereby metal is deformed while simultaneously undergoing electric current flow. Using this process, electric current level becomes a new degree of freedom for process control. In this work we present some alternative control architectures allowing for new avenues of control using such a process. The primary findings are architectures to allow for forming at constant force and forming at constant stress levels by modulating electric current to directly control material strength. These are demonstrated in a tensile forming operation, and found to produce the desired results. Combining these control approaches with previous and contemporary efforts in modeling of the process physics will allow for system identification of material response properties and model-based control of difficult-to-observe process parameters such as real time temperature gradients.

INTRODUCTION

Previous characterization of electrically-assisted forming (EAF) have demonstrated reduction in flow stress as a response to electrical current applied through the specimen during deformation [1-3]. The level of stress reduction and instantaneous surface temperature are proportional to the applied current density, and

relationships between these variables have been established [4]. EAF may be utilized as an alternative processing technique to hot working or incremental anneal forming. Certain benefits that this technique possesses are:

- 1) There is no prior processing of the part being formed for EAF in contrast to elevated temperature forming,
- 2) The forming process using EAF does not have to be discontinued as in incremental forming where thermal annealing is applied external to the forming operation,
- 3) Greater amount of strain prior to fracture is produced using EAF in comparison to room temperature deformation,
- 4) The EAF process provides a lower forming force even for very high strength metals, and
- 5) The amount of springback can be reduced using EAF.

In this work, we aim to demonstrate that the relationship between material strength, current flow and temperature can be directly incorporated to control the process using standard sensors. To begin, background discussion is given on modeling of reduction in flow stress during EAF, and how such models might be incorporated to control approaches.

Flow Stress Prediction in Electrically-Assisted Forming

Modeling of the material flow stress during EAF has taken prominent steps in recent years. Work by Bunget et al. utilized an energy-based analytical approach to separate the mechanical power required for deformation and the input electrical power to predict the material flow stress for uniaxial compression using a numeric approach [5]. Additional work by Kronenberger et al. examined the use of FEA to predict the material flow stress during EAF; however, using only the resistive heating effects, the model was inadequate at predicting the EAF flow stress [6]. Work by Jones et al. in 2010 examined the use of an empirically derived flow stress predictor for EAF [7]. This work presented a model which accurately characterized the material flow stress for small and larger strains in magnesium and copper materials. Also in 2010, Salandro et al. examined air bending of 304 Stainless Steel sheet metal [8]. Using an analytical approach, a model of the forming load was constructed for conventional bending and electrically-assisted bending. The model incorporated both mechanical and thermal effects which produced accurate approximations of the forming load during the process. However, one aspect that this work did not address was the thermal gradients present in the specimen during electrically-assisted bending. In 2011, Jones et al. examined compression testing of 304 Stainless Steel and Grade 5 Titanium which applied a constant current density throughout the specimen for the first time during the test [9]. Thus, prior work only utilized an initial nominal current density which changed as a result of specimen shape change during deformation, however, in this work the current density was constant irrespective of specimen shape change. Using these flow curves which were more representative of the actual material response to an applied electrical current field, an observed flow stress modifier was created which accurately predicted the flow stress for the EAF tests knowing the material response under conventional forming conditions. In 2011, Salandro et al. performed thermal modeling of a uniaxial EAF compression process to study the effects of electrical energy input and its contribution to resistive heating or to aiding deformation [10]. The results of the thermal modeling showed a power law form for the amount of energy that went into aiding deformation as a function of strain. In 2012, Jones introduced a multiphysics model to predict the deformation behavior of sheet metal deformation in uniaxial tension subject to a direct electrical current flow [11]. The model successfully incorporated direct electrical effects (*i.e.*

electroplasticity), bulk thermal softening from the temperature rise, and thermal expansion effects. This model is discussed in the Model-Based Process Control section.

Model-Based Manufacturing Process Control

Model-Based Control (MBC) is a term incorporating a number of approaches that introduce process models and simulation results (*i.e.* system response maps) to both real-time and user-level machine control. These methods are contrasted with traditional machine reference tracking control, where a desired path or state sequence is planned, and the control is actuated by actual deviation from plan; traditional methods can also incorporate feed-forward or look-ahead strategies to prepare for large changes in the reference, but this does not account for process physics. Model-based techniques extend this look-ahead strategy to predict how the system will respond to input changes, and control on the residual of the planned vs. predicted states.

Model Predictive Control (MPC) and other model-based methods have seen limited application to closed-loop control of processing equipment. Rather, they are employed in a limited sense as open-loop or non-real-time predictors of process condition and used to drive gross process intervention. An example is use of a tool wear predictor model to recommend a tool change frequency; this type of approach uses only limited process feedback such as accelerometer vibration data to assess departure from a “good” signature envelope.

