

Article

Comparative Analysis of Electrohydraulic and Electromagnetic Sheet Metal Forming against the Background of the Application as an Incremental Processing Technology

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Abstract: High-speed forming processes such as electromagnetic forming (EMF) and electrohydraulic forming (EHF) have a high potential for producing lightweight components with complex geometries, but the forming zone is usually limited to a small size for equipment-related reasons. Incremental strategies overcome this limit by using a sequence of local deformations to form larger component areas gradually. Hence, the technological potential of high-speed forming can be exploited for large-area components too. The target-oriented process design of such incremental forming operations requires a deep understanding of the underlying electromagnetic and electrohydraulic forming processes. This article therefore analyzes and compares the influence of fundamental process parameters on the acting loads, the resulting course of deformation, and the forming result for both technologies via experimental and numerical investigations. Specifically, it is shown that for the EHF process considered, the electrode distance and the discharge energy have a significant influence on the resulting forming depth. In the EHF process, the largest forming depth is achieved directly below the electrodes, while the pressure distribution in the EMF depends on the fieldshaper used. The energy requirement for the EHF process is comparatively low, while significantly higher forming speeds are achieved with the EMF process.

Keywords: incremental forming; electromagnetic forming; hydroforming; electrohydraulic forming



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1. Introduction

High-speed forming processes are classified as high-performance processes. In these processes, the energy required for forming is transferred to the workpiece in a very short time interval of up to 1000 ms for small forming paths [1]. The forming speeds and strain rates are therefore much higher than for conventional, quasi-static forming processes such as deep drawing. This is particularly advantageous for the processing of typical lightweight materials such as aluminum alloys, since the formability of these materials at room temperature is increased significantly [2,3]. Hence, more complex geometries with smaller radii can be produced with greater accuracy than for quasi-static processes [4,5]. Another important advantage of the technology is that inertia effects can be exploited to reduce the required clamping forces significantly [6,7]. This also reduces the required tooling costs and equipment expenses, since clamping or fixturing devices can be much simpler and less expensive. Overall, high-speed forming processes offer great potential for overcoming existing challenges such as sustainability and energy and resource efficiency.

High-speed forming can be realized inter alia through the use of explosives or via electrohydraulic and electromagnetic discharge processes [1]. Figure 1 sets out schematically

the two process principles of electromagnetic forming (EMF) and electrohydraulic forming (EHF). This article compares EHF and EMF against the background of their application as an incremental processing technology. Both processes use the same principal machine, a so-called pulsed power generator, which can be represented in simplified form by its electrical circuit parameters capacitance C_i , inner inductance L_i , and inner resistance R_i . In EHF, this pulsed power generator is electrically connected to two axially aligned electrodes that face one other in a pressure chamber filled with water. The capacitor is discharged via the electrodes within a few microseconds, thus generating a damped sinusoidal current, and the electrical energy is converted into mechanical energy by means of the liquid medium [8]. This involves the medium between the two electrodes evaporating and a plasma channel forming during the impulsive discharge. The plasma channel then expands in the radial direction at a speed of up to 1484 m/s and thus abruptly transfers its energy to the surrounding medium in the form of a shock wave [9]. The temperature inside the plasma channel reaches values of up to 10^4 K, with pressures of up to 10^4 MPa [9]. After the plasma channel has attained its maximum expansion in the radial direction, it collapses [10]. The velocity of the shock wave decreases with an increasing distance from the electrodes, due to its geometric expansion and energy dissipation [10]. The shock wave finally assumes a spherical shape [10].

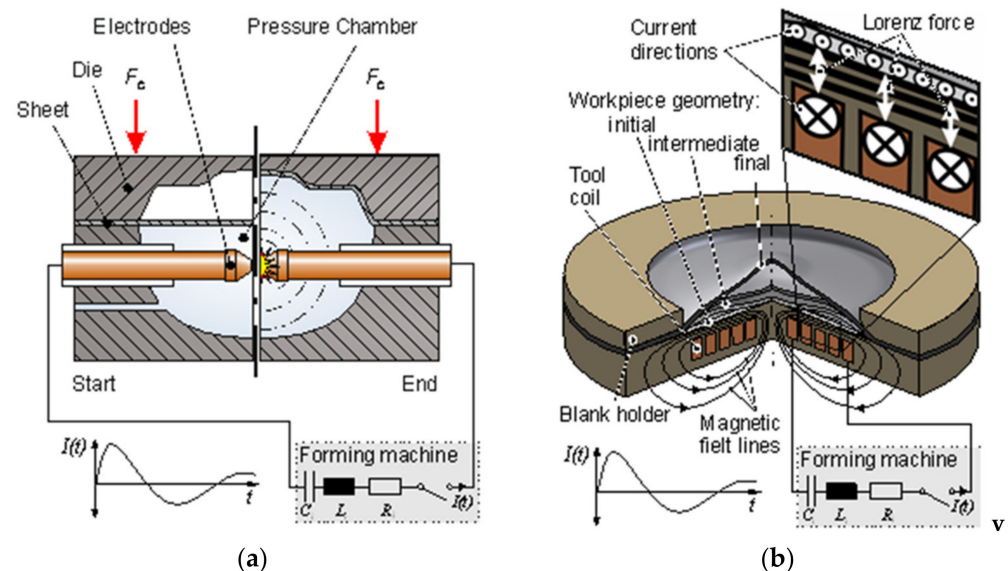


Figure 1. Process principle of EHF (a) and EMF (b).

The expansion of the plasma channel in the surrounding medium is due mainly to the rapid and pronounced pressure increase in the spark channel between the electrodes, caused by the temperature rise during the rapid and high energy input [9]. This process takes place in a time interval of less than 100 μ s in most cases [11,12]. The shock wave caused by the expansion of the plasma channel is transmitted to the surrounding medium as a pressure wave and then propagates in this at the speed of sound, which is 1500 m/s in water [7]. Reflections of the pressure wave from the walls of the pressure chamber can produce secondary waves [13,14]. Both initial and secondary pressure waves can contribute to workpiece deformation.

In EMF, the capacitor battery is discharged via a so-called tool coil or inductor. Consequently, a damped sinusoidal current with maximum values in a range of several tens of kiloamperes to several hundred kiloamperes and rise-times in the range of 10 μ s to 100 μ s flows through the coil and induces a corresponding time-dependent magnetic field. This induces a second current in the workpiece that is required to provide a high electrical conductivity and be positioned close to the coil. Interactions between the magnetic field and the currents give rise to Lorentz forces directly in the corresponding workpiece areas,

which accelerate and deform the workpiece when the resulting stresses in the material reach the strain-rate-dependent flow stress. Typical velocities are in a range of up to several hundred meters per second. The corresponding strain rates attain values of up to 10^2 – 10^6 /s. It is a specific feature of the process that the force acts without any contact and is therefore particularly gentle on the surface, without necessitating a liquid medium. The workpiece acceleration and deformation, respectively, are usually directed away from the tool coil [15].

As shown in Figure 1 EHF and EMF can be used for forming flat sheet metal [16]. If necessary, the resulting workpiece geometry can be adjusted by a female die. In addition, tube compression [17], expansion of tubes [18], and rings [19] and local forming and restriking of two- or three-dimensionally preformed hollow bodies [20] are possible. Apart from purely shaping operations, the technologies can be applied for joining by crimping [21], hemming [22], and magnetic pulse welding [23], and cutting is also possible [24]. The high potential for industrial application is shown in [25].

Due primarily to equipment-related restrictions, the area that can be formed in a single discharge process is usually limited to small-sized components and component areas. Only very rare exceptions deal with single discharge forming of large components through the use of high-level capacitor charging energy [26]. Incremental approaches, however, provide an interesting alternative that makes it possible to extend the applicability of EMF with moderate capacitor charging energy to larger parts and forming areas. The basic feasibility of incremental electromagnetic forming was proven in a structuring process [27] for the simple [28] and more complex [29] 3D-shaping of sheets as well as for the magnetic pulse welding of tubes [30] and sheet metal [31]. Incremental electrohydraulic forming was suggested in [6].

For the target-oriented process design of electromagnetic incremental forming (EMIF) and electrohydraulic incremental forming (EHIF), a deep understanding of the underlying single discharge electromagnetic and electrohydraulic forming process is indispensable. In the field of electromagnetic forming, extensive research was carried out since the process was initially suggested in [32]. A detailed review with a comprehensive discussion of the process fundamentals is provided in [33]. It shows that early work from the 1960s is based mainly on analytical calculations and empirical studies, including the necessary measurement technology. A focus is put on the calculation of the acting loads. For this purpose, the so-called magnetic pressure was defined, which can be calculated on the basis of the magnetic permeability μ and the magnetic field strength at the workpiece surfaces both facing the tool coil H_{gap} and facing away from the tool coil H_{pen} as per Equation (1), [34]. If the skin depth is small compared to the thickness s of the workpiece (i.e., the thickness is at least 1.5 times the skin depth [35]), the penetrated magnetic field at the workpiece surface facing away from the coil can be neglected, and Equation (1) can be simplified to Equation (2).

$$p(t) = \frac{1}{2} \mu \left(H_{\text{gap}}^2(t) - H_{\text{pen}}^2(t) \right) \quad (1)$$

$$p(t) = \frac{1}{2} \mu \left(H_{\text{gap}}^2(t) \right) \quad (2)$$

Early research is focused primarily on tube forming processes, because, with a relatively simple setup, the distribution of the magnetic field is known, and the field strength can be estimated analytically as is conducted in [35] for tube compression processes and in [36] for tube expansion processes. The workpiece deformation corresponding to the identified acting loads was measured in [37] inter alia and calculated with the assumption of a number of essential simplifications, such as in [38].

