On the Significance of the Die Design for Electromagnetic Sheet Metal Forming*

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Abstract

Electromagnetic Forming is a high speed forming process using a pulsed magnetic field to form metals with high electrical conductivity, such as copper or aluminium alloys. During the process, typical pressure peaks up to 200 MPa and velocities in the range of 300 $^{m}/_{s}$ can be achieved. As significant process parameters the pressure maximum as well as the local and temporal varying pressure distribution have been identified.

As of a certain drawing depth and distance between workpiece and tool coil, the pressure does not act any longer on the workpiece, but the deformation process is still driven by the inertia forces. It has been found out that the velocity distribution within the sheet metal during the forming stages as well as at the time of impact with a die significantly influences the forming result. Additionally, a special undesired effect is the rebound behaviour of flat workpiece areas being in contact with the die. To investigate the influence capability of the die concerning this effect, the parameters stiffness and damping properties have been varied by means of simulation using a mechanical substitute model.

Keywords:

Electromagnetic sheet metal forming, Tool design, Parameter variation

1 Introduction

One of the major research field at the Chair of Forming Technology, University of Dortmund, is the process of electromagnetic sheet metal forming. This topic is, inter alia, investigated by the research unit 443 “Untersuchung der Wirkmechanismen der elektromagnetischen Blechumformung”, sponsored by the German Research Foundation (DFG). Main focus of this group’s activities is fundamental research with the aim to obtain

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a deeper understanding of the process and the interaction of the significant parameters. A long-term objective is to bring this innovative forming process towards industrial realisation. Besides the analysis of the free forming process, a second focus deals with shape forming, which means that a die is used in order to achieve a certain geometry. Here, one of the main aspects is the analysis and prediction of the interaction between workpiece and die.

2 Deformation process and relevant parameters observed at free forming operations

Electromagnetic sheet metal forming is an energy-based high speed forming process, forming metals with a high electrical conductivity by a pulsed magnetic field. The basic principle of this process is shown in Figure 1.

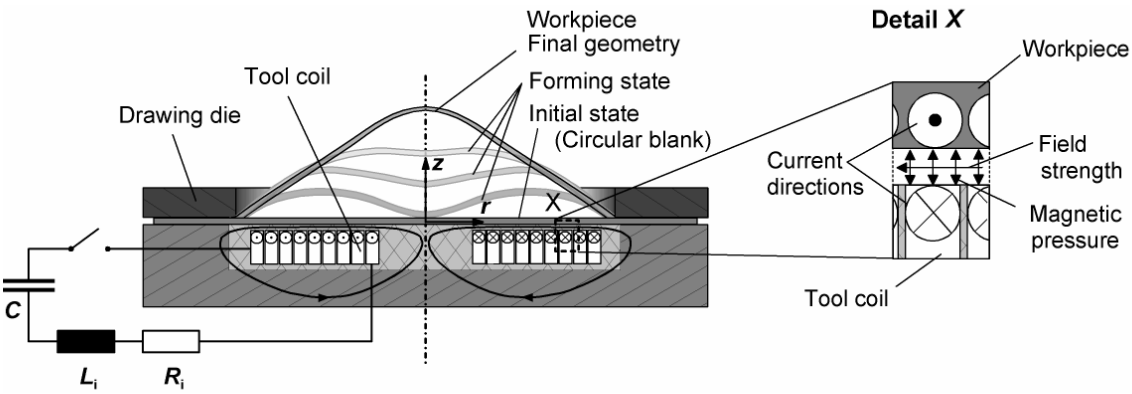


Figure 1: *Process principle [1]*

Closing the high-current switch effects a sudden discharge of the capacitor battery, thereby creating a highly damped sinusoidal current $I(t)$. The current causes a magnetic field $H(t)$ inducing a second current in the workpiece which is directed in the opposite direction of the coils current. As long as the workpiece is close to the coil, this induced current prevents the magnetic field from penetrating through the workpiece in z-direction. The energy density of the magnetic field within the gap between the sheet and the coil refers to a magnetic pressure p acting nearly orthogonal onto the workpiece's surface. If the yield point of the workpiece material is exceeded, plastic deformation occurs and the distance between workpiece and tool coil increases rapidly. Under the assumption that the magnetic field's local and temporal distribution is known the pressure can be calculated using the following equation [2]

$$p(r,z,t) = \frac{1}{2} \cdot \mu_0 \cdot H^2(r,z,t) \quad (1)$$

with
p magnetic pressure
H magnetic field
μ_0 permeability constant
r radius
z coordinate in direction of the drawing depth
t process time