Applying true model-predictive controllers to discrete parts manufacturing processes is extremely limited. Zirn et al. applied model-based control methods to machine tool axes to improve precision [12]. Itoh applied MBC to a form rolling machine to eliminate transient vibration [13]. Saffer and Doyle applied strict MPC to a paper making machine [14], and Tarău et al. applied models to the controller of a mail-sorting machine for throughput optimization [15]. Though these processes are somewhat continuous, the discrete product output highlights them as novel.

CONTROL ARCHITECTURE

Two architectures are examined for alternative control of the EAF process. The first targets forming at constant force, independent of the base material properties or strain rate (within quasi-static limits). Constant-force forming incorporates direct observation of the forming force during the process. The second approach, constant-stress forming, requires the use of a model to estimate the specimen area as a function of

strain and initial specimen dimensions. This approach introduces some simplification and resultant uncertainty to the output.

Constant Force Forming

The concept for constant force forming was realized from experimental testing where the current was manually modulated such that the forming force could be regulated to some extent. Thus, a formal control strategy was envisioned that could regulate or maintain the force during forming at a specific setpoint value. To achieve this, a block diagram (Figure 1) was first constructed to understand the flow of information and relationships. $F_{desired}$ is the desired force set point, $Force$ is the force feedback from the process, ΔF is the force error, and V_{feed} is a feed voltage that the current source uses to output current I to the process.

FIGURE 1: BLOCK DIAGRAM FOR CONSTANT FORCE FORMING

Constant Stress Forming

Constant stress forming was also performed using a similar method as described for the constant force forming. The block diagram for constant stress forming is presented in Figure 2 where $Force$ is the measured force, σ_{true} is the calculated true stress (Equation 1), $\sigma_{desired}$ is the desired set point, and $\Delta\sigma$ is the stress error. The true stress for tensile forming was calculated by:

$$\sigma_{true} = \frac{(Force)(L)}{A_o L_o} \quad (1)$$

where, $Force$ is the instantaneous measured force, L is the instantaneous gauge length, A_o is the initial cross-sectional area, and L_o is the initial gauge length.

FIGURE 2: BLOCK DIAGRAM FOR CONSTANT STRESS FORMING

EXPERIMENTAL SETUP

To realize the goal of constant force/stress forming, a Darrah Silicon Controlled Rectifier (SCR) with a current output of 0-4kA was used to supply the process with direct electrical current (Figure 3). To control the power supply, an external remote was built using a National Instruments (NI) CompactRIO (cRIO) integrated

controller/chassis containing various I/O modules programmed with NI LabVIEW software. To control the processes of constant force and stress forming, the LabVIEW software has an imbedded *PID* control block which provided reactive control to the system. For controlling the force and stress, three set points were tested for each process to show the robustness of the control application. The tests were performed on an Instron hydraulic testing machine with a platen velocity of 2.54mm/min. The Instron machine used specialized tensile grips that isolate the electricity from the testing equipment. To measure the thermal response during the tests, a FLIR A40M thermal camera (maximum temperature: 550°C, temperature resolution: 0.1°C, and frame rate: 12.5/s) was used (not shown in Figure 3). The tensile specimens were produced from warm rolled Mg AZ31B sheet that were 1mm thick and were prepared according to ASTM B557M [16].

FIGURE 3: ELECTRICALLY-ASSISTED FORMING TEST SETUP

A control schematic is presented in Figure 4, where a linear variable differential transformer (LVDT) provides displacement data (d) and a load cell provides the force data (F) to the analog input (AI) on the cRIO. Additionally, the measured current ($I_{measured}$) is collected using the AI on the cRIO. The cRIO interfaces with a computer which also records thermal data (T). The cRIO controls the power supply output (I) by applying a feed voltage (V_{feed}) from the analog output (AO).

FIGURE 4: SENSING SCHEMATIC FOR PROCESS CONTROL

RESULTS AND DISCUSSION

In the following sections, the results are presented for constant force and stress forming using the aforementioned control architectures. The force, stress, and applied current for both architectures are presented. Last, the incorporation of an EAF multiphysics model is discussed for incorporation to a model predictive control scheme.

Constant Force Forming

The force results for constant force forming at 1334N (300lb), 1779N (400lb), and 2224N (500lb) are presented in Figure 5. As the control system is turned on just after the material's yield point, the applied current quickly drives the force to the desired set point. After reaching the desired set point value, the controller is capable of accurately modulating the applied current to maintain constant force forming until the specimen fractures. The physical reason for the oscillations in the force response is not presently known. They may be a result of the cyclic behavior of the applied current from the control algorithm, a result of the material hardening and softening, or from an AC current imposed on the large DC signal.