Compared to the tube compression and expansion processes, acquiring an understanding of electromagnetic sheet metal forming processes is significantly more challenging. The reason is that the local distribution of the magnetic field is complex, and the interactions between the electromagnetic field variables and the mechanical field variables have a much stronger influence on the acting loads and the resulting deformation behavior [39] and

must be taken into consideration when analyzing the process. Mathematical description in a closed form was thus not possible [40], and little significant progress was made until the 1990s, when developments in the field of numerical modeling and simulation enabled an understanding of the influences and correlations of process parameters and advanced the technological development of electromagnetic sheet metal forming. The first complete coupled electromagnetic and structural mechanical process modeling was presented and verified in [41]. Over approximately the next two decades, multiple individual coupled simulation approaches were developed based on different self-developed [39] or commercial codes such as Ansys/EMAG and LS-DYNA [42], ANSYS [43], MSC, Marc Mentat [44]. The first commercially available full solution was implemented in LS DYNA [45]. More recently, another tool was realized in FORGE [46].

These different simulation solutions were used in combination with appropriate measurement techniques to analyze the electromagnetic sheet metal forming process. Basically, three major influencing parameters are considered. These are:

- the local pressure distribution, determined primarily by the shape of the tool coil,
- the course of the current, which depends on the parameters of the electrical circuit, specifically the capacitor charging energy, the capacitance, and the inductance,
- interactions between the workpiece and the die.

The first two aspects are frequently analyzed in a free forming operation (i.e., without a form defining die). When it comes to the pressure distribution, a more or less rotationally symmetric setup with a spirally wound tool coil is frequently considered (compare Figure 1). For this setup, a ring-shaped area of the workpiece is initially pressurized, because skin and proximity effects concentrate the current in the workpiece in the surface regions that are directly facing the coil winding. In conformity with this pressure distribution, the workpiece is deformed into a semi-toroidal shape in the early forming stages [41]. As soon as the deformation starts, the magnetic field, which is shielded by the electrically highly conductive workpiece material and therefore restricted to the initially narrow gap between the coil and the workpiece, can spread to a bigger gap volume. Consequently, the magnetic pressure collapses rapidly [47], but the deformation process continues on account of inertia forces and, depending on the inner diameter of the tool coil, the center region can be accelerated and either reach the highest displacement values or remain less deformed [48]. At all events, some areas of the workpiece undergo severe bending and unbending deformation with this setup, and efforts were therefore made to develop a coil design that provided a more uniform pressure distribution, leading to more uniform workpiece deformation [49].

With respect to the current course, it is obvious that a higher capacitor charging energy leads to a higher maximum current, higher pressure, and higher deformation. The frequency of the discharging current can be adjusted by adapting the capacity of the electrical circuit. In [48], it is shown that the same deformation can be achieved by applying either a short current pulse with a higher maximum or a longer current pulse with a lower maximum to an aluminum sheet (AA 6016). The applied energy and the forming velocity were similar in both cases. In a more comprehensive study, Risch found that, depending on the specific material changes in the current frequency, a more or less pronounced variation in the drawing depth can result [50]. This corresponds with [51], where a direct correlation between a higher frequency and a higher pressure is identified. More recently, Cao et al. claimed that two optimum frequencies exist that produce relatively large sheet deformation. These optimum frequencies correlate with the thickness of the sheet and the relative skin depth.

Concerning the interactions between workpiece and die, it is well known that the highly dynamic contact rebound of the workpiece can hinder successful shaping of the component. The impact of the rebound is significantly influenced by the process parameters (specifically the capacitor charging energy) and the elastic properties of the die [50].

In the field of EHF, fundamental research shows that the time interval between the application of the voltage to the electrodes and the beginning of the electric discharge

(discharge delay) significantly influences the efficiency of the spark discharge and thus the pressure effect inside the medium [10]. The discharge delay is influenced by the distance between the electrodes x_E , the surface conditions and the geometry of the electrodes, as well as the conductivity of the surrounding medium [14]. The discharge delay increases with a rising electrode distance x_E and a decreasing conductivity of the medium [10,52]. Reducing the inductance and also increasing the charging voltage lead to a higher expansion speed of the plasma channel and thus to a rising shock pressure wave. This is due to an increase in the temperature in the plasma channel between the electrodes [10].

The resulting pressure distribution acting on the workpiece depends essentially on the shape, length, and position of the plasma channel. The length of the channel is typically twice the length of the electrode distance x_E . Furthermore, the following parameters affect the shape and position of the plasma channel, according to [14]:

- surface condition of the electrodes,
- geometry of the “discharge surfaces” of the electrodes (by means of changes in the discharge surfaces due to the wear on the electrodes),
- local conductivity of the water,
- gas content of the water, and
- presence of particles in the water.

These influences are difficult to control and lead to inhomogeneous pressure distributions overall and to a limited reproducibility of the process. The arrangement of a conductive wire between the electrodes homogenizes the plasma channel and thus significantly improves the pressure distribution as described in [14,53]. Typical cycle times vary from one minute per part without wire to three to six minutes with wire [7,53]. Within electrohydraulic forming processes, around 20% of the electric energy of the capacitor is converted into mechanical energy by means of the pressure wave generated by the discharge. Typical forming speeds are in the range of up to 100–400 m/s [10], significantly increasing the formability of a large number of materials [3,5,54,55].

The simulative modeling of the EHF process also represents an important object of investigation. Various approaches exist for realizing this simulation via FEM. Previous publications on the numerical simulation of EHF processes can be divided up on the basis of the following aspects: the FE software used, the depth of simulative modeling, and the material modeling of the semi-finished products.

The modeling of the publications considered in this review of the state of the art makes use of two different FE solvers. Refs. [55–58] used ABAQUS CAE EXPLICIT, and the FE solver LS-DYNA was applied in the simulations of [7,59–62]. The depth of simulative modeling can generally be divided into two approaches: comprehensive modeling and reduced modeling. To model the EHF process comprehensively, the following aspects must be taken into account, according to [7]:

- the pressure generation in the discharge channel
- the vapor-temperature-pressure gradient around the discharge channel
- the compressible liquid as a pressure transmitting medium, and
- the deformation of the chamber and blank in contact with the deformable die.

Comprehensive modeling of this type for the EHF process was performed by [7,58] in the form of a 3D FE simulation. For the description of the interaction between the fluid components, an ALE multimaterial formulation was used. This modeling has the advantage of achieving good agreement between numerical and experimental results. Very fine meshing of the ALE elements is necessary, however, which significantly increases the computation time. This computation time may even increase to a point where supercomputers are needed.

In addition, the simulation includes two approaches for modeling the energy introduced into the discharge channel. The first approach involves the simulation of the discharge circuit. Here, the resistance of the channel must be known as a function of time. In the second approach, the derivation is performed through the experimental mea-

surement of the electric current and the voltage of the electrodes. Both approaches thus always involve extensive measurements on the real system and are subject to measurement inaccuracies. Ref. [60] performed a numerical comparison of EMF and EHF with respect to the EHF properties in a bid to reduce the bouncing effect in electromagnetic forming. A comprehensive FE model such as that in [7] is used in [58] for this purpose. Moreover, in this case, an ALE multimaterial formulation serves to describe the interaction between the fluid components, and a coupling mechanism was used for modeling the fluid-structure interaction. In addition, the input energy for the discharge channel was obtained from [58]. This FE model was applied in order to examine the deformation behavior of a blank using a quarter model for the forming operation. The FE model of [55,56] considers the effect of electrical spark ignition in the liquid as a pressure wave propagating inside the liquid chamber and exerting a surface pressure on the sheet metal. Special focus was placed on the simulation of the pressure wave in the water chamber, including the reflection and damping of the pressure wave after initial ignition. The vapor bubble, which is formed by the electrical discharge, was neglected. The modeling of the fluid and its interaction were not described in detail.

In addition to 3D FE simulations, approaches also exist to the comprehensive modeling of the EHF process which take the form of 2D FE simulations. Ref. [61] describes such a simulation model for the shaping of top caps for a perfume among other things. Here, the fluid is modeled as an Eulerian mesh, which is coupled with the Lagrangian mesh of the metal blank. The input variable is the realistic time-dependent electrical energy deposition. In addition, the importance of the entire dynamic history of the pressure waves is emphasized. Hence, one third of the transformation would be obtained from the initial wave, while two thirds would be obtained from the reflected waves.

