Assessing the Effective Energy for Magnetic Forming Processes by Means of Measurements and Numerical Calculation*

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Abstract

The efficiency of magnetic sheet metal forming processes is strongly depending on the facility's overall design. This mainly includes the geometric layout of forming tool, work piece and matrix but, however, will also expect the energy storage device being taken into consideration. Apart from field theoretic models the energy storage is describable by its terminal traits which the electric load - tool coil and work piece - is connected to. The paper presents a measuring method for the tool coil's terminal quantities, current i(t) and voltage u(t), which are used to provide the electric power p(t) being transferred to the load. Thus, it is possible to determine the entire energy which is dissipated by the work piece, provided that the coil's resistance is known. Besides the measurement, this approach is supported by numerical calculation intending to take a closer look at the inner losses of the work piece which are not accessible from measuring the system's terminal traits directly. Dividable into separate parts of the total energy, this information is applied to assess the forming process by means of the facility's energetic performance and to draw an overall energy balance.

Keywords

Electromagnetic Forming, Energetic Efficiency, Measurements

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1 Introduction

Electromagnetic sheet metal forming facilities typically consist of a tool coil, the workpiece and a primary energy store, which itself is built of capacitive elements just because they are very easy to handle and do not need comprehensive switching efforts compared to inductive energy stores. However, the efficiency of energy transfer will differ depending on the storage facility's layout as the load will evidently show resistive-inductive behaviour [1]. The load which is connected to the energy store in this work is pictured in figure 1 and shows a spiral coil positioned in parallel under a thin conducting metal sheet.

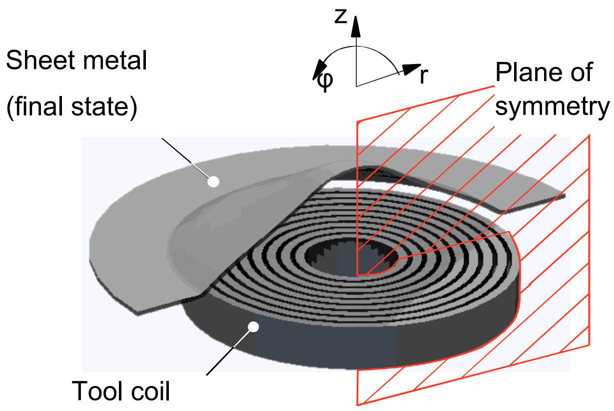

Figure 1: *Scheme of the geometric setup of the load configuration which is connected to the energy store. The numerical model is based on this setup and the measurements of voltage and current were performed at the tool coil's terminals.*

The induced eddy currents inside the work piece will interact with the coil's excited flux density making the plate bulge into a new shape. This mechanic work is to be transferred into the sheet metal by transforming the initially stored electric energy into magnetic energy. These types of energy conversion have different efficiency factors and will have to feed energy drains like eddy current heating losses [6]. The assessment of these losses compared to the initially stored energy is performed by measurements of the tool coil's terminal quantities and completed by numerical simulations in the following.

2 Measurement of the Tool Coil's Terminal Quantities

The tool coil's and work piece's electric characteristics can be determined in total by measuring the terminal quantities at the coil's input clamps which are the current $i(t)$ and the voltage $u(t)$.† The multiplication of both represents the electric power $p(t)$ which itself delivers the totally dissipated electric energy when being integrated with respect to time. The current is measured by making use of a Rogowski inductive current sensor which is already integrated into the facility setup. The more difficult challenge is to identify the

†*The measurements have been carried out at the sheet forming facility Maxwell7000 , IUL, Dortmund University of Technology.*

correct voltage at the forming tool's clamps; apart from the ability to withstand the occurring voltage stress, synchronicity between the current and the voltage signals has to be guaranteed. For these reasons, an ohmic-capacitive voltage divider is designed and mounted in close vicinity to the current signal's pick-up. Because of the symmetric structure its layout is optimized to minimize inductively coupled signals due to very high magnetic field strengths in it is surrounding. The voltage divider as well as the corresponding equivalent circuit diagram is pictured in figure 2.