FIGURE 5: CONSTANT-FORCE FORMING AT VARIOUS SETPOINTS

The conversion of the constant force results to stresses are presented in Figure 6 where the true stress increases linearly as a result of the force maintaining a constant value. This calculation was performed assuming uniform deformation as given in Equation 1.

FIGURE 6: STRESS RESPONSE FOR CONSTANT-FORCE FORMING

The current applied during the process is summarized in Figure 7 where a maximum allowable current was set (300A). As seen, the current increases to the maximum allowable current value and then shortly decreases as the forming force is reduced. After this initial spike, the current is modulated by the controller such that a constant force is maintained.

FIGURE 7: CURRENT APPLICATION DURING CONSTANT FORCE FORMING

In addition, the thermal response of the tests were recorded and the maximum temperature of the sample with respect to time given in Figure 8. As the current is applied the temperature drastically increases and then the rate of change of temperature begins to decrease as the material reaches the desired force set point (*i.e.* lower current level to maintain force). As the test continues, the temperature follows the same trend as the electrical

current which decreases until the specimen fractures. The thermal response is presented here as this could represent another possible area for control. Specifically, the temperature during forming could be controlled by modulating the electrical current applied if real-time temperature data was available. A similar approach has been presented for stationary heating using an electrical current before performing a Kolsky Bar test [17], but not for sheet forming during deformation.

FIGURE 8: THERMAL RESPONSE FOR CONSTANT FORCE FORMING TESTS

The significance of constant force forming allows for the forming force to now be specified as a control parameter and not just monitored as a process output. As a result, this technique could allow for lower capacity (*i.e.* smaller force) machines which often have smaller capital investments to form high strength materials. Additionally, with having the capability to form a greater range of material on a lower capacity machine, this reduces the number of individual machines that a company may require.

Constant Stress Forming

The force results are shown in Figure 9 for the constant stress forming tests. As seen, the force is immediately reduced with the application of electrical current to the desired stress level and the force decreases linearly over the length of the test to maintain a constant flow stress. Again, the physical reason for the oscillations in the force response is not presently known.

The flow stress results are given in Figure 10 and the true stress during forming is maintained at the correct set point values of 100MPa, 150MPa, and 200MPa.

FIGURE 9: FORCE RESPONSE FOR CONSTANT-STRESS FORMING

FIGURE 10: STRESS RESPONSE FOR CONSTANT-STRESS FORMING

The current supplied to the process is summarized in Figure 11 for the three test cases performed (100MPa, 150MPa, and 200MPa). The current quickly increases to the maximum allowable current (300A) once the controller is activated and quickly decreases at the point where the material reaches the desired stress state. Once the stress state is reached, the current slowly decreases until the specimen fractures.

For the constant stress forming results an assumption of uniform strain was assumed for the entire test length. However, as a result of the testing setup, there is a thermal gradient within the test samples which causes diffuse necking during the test (see Figure 12). Due to the diffuse necking, this modifies the actual local stresses within the material due to the presence of an area gradient along the sample length. Consequently, the presented

response is an averaging of the true stress within the sample and it can be seen that the experimental response decreases slightly near the end of the tests due to larger amounts of diffuse necking present just prior to fracture.

FIGURE 11: CURRENT APPLICATION DURING CONSTANT-STRESS FORMING

FIGURE 12: CONSTANT STRESS FORMING SPECIMEN

With the introduction of constant stress forming, this opens additional areas of research for determining the desired or optimal material flow stress response during forming for a given material/process combination. Additionally, this demonstration also leads to the opportunity for present forming machine architectures/designs to be modified with the goal of becoming more flexible which is highly desirable in industry.

Model-Based Process Control

Model Based Control (MBC) is a control method where the control system incorporates a process model in the control algorithm. Within MBC, there have been numerous approaches developed and this work focuses on Model Predictive Control (MPC). In MPC, the model of the process is used to estimate the response of the system to apply control action instead of waiting for feedback

from the process as was demonstrated in the constant force/stress forming in this work. Specifically in MPC, a weighted objection function is defined, the response of the system to the inputs is predicted over a finite time horizon, the performance of the system is optimized with respect to the objective function using design variables as system inputs, and the system is driven toward the optimized state [18]. This type of strategy has two main advantages over traditional control in that it 1) better the performance as a result of an understanding of the system physics instead of reactive compensation, and 2) the process output can be optimized to any parameter(s) while the underlying model may contain uncertainty [19]. A general MPC architecture is shown in Figure 13.