Comprehensive modeling of the EHF process goes hand in hand with a deeper understanding of the process. Furthermore, a wide range of applications for both process investigation and optimization can be realized with these FE simulation models. These models, however, also require complex and time-consuming measurement series, which serve as input data. For the FE simulation itself, the complex interaction of modeling partners, such as fluid and structural components, as well as the complex contact situations must be implemented. The representation of the fluid also requires a very fine discretization, which often results in exorbitant calculation times.

Due to these difficulties, researchers have also resorted to reduced modeling of the EHF process. Reduced modeling was investigated in [57]. In this case, the pressure wave was modeled by an evenly distributed pressure pulse with a uniform pressure on the surface. The fluid was not modeled. This reduced modeling is based on the assumption that the energy of the electric discharge is converted into pressure inside the fluid in the discharge chamber. This simulation was used to investigate the free forming of a semi-finished product using a drawing ring. Validated results were obtained by comparing simulated and experimental dome heights. The latter was obtained from the investigations of [56]. Ref. [59] also describes a reduced FE simulation for the EHF process. The simulation is used in conjunction with simple analytical models in order to demonstrate their possibilities for the forming processes in the EHF process.

Reduced modeling is characterized by considerably lower computational costs and a reduced modeling effort. Nevertheless, it allows simulation models to be used for targeted areas of process optimization. The reduction assumptions must, however, be made and validated specifically for these application areas. Reduced models are therefore not permissible for a holistic process investigation and optimization.

The characteristics of the EHF and EMF processes place specific requirements on the material modeling of the semi-finished products. Specifically, the strain rate sensitivity must be taken into account. Two commonly used material modeling methods fulfill this requirement. The Johnson Cook model was used by [55–57,61] assuming isotropy and also without taking temperature dependencies into account. In the second material modeling method, strain rate sensitivity is accounted for by a hardening law.

Refs. [7,59–61] used the power law material model for this purpose, which is also known as the Cowper-Symonds model. This hardening law can be considered in LS-DYNA inter alia by two elastoplastic material models: *MAT_POWER_LAW_PLASTICITY (*MAT_018) and *MAT_PIECEWISE_LINEAR_PLASTICITY (*MAT_024). These two material modeling methods were mainly applied to steels (mild to high strength) and aluminum alloys. In addition, Ref. [61] has specified the Zerilli-Armstrong model for semifinished products made from niobium or copper.

Altogether, considerably less generally accepted knowledge is available on process analysis and design in the field of electrohydraulic forming than in electromagnetic forming. This lack of knowledge complicates the application of the technology for an incremental forming process. This paper is thus dedicated to fill this gap by examining the influence of major process parameters in EHF and directly comparing them with corresponding correlations in EMF in order to point out similarities and differences between these high-speed forming processes.

Therefore, numerical as well as experimental analysis of the processes was conducted. Specifically, by doing free forming tests, the current course, the resulting deformation (especially the achievable drawing depth), and the speed in the process were observed. Furthermore, to analyze the pressure distribution, forming operations into a perforated sheet were realized. Against the background of the prospectively planned incremental approach, the influence of component size and blank holder distance was investigated by using numerical methods.

2. Materials and Methods

2.1. Experimental Setups for Analysis of the EHF and EMF Processes

The electrohydraulic forming tests were carried out at the LUF using an SSG-0620 pulsed power generator from Poynting GmbH, Dortmund, Germany. Table 1 summarizes the key nominal characteristics of the machine as specified by the manufacturer.

Table 1. Nominal characteristics of the SSG-0620 available at the LUF.

Max. Capacitor Charging Energy	Max. Capacitor Charging Voltage	Max. Capacitance	Max. Discharge Current ¹	Max. Frequency of the Discharge Current ¹
6 kJ	20 kV	30 μ F	160 kA	100 kHz

¹ In short circuit discharge.

The pulsed power generator is operated with the EHF tool system that is shown in Figure 2 in a half section. The tool system can be connected to a support system or to an industrial robot. The clamped workpiece can thus be moved relative to the EHF tool. The forming tool consists primarily of a pressure chamber with a diameter of 150 mm in which two rotationally symmetric electrodes in CuCrZr12 are arranged coaxially, facing one other. The electrode tips are an axial distance of x_E from each other, which can be adjusted. Underneath the electrodes, the pressure chamber is closed at the bottom with an expandable membrane in high-grade NR-SBR (hardness = 40 Shore) with a thickness of $t_{M,0} = 3$ mm, so that the fluid medium inside the pressure chamber is encapsulated. Due to the membrane, the EHF process can be repeated without need to evacuate and refill the pressure chamber after each forming process. This significantly reduces the cycle time. The comparatively small tool system limits the size of the forming zone to a diameter of 150 mm. Connecting the EHF tool to the industrial robot, however, enables the tool system to be used for incremental forming processes in future investigations.

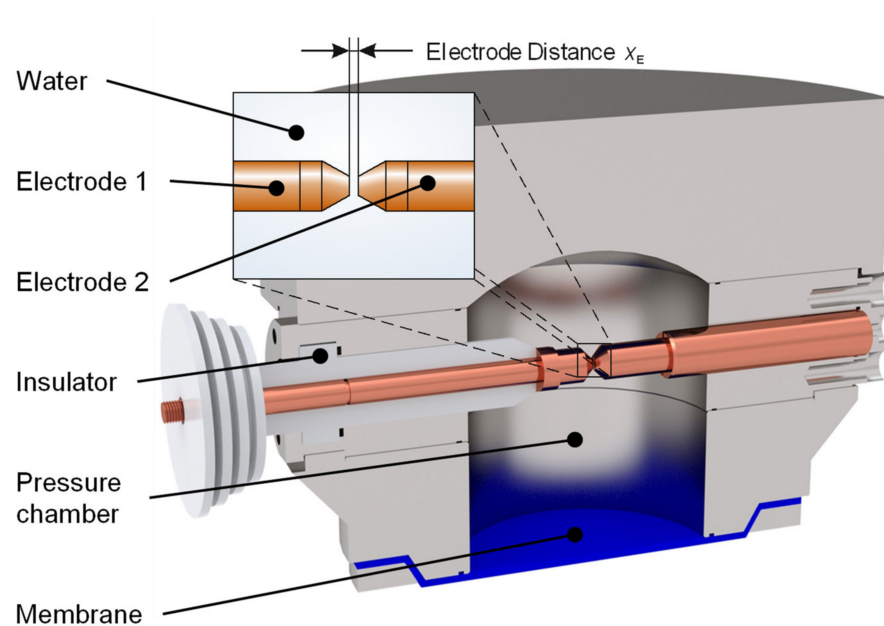


Figure 2. Half section of the EHF tool.

For the experimental investigations, the EHF forming tool is positioned at a distance of 0.5 mm above the non-clamped workpiece, and the pressure chamber is filled with water. For free forming tests, performed to investigate the drawing depth and the forming speed, a drawing ring with an inner diameter of $D_i = 100$ mm and a feed radius of $R_F = 20$ mm is used. For the investigations relating to the characterization of the local pressure distribution, a methodology according to [14] is used. By performing multiple cupping operations at one and the same time with the help of a perforated sheet (tool), it is possible to determine the acting pressure distribution. The perforated sheet used as a tool has a thickness of $t_{M,0} = 3$ mm and hole diameters of 8 mm; a distance of 12 mm between the holes restricts deformation. The discharge current is measured by a flexible Rogowski coil of type 1232/X with a passive integrator suitable for measuring currents of up to 1000 kA from Rocoil Limited, North Yorkshire, United Kingdom.

In order to characterize the workpiece deformation as a function of time, two different measurement principles were used. The first one is a LK-H157 laser displacement sensor from Keyence, Osaka, Japan. To guarantee proper measurement, the laser must be oriented orthogonal to the workpiece surface throughout the entire measurement process. The deformation can then be recorded solely for the center point of the workpiece, because all the other surface points change their orientation during the deformation. In order to verify the measurement, a tactile measurement was implemented by way of a second measurement principle. This is based on the contact pin method described in [62] and makes it possible to measure the precise moment at which the workpiece surface attains a specific displacement. For this purpose, so-called contact pins are arranged at a pre-defined distance from the workpiece, and an electrical voltage (here 9 V) is applied between the workpiece and the contact pin. As soon as the workpiece touches the workpiece, a current flows, and the voltage collapses. This effect is recorded by an oscilloscope. The displacement-time curve can be composed of discrete measurement points determined in a series of experiments with constant process parameters if the contact pins are positioned at different distances from the workpiece surface.

The electromagnetic forming tests are being carried out at Fraunhofer IWU using a PS 103-25 Blue Wave pulsed power generator from PSTproducts GmbH, Alzenau, Germany. The key nominal characteristics of the machine as specified by the manufacturer are summarized in Table 2.

Table 2. Nominal characteristics of the PS 103-25 Blue Wave pulsed power generator available at Fraunhofer IWU.

Max. Capacitor Charging Energy	Max. Capacitor Charging Voltage	Max. Capacitance	Max. Discharge Current ¹	Max. Frequency of the Discharge Current ¹
103 kJ	25 kV	320 μ F	2.2 MA	60 kHz

¹ In short circuit discharge.