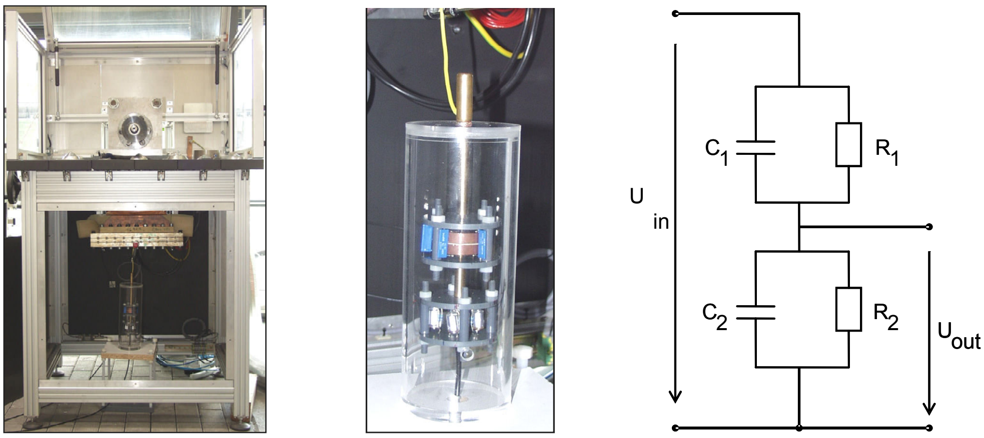

***Figure 2**: The resistive-capacitive voltage divider is placed in the tool coil's close vicinity and is coaxial symmetrically designed to minimize current-induced failure voltages.*

The intended impedance in the upper and lower branches are designed to R_1 = 50 kΩ, C_1 = 50 pF and R_2 = 50 Ω, C_2 = 50 nF to obtain a divider ratio of T = 1000 which is not a function of the frequency. However, due to parasitic influences of the surrounding the divider's ratio between input voltage to output voltage is depending on the frequency and amounts T = 983 for a frequency of f = 15 kHz. Figure 3 gives an overall view on the forming facility to show where the measuring sensors have been mounted.

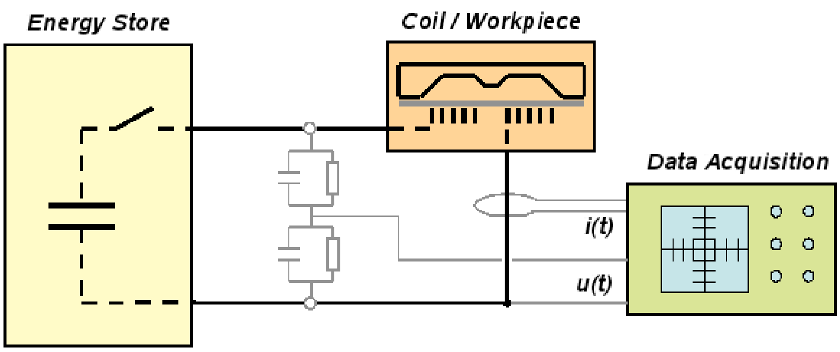

***Figure 3**: Schematic block diagram of the forming facility consisting of energy store, tool coil and work piece. To obtain the input power a voltage divider and an inductive current sensor provide the signals which are picked up by the data acquisition setup.*

Both, the current i(t) and the voltage u(t) at the coil's terminals have been recorded synchronously and are used afterwards to determine the electric input power p(t) which is transferred into the system 'tool coil – work piece'. The following figure 4 reveals the measured current and voltage for an electromagnetic forming process as well as the resulting electric power *p*(t).