With regard to Figure 2b-c, the acting magnetic pressure depends on the local as well as on the temporal distribution, which reveals the complexity of the analysing electromagnetic sheet metal forming. Therefore, a finite element analysis is used to calculate the magnetic pressure, coupling two different software tools [3]. The first one, FEMM [4] is used for the determination of 2-dimensional harmonical magnetic fields. The second code, MARC, is used for the transient calculation of the forming process which is caused by the magnetic pressure. The calculated field distribution is used as input data in the transient mechanical simulation. The mechanical simulation stops when the deformation exceeds a defined value. In a next step, a new field distribution is determined with the formed workpiece geometry. This exchange is repeated until the magnetic pressure does not act any longer. In [5] the results of this coupled simulation have been compared with the results of a coupled simulation using a transient field analysis with EMAS instead of the harmonic field analysis with FEMM. Because of the similarity of the results the harmonic analysis will be preferred due to the less efforts regarding computation time.

Figure **2** shows the results of such a coupled simulation: there are some characteristic deformation stages from the mechanical simulation as well as the corresponding pressure of the electromagnetic simulation.

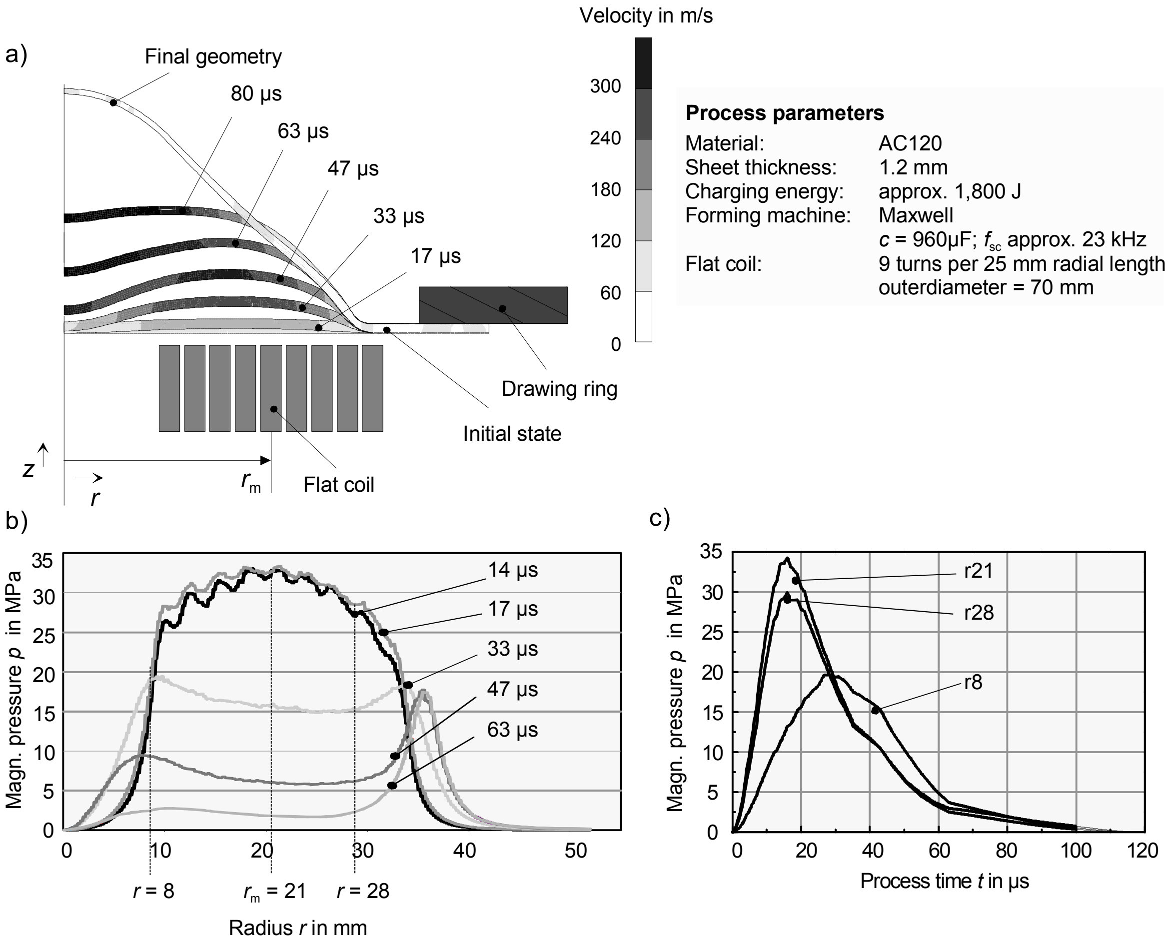
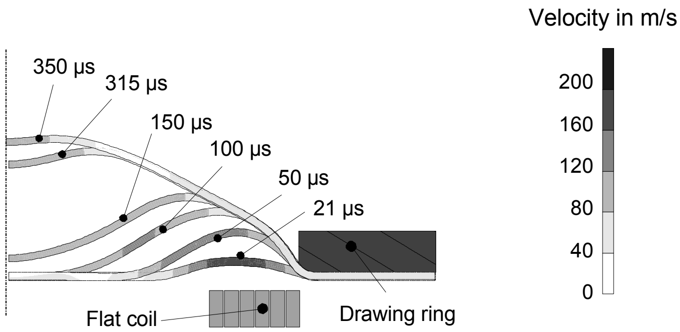