The machine is operated with a cylindrical tool coil including a fieldshaper, which redirects the magnetic pressure to the flat sheet metal workpiece as shown in Figure 3. The coil is designed as a Bitter coil [63]. This means that the coil winding is composed of individual conducting discs, which are separated by corresponding insulating discs. The fieldshaper surface facing the workpiece is insulated with Nomex paper in a thickness of 0.25 mm and Kapton foil. The workpiece is positioned directly on the insulation and fixed with two clamping bars. For the free forming tests, performed to investigate the drawing depth and the forming speed, use is made of a drawing ring with an inner diameter of 100 mm and a drawing radius of 5 mm. For the tests relating to the characterization of the local pressure distribution, the same perforated sheet that was used for EHF restricts the deformation. In the free forming experiments, a drawing ring is applied (compare Figure 3a).

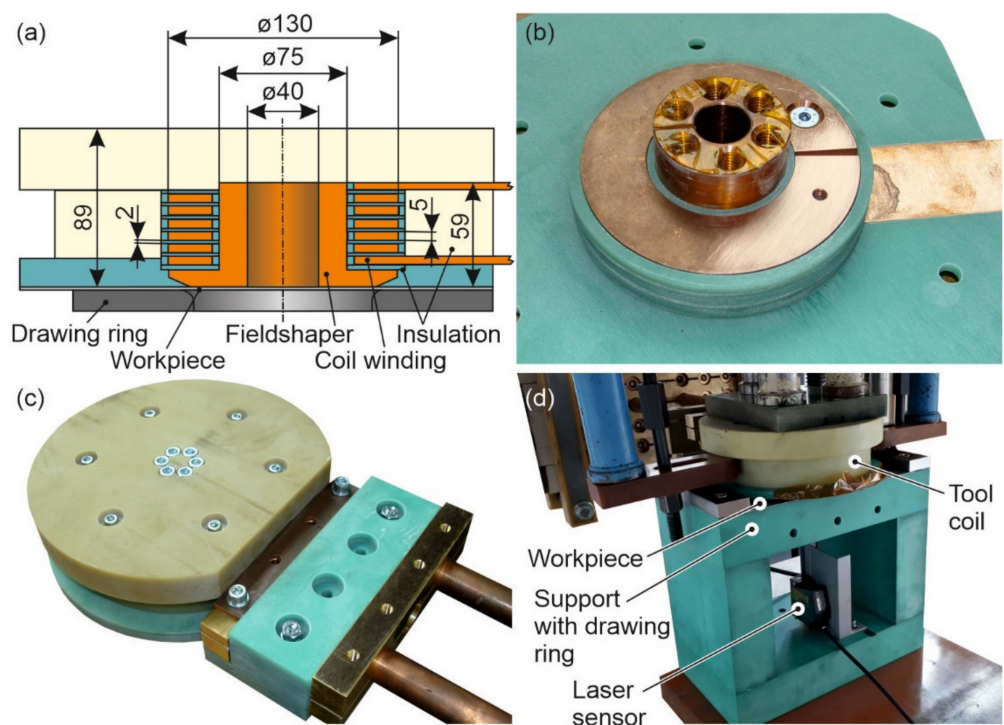


Figure 3. Setup for electromagnetic forming tests: cross-section of the tool coil (a), assembly stage of the tool coil (b), completely assembled coil (c), full view of the setup (d).

A CWT5000XB/2.5/1000 Rogowski coil by Power Electronic Measurements Limited, suitable for measuring peak currents of up to 1000 kA, is used for recording the coil current. The time dependent displacement is measured with the same LK-H157 laser displacement sensor from Keyence that was used for the electrohydraulic forming tests. In the same way as for electrohydraulic forming, the measurement is performed here too for the center point of the workpiece in order to guarantee that the laser beam remains oriented orthogonal to the workpiece throughout the entire deformation process.

2.2. Numerical Modeling of the EHF and EMF Processes

The numerical investigations of the EHF process were realized in the form of reduced modeling with the LS-DYNA FE software (version R12.1), using its explicit solver. In order to gain experience and knowledge on this process simulation, the modeling focuses on the free forming tests with a single discharge of 1.5 kJ as described in Section 3.4. It should be noted that previous numerical investigations, which were presented in Section 1, referred to the EHF process without a membrane. The reduced model for the EHF process with a membrane should be applicable for an investigation of the resulting deformation, more specifically the attainable drawing depth, and also for an investigation of the influence of the blank holder distance, whereby the experimentally determined forming speed is used as input data.

The FE model is composed of the following parts, as shown in Figure 4: pressure field, blank holder, circular sheet, and drawing ring. The blank holder is to be interpreted as the actual spatial limitation of the circular sheet by the tool head. The distance between the blank holder and the circular sheet is defined by x_{bh} , which can be seen in Figure 4. The model was reduced by the modeling of the active medium, e.g., the water, and the impulsive discharge, which were described in Section 1. The pressure distribution as a result of the discharge was thus assumed in simplified terms. In addition, the reflection of the pressure wave was initially neglected. Based on the findings of [10] and the modeling of [57], the pressure field was realized as a uniformly distributed pressure pulse. The influence of the membrane was taken into account by the contact formulation, employing the coefficient of friction for the interaction of the membrane and the steel plate. The drawing ring and the blank holder were both modeled as rigid bodies consisting of quadratic shell elements with a linear regression function. All the spatial degrees of freedom of both components are locked. For the numerical modeling of free deformation, a circular sheet of DC04 with a diameter of $D_0 = 100$ mm and a thickness of $t_{sh} = 1.0$ mm was examined. As before, use was made of quadratic shell elements with a linear regression function. The implementation of the displacement boundary conditions can be performed in various ways, as is discussed in more detail in Section 3.3.

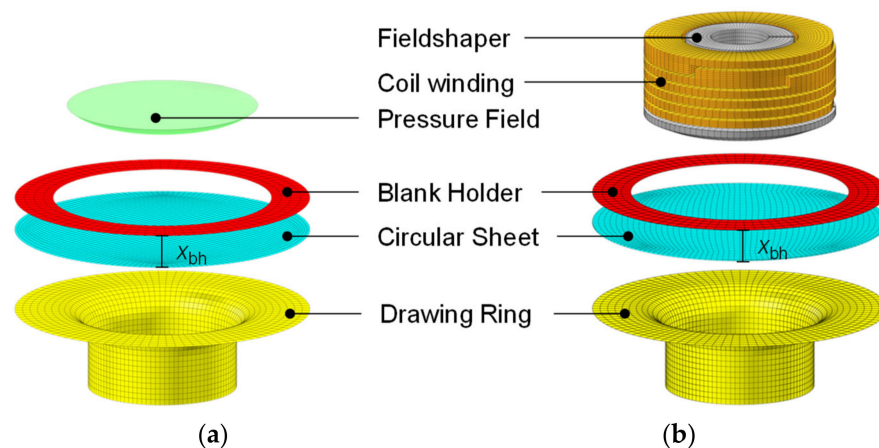


Figure 4. Numerical model setup of the EHF (a) and EMF (b) process.

To represent the strain-rate-dependent material behavior of the circular sheet, the Johnson-Cook model *MAT_224 or rather *MAT_TABULATED_JOHNSON_COOK was used. This model represents elasto-viscoplastic material behavior with the possibility of considering arbitrary stress-strain curves for arbitrary strain-rate dependencies. The model is based on the classic Johnson-Cook model, which is implemented in LS-Dyna as *MAT_015 or *MAT_JOHNSON_COOK, respectively. Moreover, unlike the Steinberg-Guinan model, for example, the Johnson-Cook model remains valid at low strain rates and even into the quasi-static range. It is thus suitable for modeling, among other things,

impact loads (crash), ballistic penetration, explosive metal forming, and hence material modeling for the EHF process

The experimental setup described for the EMF is modelled in LS-DYNA too. The tool coil, fieldshaper, workpiece, drawing ring, and the lower part of the insulation are implemented as fully integrated solid elements (see Figure 4). The workpiece is an elastic-plastic von-Mises material, while the other parts are rigid bodies with constrained rotatory and translational degrees of freedom. On the outer nodes, the workpiece is constrained in all the translational degrees of freedom.

The experimental setup described for the EMF is modeled in LS-DYNA too. The tool coil, fieldshaper, workpiece, drawing ring, and the lower part of the insulation are implemented as fully integrated solid elements (see Figure 4). The workpiece is an elastic-plastic von-Mises material, while the other parts are rigid bodies with constrained rotatory and translational degrees of freedom. On the outer nodes, the workpiece is constrained in all the translational degrees of freedom.

For the material parameters, measured data from [64] are used. To take the effects of the high forming velocity into consideration, a logarithmic strain rate sensitivity parameter c of 0.0947 is applied. Based on the measured material data, the failure strain ϵ_{fail} is set to 0.23.

The calculations were carried out in the form of a coupled electromagnetic and structural mechanical simulation. For the electromagnetic part coil, the fieldshaper and workpiece are considered, while, for the structural mechanical calculations, the blank holder, work piece, and die are taken into account. The coupling time step size is 10 μ s up to 100 μ s process time and 20 μ s afterwards. This graduated time step size makes allowance for the decreasing influence of the coil current with increasing deformation of the workpiece.