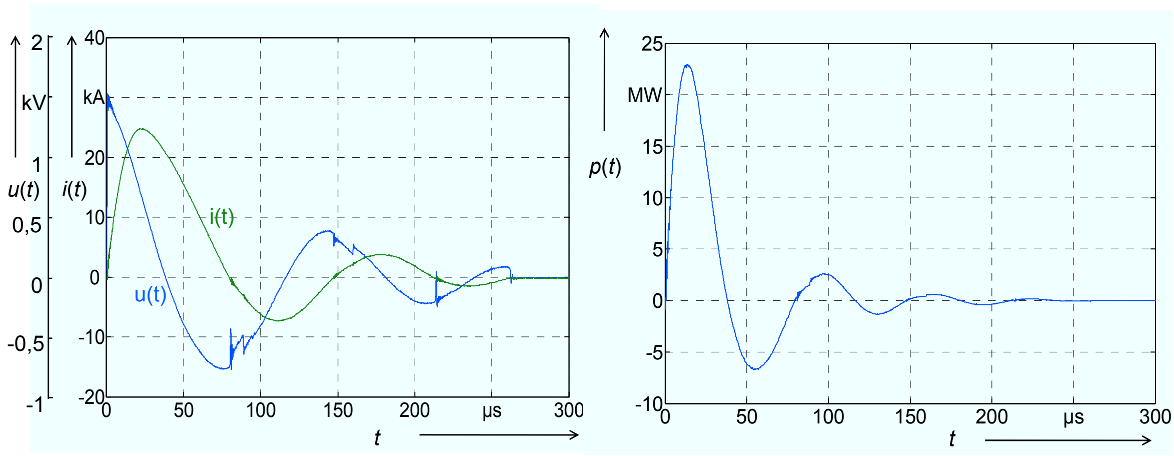

***Figure 4**: Current i(t) and voltage u(t) (left figure) measured at the tool coil's terminals while forming an aluminum sheet (AlMgSi0.5, d = 1.2 mm, W_{charge} = 556 J) from which the electric power p(t) (right figure) is calculated.*

The voltage at the tool coil's terminals for $t = 0$ represents the capacitor bank's charging voltage as there is no voltage drop along the connecting wires. This value amounts U_{charge} = 1483 V in this experiment and therefore the charging energy is determined by knowledge of the energy store's capacity of C = 505.2 µF to

$$W_{charge} = \frac{1}{2} \cdot C \cdot U_{charge}^2 = 556\ J \qquad (1)$$

The measured voltage shows some unsteady and repetitive leaps which may be caused by sudden cut-offs of the ignitron switching devices as this effect happens for the current crossing zero. However, this phenomenon is smoothened regarding the electric power and will therefore only have little effects on the totally transferred energy.

3 Assessment of the Effective Energy

3.1 Assessing the Effective Energy Transfer by Measurement Data

The electric power *p*(t) which enters the tool coil's terminals is integrated with respect to time in order to obtain the total energy which is transferred into the system 'tool coil – work piece'. A classic energy balance only uses the values for the electric process having completely finished; disregarding this, figure 5 reveals the different parts of energy as functions of time, because especially in the current waveform's beginning there are huge parts of energy temporarily being stored in the magnetic field. This energy is given back to the primary capacitive energy storage device as long as the product of coil current and voltage is negative. In the beginning of the impulse current the energy that enters the coil's terminals is higher than the finally transferred energy. The exponentially damped but freely oscillating discharge causes irreversible losses in the conducting structures of the entire facility but even though, a part of it is used to support the aim of bulging the aluminium sheet into it's new shape.

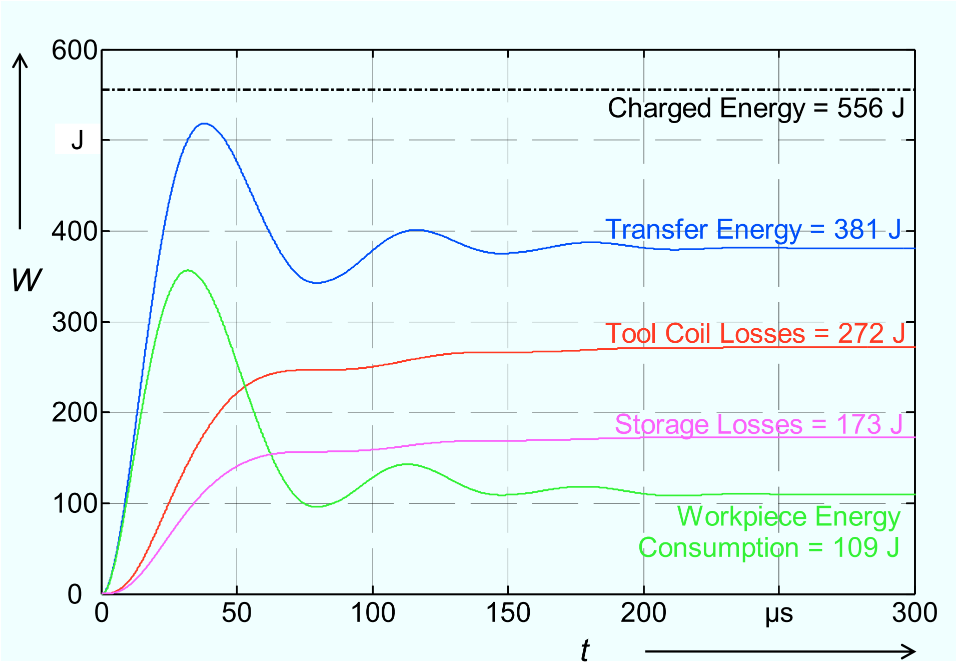

***Figure 5**: The cumulative parts of energy calculated from measured terminal quantities draw a complete energy balance of the energy transfer.*

In the beginning of the impulse current the energy that enters the coil's terminals is higher than the finally transferred energy, which is due to the fact, that this amount of energy is stored in the magnetic field temporarily and pushed back to the capacitor.