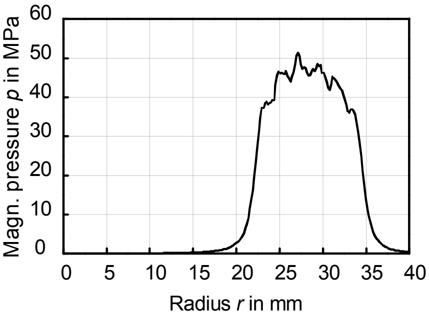
***Figure 2:** Forming states and according local and temporal pressure distribution*

Figure 2a-b clearly shows the strong influence of the workpiece's movement on the pressure decrease. During the first stage, the maximum pressure occurs at position r_m, which refers to the medial coil radius where the movement starts. In contrast to this, there is no pressure in the centre of the coil. In the following deformation stages a continuously decreasing pressure can be observed due to the decreasing magnetic field strength with the increasing gap volume. It should be mentioned that the pressure decreases in a much shorter period than the coil current [1]. As a result of the inertia forces, the workpiece still moves on. These inertia forces act mainly in the area of r_m dragging the middle part ($r < r_m$) towards the drawing direction (positive z-direction). This effect causes a strong acceleration of the sheet metal centre which results in a large deformation. As soon as the workpiece leaves the influence area of the coil, only the inertia forces act on the sheet metal and a possible active influence on the movement is lost. But nevertheless, the responsible forces can be influenced by the relevant parameters charging energy and coil design as well as by the mass or the stiffness of the workpiece [1]:

- An increase of charging energy causes a higher pressure maximum which leads to a higher drawing depth, but to a higher velocity during the forming process as well.
- The pressure distribution will be created by the coil design. In particular the characteristic parameters are the inner and outer coil diameter as well as the winding density (number of turns per unit of length).

Starting from numerical analysis as described in [1], some experiments with different pressure distributions have been carried out to justify these assumptions. For example, Figure 3 shows the simulation results of a quite different pressure distribution compared to Figure 2. As expected, the workpiece deformation starts in those areas of the sheet where the winding is located. The other regions have to be accelerated by inertia forces. The example in Figure 3 shows how these acting forces can be distributed to influence the velocity distribution during the forming process.





Process parameters:

Material:	Al 99.5
Sheet thickness:	1.0 mm
Forming machine:	SMU1500; c = 80 µF; f_{sc} approx. 65 kHz
Charging energy:	400J
Inner diameter of the drawing die:	70 mm
Tool coil:	6 turns per 12 mm radial length Outerdiameter = 70 mm

Figure 3: *Pressure distribution and according workpiece deformation*

The final geometry is completely different. The investigations have shown clearly that the forming result as well as the velocity distribution can be influenced by the pressure distribution. As a consequence, it seems to be useful to determine a matching pressure distribution by means of simulation for each forming task.