The coil current is calculated by LS-DYNA with the circuit input data of the pulsed power generator determined through short circuit measurements, specifically an inner inductance of 100 nH and an inner resistance of 5 m Ω . The capacitance value (330 μ F) is known from the machine data set out in Table 2. The input voltage varies depending on the capacitor charging energy.

3. Results

3.1. Analysis of the Free Forming Process

To analyze how the workpiece reacts to the pressure applied by the active medium in EHF and the magnetic pressure in EMF, respectively, free forming tests and corresponding simulations were carried out. Figure 5 compares forming results set out by way of example for both technologies. In this comparison, the capacitor charging energy was adjusted in such a way that approximately the same drawing depth—a depth of 15 mm—was achieved. A capacitor charging energy of 2.5 kJ was necessary to this end in EHF, while EMF required 16.5 kJ. One reason for this huge energy difference is that the observed workpiece is made of steel, and it is well known that, for materials with such a low electrical conductivity, the process efficiency of electromagnetic forming is limited. Moreover, the efficiency of an electromagnetic forming process depends significantly on the specific coil system. The setup considered here uses a cylindrical coil together with a fieldshaper that leads the acting forces to the sheet metal workpiece, redirecting them from being mainly radially acting forces to mainly axially acting ones (see Section 4). The setup thus ensures flexibility in the use of coils and avoids changing the load on the coil winding as described in [33]. These load changes are typical of electromagnetic sheet metal forming with the spiral flat coils that are frequently used and can lead to early coil failure. The redirection of the force via the fieldshaper, however, comes at the expense of process efficiency, because the current in the fieldshaper causes additional Joule and inductive losses.

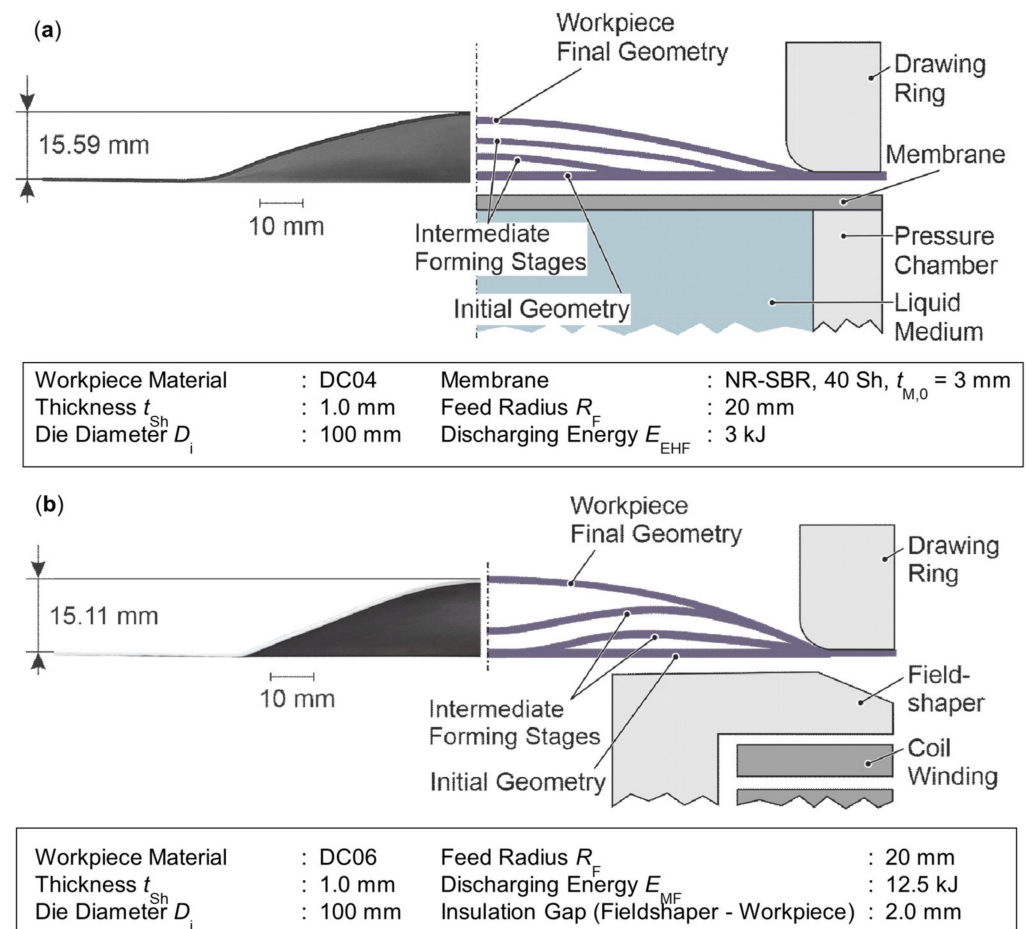


Figure 5. Representative result of (a) electrohydraulic forming and (b) electromagnetic forming.

The final shape achieved in electrohydraulic forming is spherical and comparable to the typical result of a quasistatic bulge test. Electromagnetic forming, by contrast, leads to a more tapered shape. This forming result is typical of the technology and results from the process-specific course of the deformation, including the distinctive bending and unbending in the center region and the corresponding local strain-hardening history [47]. To illustrate this effect and the differences in the deformation course between electromagnetic and electrohydraulic forming, intermediate forming stages are depicted for different points in time and at the end of the process in Figure 5 too.

In the next step, the influence of the capacitor charging energy was studied more comprehensively (see Figure 6). As expected, the depth increases with an increasing capacitor charging energy and a corresponding increase in pressure with both technologies. For electrohydraulic forming, it is also shown that the same capacitor charging energy leads to a higher deformation if the sheet thickness is reduced. In the observed range of capacitor charging energies (2.5 kJ to 6.0 kJ), a reduction in the thickness from 1.0 mm to 0.5 mm leads to an increase in the drawing depth of approximately 5 mm, independently of the capacitor charging energy and the corresponding absolute drawing depth.

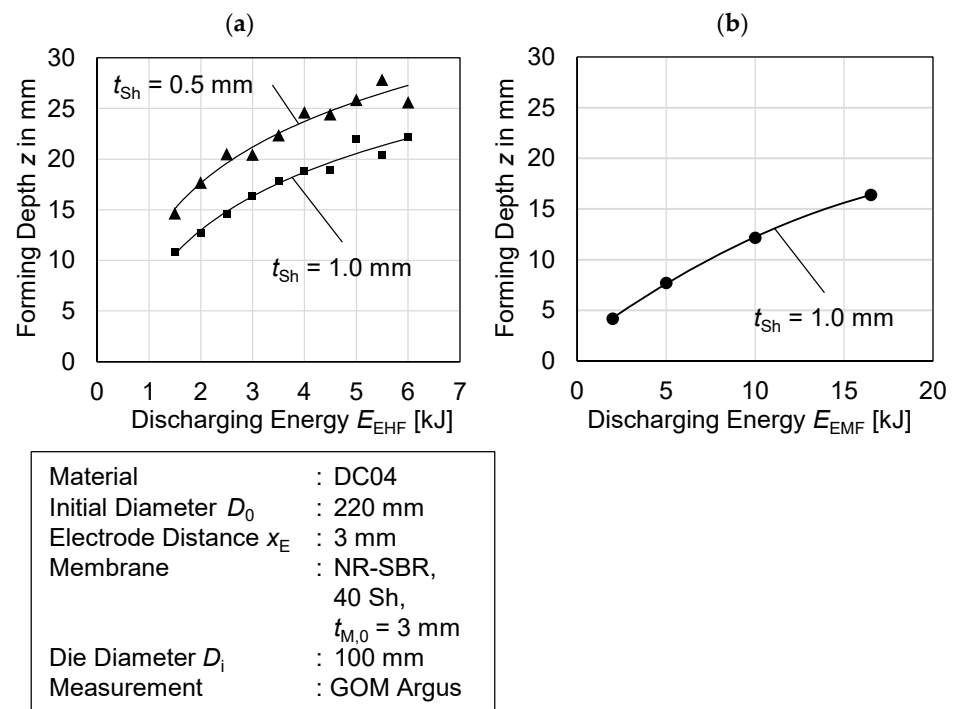


Figure 6. Influence of the capacitor discharge energy on the forming depth for (a) electrohydraulic forming and for (b) electromagnetic forming.

Deeper insight into the process can be gained by considering the course of the displacement time. A laser displacement sensor and, in electrohydraulic forming, a tactile measurement approach with contact pins too is thus applied for recording the movement of the workpiece's center point (compare Section 2). Sample results are set out in Figure 7. Again, specimens with a maximum deformation of approx. 15 mm are compared. The figure sets the displacement curve over time against the associated electrical current and time-dependent velocity curves, which correspond to the deviation of the displacement-time curve.

The comparison of the current curves shows the typical damped sinusoidal curve of a RCL circuit in both cases but, in electrohydraulic forming, the current pulse is much faster than in electromagnetic forming, indicating a much smaller capacitance and/or inductance. This corresponds well to the different machine parameters listed in Tables 1 and 2, respectively. The comparison shows that the pulsed power generator used in EHF has a capacitance that is approximately 10 times smaller than that of the machine used in EMF. The significantly smaller amplitude in the case of electrohydraulic forming is caused by the relatively low capacitor charging energy under observation here.