The part of energy which passes the tool coil's terminals is dividable into tool losses and the effective energy which is dissipated by the work piece. The storage losses are calculated from the initially stored energy and the part of energy which has been totally transferred to the tool coil and the work piece. However, the energy storage does not discharge completely on the tool coil; there is still some voltage ($U_{t=260\mu s}$ = 85 V) left on the capacitors at t = 260 µs and the ignitron devices do not switch again, which is evident as the current falls to zero and does not rise again (see fig. 4). Therefore, this part of energy, which is definitely not transferred to the load, is taken into consideration for reasons of accuracy which reveals the storage losses to:

$$W_{storage} = \frac{1}{2} \cdot C \cdot \left((1483\,V)^2 - (85\,V)^2 \right) - W_{transfer} \approx 173\,J \qquad (2)$$

With this value it is possible to determine the inner ohmic resistance $R_{storage}$ of the energy storage. The dissipated energy can be expressed by the current and reveals a conditional equation for the storage loss resistance:

$$W_{storage} = \int R_{storage} \cdot i(t)^2 \, dt \quad \Rightarrow R_{storage} = \frac{W_{storage}}{\int i(t)^2 \, dt} = 6.98 \, m\Omega \qquad (3)$$

In earlier works [2], the coil's network elements have been identified from which in detail the ohmic coil resistance R_{coil} = 11.2 mΩ is of particular interest in this case. With this value the tool coil losses are calculated as cumulatively shown in figure 4 reaching an end value of 272 J.

The amount of energy which is dissipated by the work piece contains the mechanical energy but also the part being responsible for joulean heating of the aluminum sheet and amounts 109 J after the electric process has finished at approximately t = 260 µs. There is no direct access to the current density within the work piece making it not possible to distinguish between both from the measurements.

3.2 Assessing the Effective Energy Transfer by Numerical Calculation

Numerical field calculation methods are useful to get a deeper insight into the forming process. An electromagnetic field calculation system like FELMEC 2 ½ D calculates the magnetic vector potential on the cross section of an axially symmetrical arrangement as in figure 1. From the vector potential the remaining magnetic field quantities as well as the forces on the work piece can be calculated. A structural mechanic simulation system like SOFAR calculates the movement of the forming object from the exerted forces. The programs FELMEC and SOFAR have been developed at Dortmund University of Technology by the research group FOR 443 as well as the coupling of both. The coupled programs use the time stepping method to allow transient calculation of the forming process. The explicit coupling alternately determines the electromagnetic forces and the movement of the work piece during each time step. Since the methods are already presented in the literature ([3], [4] and [5]), just the most important aspects are described here.

In many previous investigations a measured current is used as an excitation for the simulation of the forming process in coupled simulations. The necessity of preceding measurements is reasonably unsatisfying when simulation tools are applied to predict the forming result. The coupling of SOFAR and FELMEC is able to follow that procedure, but nevertheless a further coupling of electric networks allows the consideration of equivalent network elements for the capacitor bank. The results presented in this chapter are based on numerical field calculations of the forming process by only giving the initial voltage and capacity of the energy storage device. By this approach the current is a degree of freedom in the calculation and preceding measurements are not required for the simulation of a forming process. Thus, arbitrary combination of capacities and initial energies may be simulated for parameter studies with respect to the efficiency like presented in [6].

However, measurements are useful to enhance the accuracy of any simulation. Using the results presented above, an ohmic resistance can be calculated which represents the total losses in the capacitor bank and the power lines to the tool coil for this special example. It is used as a lumped element in the coupled numerical field calculation of the example set up in chapter 2 with a capacity of 505 µF and an initially stored energy of 556 kJ.