3 Typical effects and interactions at forming operations into a die

One research objective within the above mentioned research group is to achieve a given geometry using the electromagnetic sheet metal forming process. Therefore, tools like a die have to be used within this process. During the first stage by forming into a die, the workpiece passes through the same stages as in the free-forming process which means that the existing knowledge can be transferred for this special time slot. As already shown in Figure 2a, the workpiece has a very high velocity, especially in the middle area which reaches up to 300 $^{m}/_{s}$. This means that the workpiece locally has a very high kinetic energy. In the case of forming into a die, this energy must be transferred to the die when the workpiece movement is stopped by the die surface. This causes undesired effects, like for example,

- the generation of a strongly inhomogeneous velocity distribution in the sheet metal and
- the rebound-effect caused by the kinetic energy of the workpiece.

These two undesirable effects are discussed in the following.

3.1 Influence of the inhomogeneity of the velocity distribution

As known from the free-forming process, the velocity distribution in the sheet influences the forming process in a significant manner. Corresponding to different velocity distributions the workpiece passes through different geometrical forming stages. This behaviour causes a problem, if a tool is used to obtain the desired geometry. This should be explained by an example shown in Figure 4. Here, the simulation results with a spherical die using different charging energies are shown. In the case of the higher charging energy (see Figure 4b) the workpiece area A, where the maximum pressure dominates, has a very high velocity while area B still remains at its initial position. Later on, the faster area hits the die at first which causes an abrupt deceleration on the one hand. On the other hand, area B of the sheet material becomes very stiff due to the strain hardening as well as to the geometrical stiffness caused by the changed geometry. Due to these facts the inertia force which is the driving force during this process stage does not act any longer. Therefore, the centre of the workpiece (area B) is not being deformed anymore.

Contrary, in the case shown in Figure 4a, a lower charging energy influences the forming process in a positive manner. As a result of the lower energy, the forming velocity is lower at large. Additionally the velocity distribution is more homogenous which allows a better use of the inertia forces during a larger time period of the process. Thus, the geometry of the intermediate stages are less stiff and the sheet achieves the die geometry as desired.

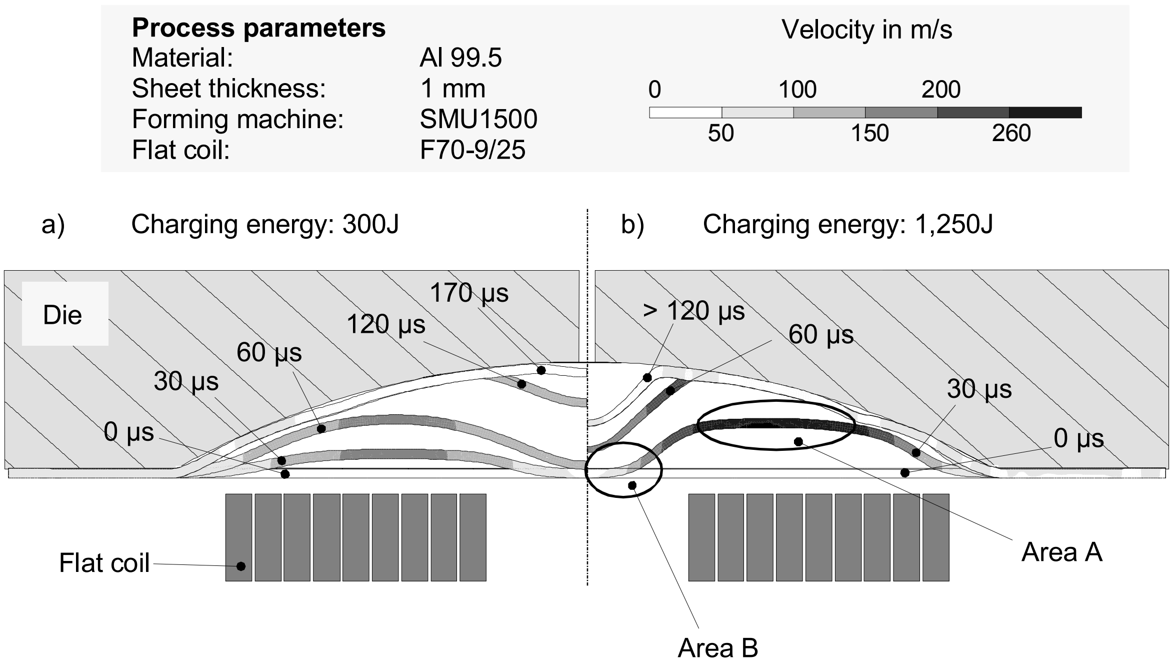


Figure 4: *Comparison of the velocity distribution depending on different charging energies*