In the figure, the three original displacement-time curves measured during electromagnetic forming experiments with the same process parameters are shown together with the averaged and smoothed curve. The measurement curves reveal characteristic steps, indicating that the laser sensor is acting at its limit with regard to the sampling rate. After averaging and smoothing, however, the curve has the typical shape that is well known from the literature, proving its plausibility. The workpiece deformation is initiated after a short delay and is characterized by a rapid rise of the curve, followed by a slight springback [48]. It is remarkable that, to begin with, a slight negative displacement occurs. This is due to the fact that the workpiece is mainly pressurized in the area between $r = 20$ mm and $r = 40$, and, on account of this pressure, the region between $r = 10$ mm and $r = 50$ mm is formed in a positive displacement direction. As a consequence, the center region is bent in a negative displacement direction and pressed firmly to the tool coil. The slight negative displacement indicates that, in addition to the insulation, there was an initial air gap of approximately 0.3 mm between the coil surface and the workpiece. Approximately 55 μ s after the current

rise ($t = 0$), the workpiece center starts to move in a positive displacement direction. From this time on, the displacement curve rises quickly, reaches its maximum at $t = 205 \mu\text{s}$, and then recedes again by a few tenths of a millimeter.

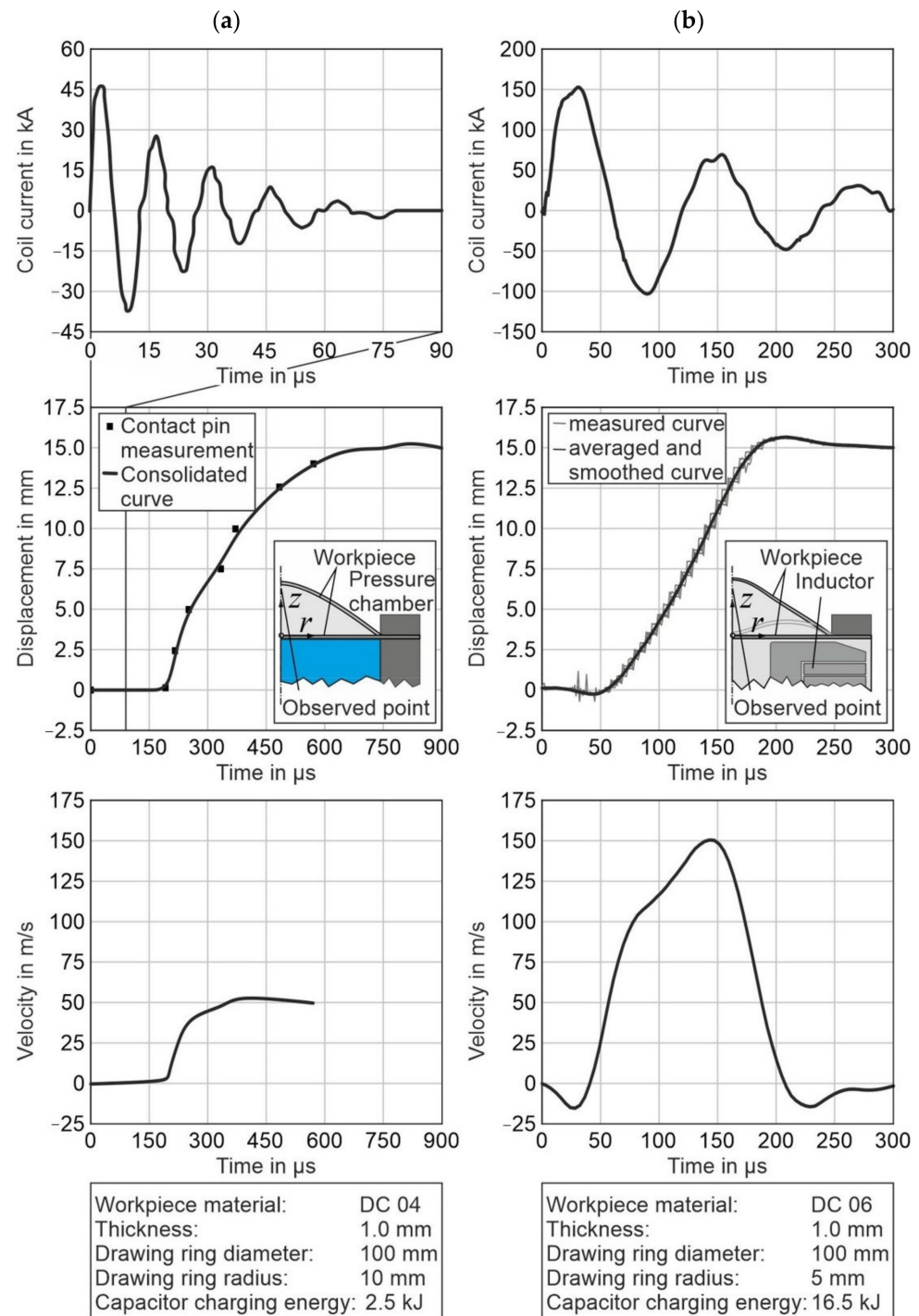


Figure 7. Time-dependent current, displacement, and velocity course in EHF (a) and EMF (b).

In the case of EHF, the displacement-time curve is also characterized by an initial delay, followed by a rise and quickly fading oscillation. Despite the much faster current pulse, however, the deformation is initiated much later than for electromagnetic forming (i.e., after $190 \mu\text{s}$ instead of $55 \mu\text{s}$). This suggests that the pressure wave initiated by the spark between the electrodes and the corresponding plasma channel formation has traveled through the active medium and reached the workpiece after $190 \mu\text{s}$. In the case under

observation, the distance between the electrodes and the workpiece surface is 113 mm. The mean wave propagation velocity is thus about 600 m/s. This corresponds to approximately 40% of the sonic speed in water, which is 1484 m/s. By definition, it is thus a pressure wave and not a shock wave. The subsequent increase in the displacement takes much longer and is less steep than in electromagnetic forming. The maximum deformation is attained approximately 700 μ s after the current rise. Between 370 μ s and 670 μ s, the laser measurement displays a distinctive oscillation, which cannot be validated by the contact pin measurement. A critical review of the measurement setup would suggest that this is an artifact caused by a slight relative movement of the clamped workpiece and the laser sensor. Up to 370 μ s, however, the laser signal and the contact pin measurement are in good agreement with each other. The consolidated curve therefore combines information from the laser measurement, the contact pin measurement, and the final drawing depth in a technologically plausible way.

The corresponding velocity curves are calculated as the deviation of the averaged and smoothed displacement-time curve in the case of electromagnetic forming and as the deviation of the consolidated and smoothed curve in the case of electrohydraulic forming. Due to the post-processing of the measurement signals, the accuracy with which the absolute velocity can be specified is limited. However, it can be assumed that the maximum values are in the range of ± 10 m/s around the specified values. For both technologies, the velocity-time curves reflect the described movement of the workpiece. In the case of electromagnetic forming, speeds of about 10 m/s are initially attained during the movement in the negative displacement direction, before the workpiece motion is reversed. The maximum speed of about 160 m/s is reached 150 μ s after the current increase. After this, the velocity drops to values close to 0 in approx. 50 μ s, and the workpiece movement slows down. In the case of electrohydraulic forming, the velocity rise has approximately the same short duration as in electromagnetic forming but, at approximately 50 m/s, the maximum velocity is significantly lower.

3.2. Analysis of the Blank Holder Distance

By contrast to the single discharge forming considered above, the clamping situation is completely different when it comes to incremental forming. Here, the large sheet metal workpiece can be clamped in the edge area only, while the complete forming area can oscillate freely, and there is no possibility of influencing the material flow in the immediate vicinity of the local forming operation e.g., via blank holder forces. To obtain an impression of how this affects the process and the workpiece behavior, the influence of the blank holder was analyzed in numerical simulations for the EHF process. It should be noted that similar influences of the blank holder distance on the forming result are to be expected for both the EHF process and the EMF process, since the blank holder distance does not represent a typical process characteristic of the respective processes. In addition, these investigations were carried out for Case-II displacement boundary conditions in Section 3.3 in order to show the influence of the blank holder distance as an example of free forming for a single discharge.

The influence of the blank holder distance on the drawing depth in the EHF process is shown in Figure 8. It can be best analyzed by means of the time curve of the attainable drawing depth for four different spacings $x_{bh} = 0.1, 0.5, 1.0$ and 5.0 mm. If a process time of 0 to 5000 μ s is considered, it becomes apparent that more elastic vibrations are introduced into the workpiece with a greater blank holder distance. This in turn leads to the loss of forming energy, and the attainable drawing depth in the decayed state decreases with an increasing blank holder distance. This also becomes clear when looking at the contour plots of the workpiece in Figure 8. These plots show the z-displacement of the workpiece at time $t = 10,000$ μ s for a blank holder distance of 0.1 mm and 5.0 mm. Here, the attainable drawing depth decreases from 11.12 mm to 10.89 mm. In addition, negative z-displacements at the workpiece edge can be seen in the contour plot for $x_{bh} = 5.0$ mm. These are not caused by plastic wrinkling but are elastic oscillations which have not yet

subsided after 10,000 μs . With an ideal blank holder distance of 0.1 mm, no more elastic oscillations can be detected at this point. These observations are in agreement with the experimental investigations. Figure 8 shows two formed circular sheets with a blank holder distance of 0.1 mm and 5.0 mm. Here, it can be seen that the workpiece has undergone more deformation at the minimum blank holder distance. The simulative model, however, overestimates the attainable drawing depth for the larger blank holder distance. This might be due to the reduced modeling of the pressure wave as discussed in more detail in Section 4. Moreover, this is difficult to distinguish due to the metallic surface. The photos were therefore subjected to editing to emphasize these differences.