FIGURE 13: ALTERNATIVE ARCHITECTURE FOR MODEL-BASED PROCESS CONTROL

When considering this control strategy for EAF, the previous sections used a *PID* controller which employed a compensation strategy instead of predictive action. Additionally, the desired state was directly measurable or capable of being directly calculated from the actual state of the process. For advanced control of EAF processes, the incorporation of MPC and physics-based models could allow for immeasurable process outputs to be controlled by the use of measurable processes feedback. Work by Jones produced an EAF thermo-mechanical model that is capable of predicting the local material strain, the required force or stress during deformation, and temperature profile of a uniaxial tension sample [11].

This EAF multiphysics model incorporates bulk thermal softening effects, direct electrical effects (*i.e.* electroplasticity), and thermal expansion effects [11]. To calculate the division of the three effects, the stress reduction due to thermal expansion can be directly calculated using the model temperature response at a given time step. Also, assuming all of the applied electrical energy goes into material heating, the flow stress reduction can be calculated and compared to a constitutive equation that predicts the material response at varying temperatures and strain. The difference in these

two values provides the purely thermal softening influence and the direct electrical effect influence.

An example output for forming of magnesium sheet metal in uniaxial tension subject to a square wave input of 500 A with a duration of one second and a pulse period of 60 seconds is provided. As shown in Figure 12, a diffuse neck is commonly present in EAF due to thermal gradients along the axial length of the part being formed. As a result, greater amounts of strain exist in certain regions (*e.g.* center region for uniaxial tension). From the multiphysics model, a predicted strain distribution is given in Figure 14 where a greater amount of strain is predicted for the center region of the specimen. The element number axis corresponds to the specimen length axis.

FIGURE 14: LOCAL STRAIN PREDICTED BY EAF MULTIPHYSICS MODEL

Also, the multiphysics model is capable of predicting the stress-strain response during forming. This result is presented in Figure 15 where the model is capable of predicting the flow stress reduction during the application of current (*i.e.* stress discontinuity is where the pulse of electrical current is applied).

Last, the temperature response of the sheet is able to be predicted during EAF using this model. An example response is provided in Figure 16 where the temperature rises quickly as the electrical current is applied. After the current is discontinued, the sample cools before the subsequent current application. Also, it can be seen that a thermal gradient exists along the elements numbers (*i.e.* specimen length) as a result of diffuse necking which results in non-uniform deformation.

FIGURE 15: STRESS-STRAIN RESPONSE PREDICTED BY EAF MULTIPHYSICS MODEL VERSUS EXPERIMENTAL RESULT

FIGURE 16: THERMAL RESPONSE PREDICTED BY EAF MULTIPHYSICS MODEL

As a result, one strategy using the thermo-mechanical process model for EAF developed by Jones could allow for the temperature of the formed tensile sample to be controlled. Although the temperature is a measurable output, there are difficulties in measuring the entire thermal response (*i.e.* large thermal gradients during EAF sheet forming) as a result of image/data processing. Hence, real time feedback may be limited to point measurements on the tensile sample. The forming process could be controlled such that the temperature does not exceed a certain value or the part is formed in a certain temperature range. In addition, the input electrical energy to the process could be minimized while still maintaining the constraints for temperature. The block diagram is shown in Figure 17 where the process measurements could include temperature (most likely point measurements), current, force, and displacement.

FIGURE 17: MPC BLOCK DIAGRAM FOR TEMPERATURE CONTROL DURING EAF

The thermo-mechanical process model would allow for temperature prediction such that the control actions could be set before the actual feedback or past output measurements are provided. Again, the MPC is shown providing a feed voltage (V_{feed}) which the current source translates to direct electrical current (I) to the physical process.

Additional strategies could include maximizing the elongation before failure or providing a desired elongation while minimizing the amount of electrical energy applied to the component. Also, with further work in microstructure analysis of EAF samples, this could allow for grain size control using current and the deformation rate as the control variables.

CONCLUSION AND FUTURE WORK

The main conclusions drawn from this study are:

- Several control approaches were envisioned, created, and demonstrated for forming using an electric current field.
- The first examples of constant force forming and constant stress forming using modulation of electric current flow through the workpiece were demonstrated and successful at maintaining the desired set points.
- The constant force forming control approach allows for the forming force to be a specified process input and not just an output of the process. This can allow for lower capacity machines to be used on a wider range of materials with various strength properties.
- The constant stress forming was successfully demonstrated for three flow stress set points. With this introduced capability there are now additional areas where future research could be performed. For example, the desired or optimal stress response when forming a material using a certain process could be a possible area. Additionally, this also leads to the opportunity for forming machine architectures/designs to be modified to allow for

more flexibility in material deformation which is highly desirable in industry.

- Model Based Control (MBC) has potential applications for controlling EAF processes using derived physics-based models. In MBC, the model of the process is used to estimate the response of the system to apply control action instead of waiting for feedback from the process. One control application was presented using the thermo-mechanical process model for EAF such that the temperature during forming could be controlled.

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