These results are verified by according experiments. Figure 5 shows the contour (upper surface) of the workpiece measured with a Coordinate Measurement Machine (CMM). Compared to Figure 4, the simulation results are in good qualitative agreement with the performed experiments.

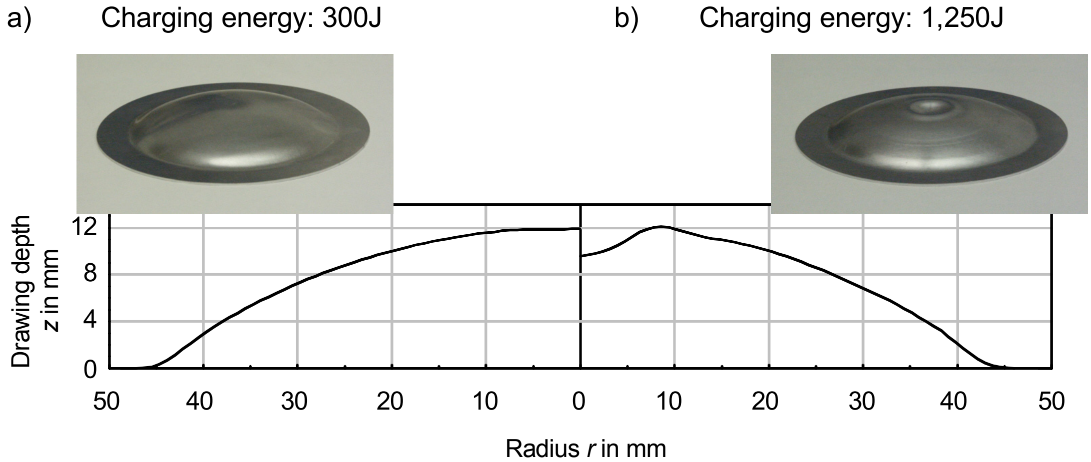


Figure 5: *Contour of the final geometry resulting from the experiments with different charging energies*

3.2 Rebound-effect caused by the kinetic energy

Due to its high velocity, the workpiece has a very high kinetic energy during the EMF process. This implies a difficulty when the workpiece contacts a die because at the time of impact the high kinetic energy should be transferred from the workpiece to the die. If the energy cannot be dissipated completely, the so called rebound-effect may occur. An extreme example of this effect is shown in Figure 6, where those workpiece areas being in contact with the die has been thrown back into the direction of the tool coil.