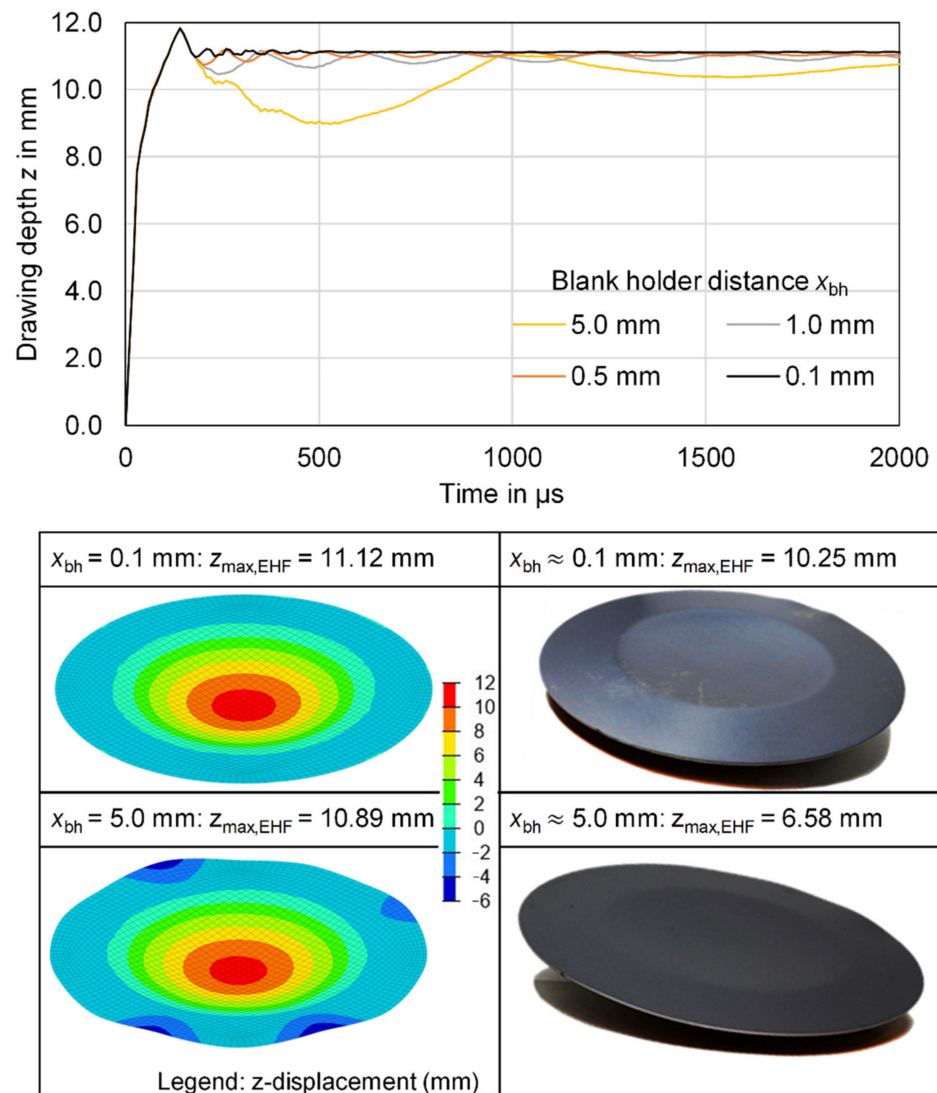


Figure 8. Influence of the blank holder distance on drawing depth in EHF and comparison of the simulated and experimental forming result.

A study of the influence of the blank holder does, however, show that the smallest possible distance should be aimed for in order to achieve the highest drawing depths. In the context of the blank holder distances investigated here, $x_b = 0.1$ can thus be described as the ideal blank holder distance.

3.3. Analysis of the Pressure Distribution

To determine the influence of the fundamental process parameters of electrode distance x_E and discharge energy E_{EHF} on the pressure distribution of the EHF process, the

perforated sheet described in Section 3.4 is used as a multi-point pressure gauge. With this setup, conclusions can be drawn regarding the resulting pressure distribution of the EHF process by comparing the resulting forming depth distribution of the formed dents. The (local) resulting pressure of the shock wave can be estimated by the equivalent static pressure that causes the same sheet deflection. According to the Laplace formulation for spherical elements, the static pressure can be calculated using the following equation:

$$p = \frac{2 \cdot \sigma \cdot t_{sh}}{h} \quad (3)$$

In this equation, σ is the tensile strength of the material; t_{sh} represents the thickness of the sheet; and h indicates the height of the spherical dent. The specimens used are circular sheets made of DC04 with a thickness of $t_{sh} = 0.5$ mm and an initial diameter of $D_0 = 150$ mm. The membrane consists of high-grade NR-SBR that has a thickness of $t_M = 2$ mm and a hardness of 40 shore. Figure 9 compares representative experimental results from EHF and EMF. The deformation depth is obviously much more homogeneous for EHF than for EMF. In order to provide more detailed insight into the pressure distribution, the resulting forming depths were measured tactilely at the LUF on a coordinate measuring machine. The forming depths achieved in electrohydraulic forming and electromagnetic forming are shown in Figure 10 on the left-hand side. The EHF example presented was formed with a discharge energy of $E_{EHF} = 3$ kJ and an electrode distance of $x_E = 3$ mm. The distance of the measuring point from the center of the circular specimen R_S is shown on the abscissa, and the forming depth achieved is shown on the ordinate. In this example, the pressure distribution has a similar pattern for all the specimens formed with these process parameters. In the center of the specimen, the highest forming depth is recorded in the middle of the sheet, at 0.82 mm. The forming depth decreases continuously and almost linearly up to a distance of $R_S = 30$ mm. As the distance increases from $R_S = 30$ to $R_S = 45$ mm, the forming depth achieved remains almost constant at a value of 0.52 mm. With an increasing distance of R_S to more than $R_S = 45$ mm, the forming depth rises again slightly up to a value of 0.60 mm. It can be concluded from this that the greatest pressure is recorded in the center of the specimen and that it decreases slightly with an increasing distance R_S from the center of the specimen. It then increases again slightly towards the edge of the forming zone. With this combination of electrode distance x_E and discharge energy E_{EHF} , in particular, both good reproducibility and a reliable impulsive discharge between the electrode tips can be achieved.

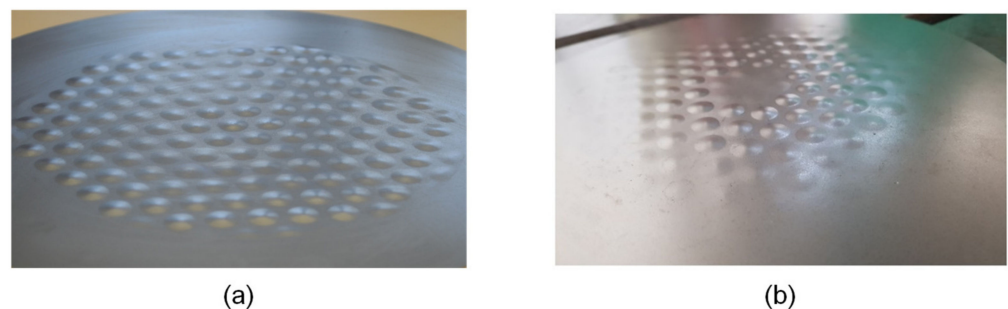


Figure 9. Forming result for EHF (a) and EMF (b) in a perforated plate.