The evaluation also focuses on the different influences of the forming facility's modules on the process in terms of energy drains. Now a complete energy balance may be drawn because the thermal losses can be calculated by knowledge of the current density on the cross section of the tool coil in the *r*,*z*-plane. The mechanical power absorbed by the work piece is determined by (4) since the force and the velocity are known quantities of the field calculation.

$$p_{mech}(t) = \int f(t) \cdot v(t) \, \mathrm{d}A \quad (4)$$

The ohmic losses due to the resistance of the storage device can be directly calculated by equation (5).

$$p_R(t) = i(t)^2 \cdot R \quad (5)$$

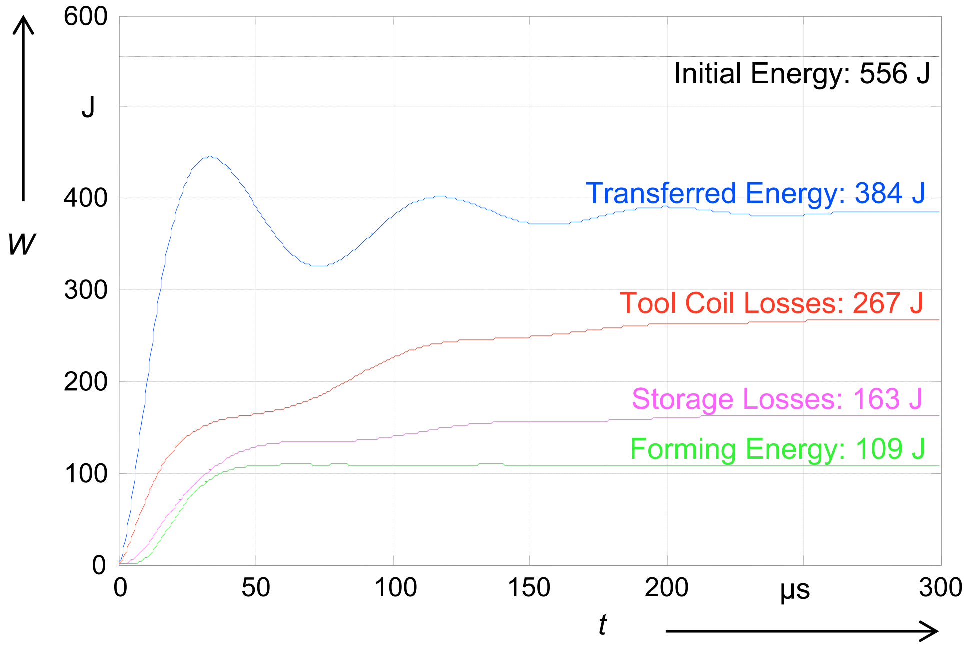

Figure 6: *Variation of the different kinds of energy over time determined by the numerical field calculations for a forming process with a capacitor bank of 505 µF and an initial energy of 556 J.*

The apparent power transferred into the sub system tool coil and work piece is given by the multiplication of the voltage and current as in the case of the measurements. The energy at each time step is determined by integrating the power with respect to time. The curves in figure 6 are the cumulative sums of the energy calculated at each time step and show the energy dissipation of the different modules of the facility as results of the simulation.

The ohmic loss energies represent the dissipation into thermal energy of the storage device and the tool coil. The effects are not reversible in this application and the curves are continuously increasing as can be seen for the mechanical energy. The transferred energy instead may temporarily be higher than the totally transferred energy at the end of the forming process, since the reactive energy oscillates between the tool coil and the work piece. The results show quite good accordance with the measurements.

4 Summary and Conclusions

This work focussed on assessing magnetic sheet metal forming facilities regarding the effective energy which is transferred from a primary capacitive energy storage device to a time-variant load consisting of forming coil and workpiece. The results are obtained by measuring the tool coil's terminal quantities current and voltage from which the totally transferred power as well as the energy are calculated. Different parts of energy can be separated which makes it possible to draw a comprehensive energy balance for the forming process as a function of time.

The experiments are compared to simulation results where both, the measured results as well as the numerically obtained match each other exactly in revealing the fact, that the main part of the initially stored energy is used to cover any unwanted drains and energy losses and only less than 20 % can be used mechanically. Almost half of the energy is needed for heating up the tool coil; this shows the necessity to design a forming tool which is appropriately fitted to the demands of the volume forces' radial distribution and even more to optimize existing energy storage devices including innovative and appropriate switching technologies.

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