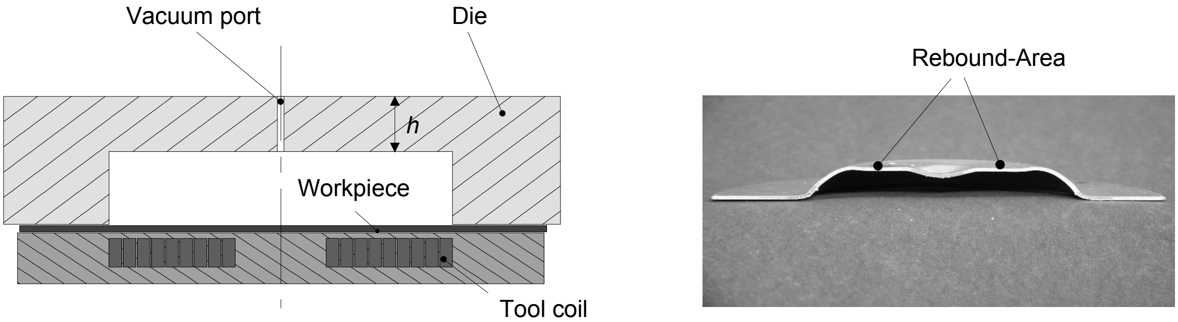


Figure 6: *Example of a workpiece geometry caused by the rebound-effect*

To regard the contact period of time more detailed, the coupled FEA as described in paragraph 2 has been used. For the qualitative interpretation of the simulation it was necessary to mesh the die completely. Additionally, it turned out that a very fine discretisation of the time domain is necessary to visualise the dynamic processes within the die. It could be observed how the energy transfer at the time of impact causes a deformation wave spreading out trough the die, analogue to an acoustic wave. In Figure 7 three stages of the spreading wave within the contact period are shown: the initiated deformation wave (a) spreads out through the die (b) until it is reflected on one of the die's surfaces (c) as indicated by the arrows.

Process parameters			
Die material :	Steel	Sheet material:	Al 99.5
Die's height h:	20 mm	Sheet thickness:	1.5 mm
Young's modulus E:	210,000 MPa	Forming machine:	SMU1500
Specific mass ρ:	7.81 g/cm³	Charging energy:	1,250 J

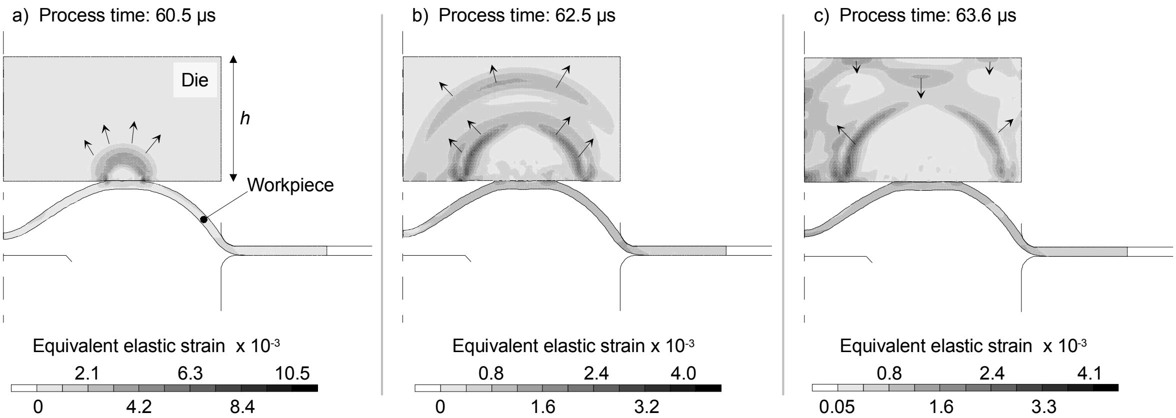


Figure 7: *Propagation of the deformation wave in the die during the contact period of time*

The impulses runtime depends on the sound velocity of the die material and can be estimated by

$$t_{run} = \frac{2 \cdot h \cdot \sqrt{\rho}}{\sqrt{E}} \tag{2}$$

with	t_{run}	impulse runtime
	h	die's height (marked in Figure 6)
	E	Young's modulus
	ρ	density of the die's material

Because the contact time between workpiece and die, typically, is longer than the runtime of the deformation wave, the rebound-effect is feared to be intensified, if the backward impulse would be transferred to the sheet again. It could be regarded that the reflected wave usually crosses the incident wave which leads to favourable extinguishing effects. Nevertheless, the rebound-effect occurs. It should be mentioned that the considered example of a cylindrical die with a flat bottom is very sensitive to this effect, because the flat workpiece areas are not very stiff and the magnetic pressure does not act any more to support those sheet areas which are in contact with the die.

Following up the idea that the kinetic energy of the workpiece shall be dissipated at the contact with the die, the influence capability of the die properties has been investigated. Therefore the parameters stiffness and damping properties have been varied using a mechanical substitute model of the die. More precisely, a spring-dashpot-system has been used (see Figure 8a) to represent the die's physical behaviour without the need of a complete meshed die. In this way the number of degrees of freedom is reduced as well as the calculation time. In comparison to the completely meshed FE-model (see Figure 8b) now the stiffness of the spring C represents both, the material stiffness (Young's modulus) as well as the geometrical stiffness (for example, the height of the die). In the same way the damping coefficient η represents the material damping property as well as the constructive change, like for example the use of an additional shock absorber.

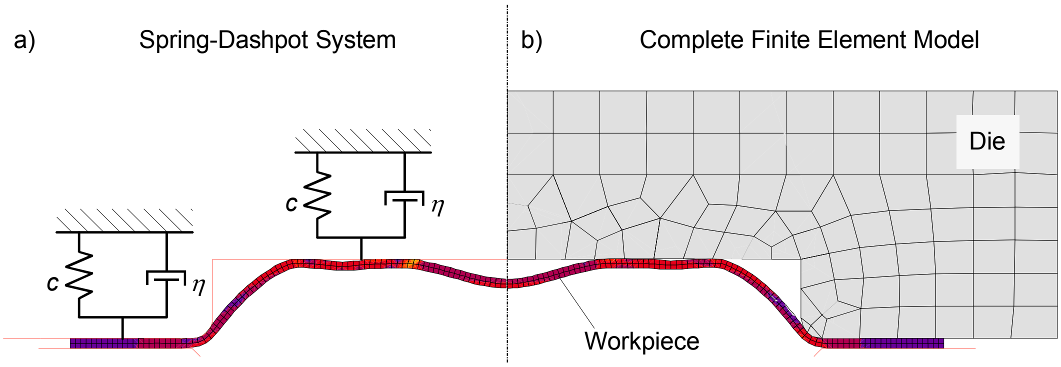


Figure 8: *Mechanical substitute: spring-dashpot system*

The parameter variation has been performed within a coupled simulation whereby the measured coil current was used as input. The cylindrical die geometry as well as thickness and diameter of the blank has been taken from the corresponding experiment. The parameters of the substitute die model have been varied starting with zero values for stiffness C and damping coefficient η. In Figure 9 an excerpt from the results is shown. It can be seen that for a constant spring stiffness an increase of the damping coefficient seems to improve the workpiece geometry up to an optimum followed again by a worse geometric accuracy if the damping will be increased further on: an optimal damping coefficient for a special spring stiffness seems to exist. On the other hand it is remarkable, that a flat bottom of the workpiece geometry can be achieved with best accuracy when the stiffness is at comparable low values. A very low stiffness means that the die, particularly the bottom of the die, can be moved by the workpiece at the time of contact. In this case the kinetic energy of the workpiece will be obviously dissipated, but a realisation of this possibility is still a problematic point.

Process paramters			
Material:	Al 99.5	Sheet thickness:	1.5 mm
Forming machine:	SMU1500	Charging energy:	1,250 J

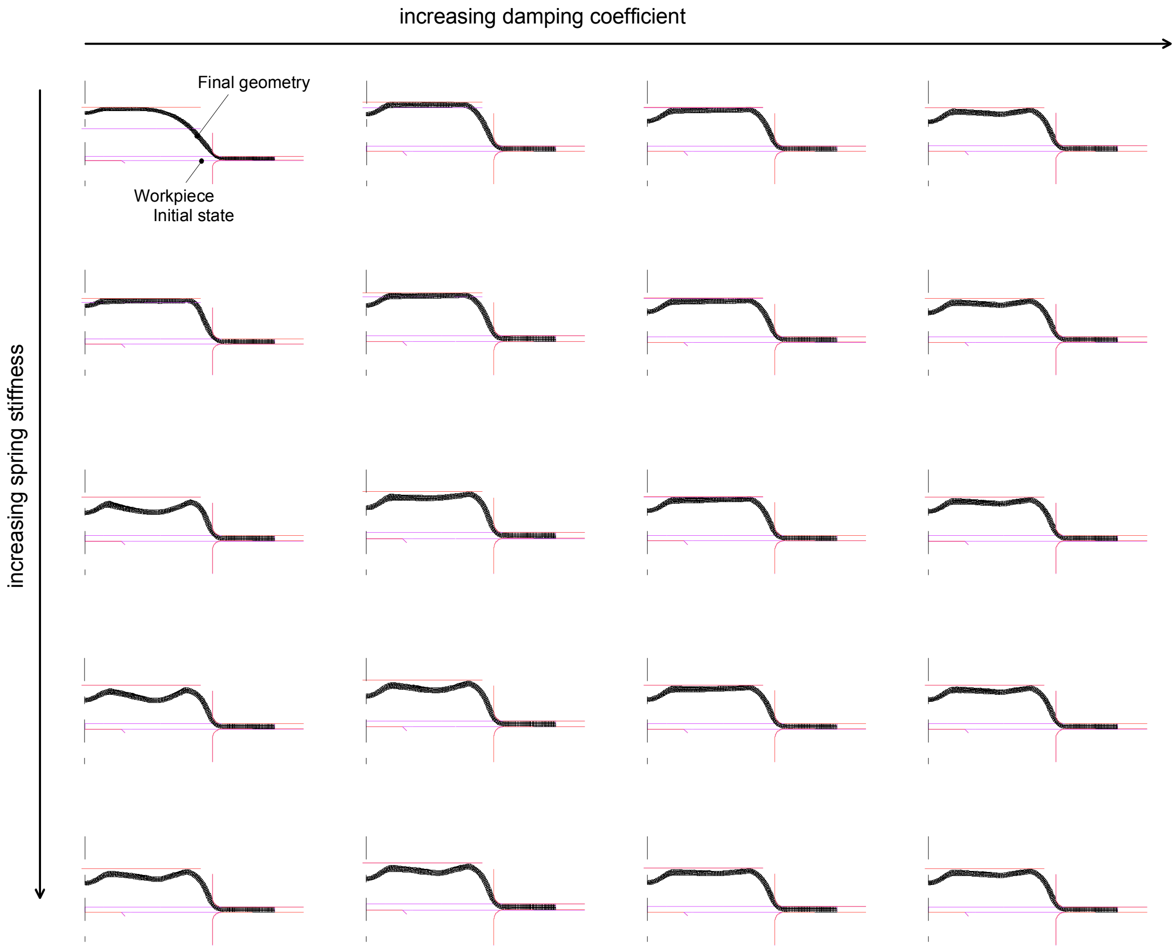


Figure 9: *Excerpt from the results of a parameter variation*

Furthermore, the parameter variation did not lead to a change of the significant shape of the workpiece, which occurs due to the inhomogeneous pressure distribution and the dimensions of the die. A better form filling can only be achieved at more process related geometries of the die, like e. g. by spherical, conical or other stiffening geometry elements, or by means of process combinations where an additional media is used to support the workpiece while it is in contact with the die. To determine such process related geometries the consequent use of the coupled simulation as well as further experimental investigations are necessary. Finally, as promising examples Figure 10 shows some workpieces without the described rebound-effect.

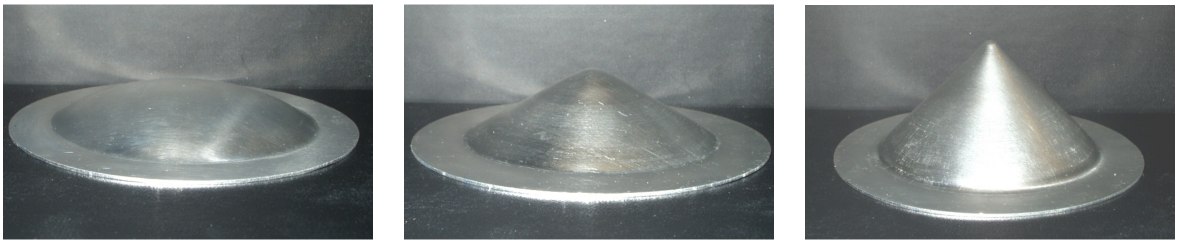


Figure 10: *Promising examples produced by forming into a die without the rebound-effect*

4 Summary

The investigation of the strongly interdependent working mechanisms of the electromagnetic sheet metal forming is the main objective of an interdisciplinary research group at the University of Dortmund. At the Chair of Forming Technology a special focus lies on the process and the tool design. Fundamental for this research work is the knowledge of the relevant process parameters, which have been identified in a first step on the basis of the free forming process. Here, the influence of the acting magnetic pressure and its distribution as well as the forming velocity and its distribution has been considered by examples.

A reliable simulation tool has been used as the basic requisite for first investigations of the interactions between the acting forces and the workpiece deformation as well as the interactions between the workpiece and the die at the time of impact. Undesired effects preventing the workpiece to get the desired shape are for example the inhomogeneous velocity distribution during the free forming stages as well as at the time of contact between workpiece and die. As a special case the so-called rebound-effect, where flat areas of the workpiece will be thrown back by the die surface, has been pointed out.

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