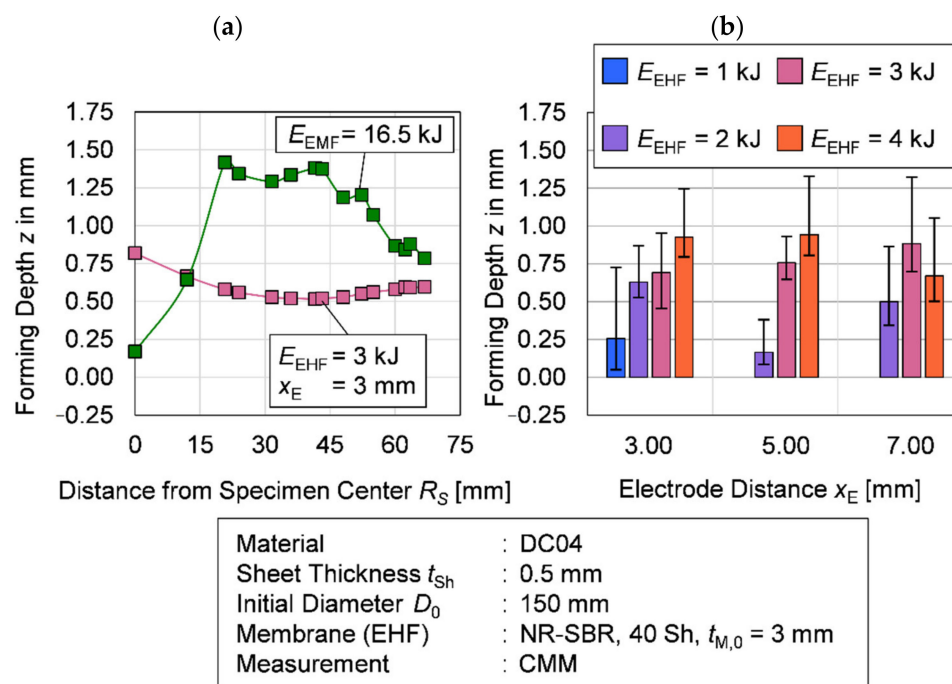


Figure 10. Measured forming depth distribution for EHF and EMF processes (a) and influence of the capacitor discharging energy and the electrode distance on the pressure distribution in EHF (b).

The EMF process taken by way of example, which is also included in the diagram, was carried out with a capacitor discharge energy of $E_{EMF} = 12.5$ kJ. As already observed in Figure 9, the distribution of the forming depth in the EMF process differs significantly from that in the EHF process. The lowest forming depth is obtained in the center of the specimen. This amounts to 0.17 mm. The forming depth then increases very sharply with an increasing radius up to a value of 1.42 mm at a radius of $R_S = 20$ mm. In the range from $R_S = 20$ –40 mm, the forming depth achieved is between 1.37 and 1.29 mm, up to a radius of about $R_S = 40$ mm. As radius R_S increases, the forming depth decreases significantly. At the edge of the forming zone, the forming depth achieved is 0.78 mm. This course, which is characteristic of the geometry of the fieldshaper, can be explained on the basis of the progression of the magnetic pressure effect. The fieldshaper transforms the predominantly radially acting magnetic pressure field of the coil into an axially acting pressure field. In the same way as spirally wound flat coils, this inductor also provides no magnetic field and consequently no magnetic pressure in the center of the bore of the fieldshaper. The magnetic pressure increases sharply with an increasing radius and has its maximum at the inner edge of the fieldshaper. It then decreases again significantly. This distribution of the forming depth is in good agreement with the distribution of the current density, the magnetic field strength, and the magnetic pressure calculated for a similar setup used in [64] for accelerating a hammer in a test setup for material characterization.

In Figure 9 on the right, the influence of the electrode distance x_E and the discharge energy E_{EHF} on the distribution of the resulting forming depth is compared in a bar chart. With an electrode distance of $x_E = 3$ mm, a minimum discharge energy of $E_{EHF} = 1$ kJ is required to generate an impulsive discharge between the electrode tips and carries out the forming process. With an increasing electrode distance x_E , higher discharge energies E_{EHF} are required. For an electrode distance of $x_E = 5$ mm, the minimum discharge energy required is $E_{EHF} = 2$ kJ. The attainable forming depths increase with higher discharge energies. The bar diagram also shows that increasing the electrode distance x_E , in particular, leads to a greater scattering of the forming depths achieved.

An electrode distance of $x_E = 3$ mm thus holds great potential for achieving reproducible pressure distributions with the EHF tool setup used. Especially with a view to the

planned use of the tool system for an incremental forming process in the future, a comparatively low discharge energy of $E_{EHF} = 3$ kJ offers great potential for low wear on the electrode tips, thus enabling reproducible forming results.

3.4. Analysis of the Mechanical Support Applied to the Workpiece and the Displacement Boundary Conditions, Respectively

In single discharge forming, the mechanical support of the workpiece is of great importance in both the EHF process and the EMF process. Its influence was thus investigated numerically considering the following three critical cases that are shown in Figure 11.

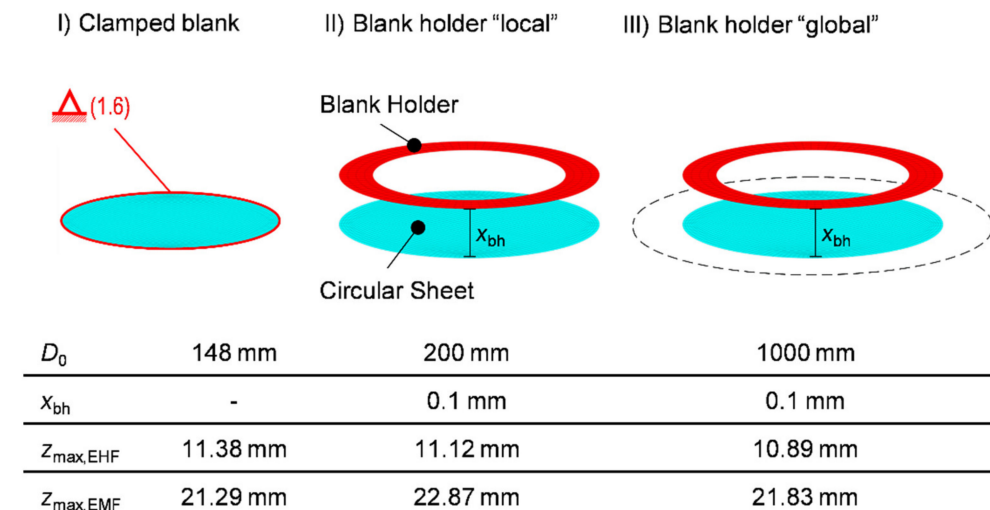


Figure 11. Critical cases of the mechanical support for the workpiece and their effects on the attainable drawing depth for the EHF and EMF process: (I) Clamping the edge of the circular blank, (II) blank holder with ideal distance and a circular blank with a smaller diameter for the investigation of the local deformation and (III) blank holder with ideal distance and a circular blank with a larger diameter for the investigation of the global deformation.

The restraint of all spatial degrees of freedom of the workpiece edge at the height of the blank holder's inner diameter of 148 mm. In this case, the numerical modeling of a blank holder can be dispensed with.

- The limitation of the displacement boundary conditions by means of a blank holder with the ideal distance of $x_{bh} = 0.1$ mm for a blank diameter corresponding to the outer radius of the drawing ring of $D_0 = 200$ mm. Section 3.4 explains why this is referred to as the ideal distance.
- The limitation of the displacement boundary conditions by means of a blank holder with the ideal distance $x_{bh} = 0.1$ mm for a blank diameter of $D_0 = 1000$ mm.

The aim of these cases is to test different displacement boundary conditions with regard to the drawing depth that can be achieved with them, and ultimately also to transfer these findings from single discharge to incremental forming. Critical case I represents the mechanical support of the workpiece when the tool is completely closed. In critical case II, the tool or blank holder is at an optimum distance from the workpiece. In this case, the local influence on the forming result is investigated due to the small diameter of the blank. To investigate the influence on large workpieces ("global"), which are typically used for incremental forming, a circular sheet with a large diameter was investigated using critical case III. The effects of these critical cases on the forming result and, in particular, on the attainable drawing depth $z_{max,EHF/EMF}$ were investigated for the EHF and the EMF process.

The attainable drawing depth of both processes $z_{max,EHF}$ and $z_{max,EMF}$ is shown in Figure 11. As far as the EHF process is concerned, it is noticeable that the drawing depth is at its maximum in critical case I, at 11.38 mm. However, due to the clamping of the

workpiece edge, the circular sheet behaves as a vibrating membrane in this case. This elastic oscillation results in a loss of energy, which reduces the attainable drawing depth for case I. The comparison of case II and case III shows that the diameter of the circular sheet also has an influence on the attainable drawing depth. It decreases with a larger diameter. Thus, in the EHF process for case II, a drawing depth of 11.12 mm could be achieved. For case III, the achievable drawing depth decreased with 10.89 mm. This can also be attributed to an energy loss, which results from elastic vibrations over the entire workpiece surface. For the EMF process, it can be seen that, in case II, the largest drawing depth is achieved at 22.87 mm. As with the EHF process, the attainable drawing depth decreases with increased diameter of the circular sheet. For case III, a drawing depth of 21.83 mm is achieved. Contrary to the EHF process, drawing depth attainable with the displacement boundary conditions for case I is at its lowest at 21.29 mm, whereby no distinctive elastic oscillations occur.

The observations of cases I to III show that the displacement boundary conditions of case II would appear to be most suitable for modeling the single discharge on account of the small blank size, which depicts reality well for this purpose. Here, the material can flow unhindered under the blank holder with a distance of $x_b = 0.1$ mm. As a result, the forming behavior here tends to correspond to a deep drawing process. In the case of incremental forming processes, it can be assumed, based on the blank size, that it is more difficult for the material to flow on, especially at high forming speeds. The opposite (extreme) case I clamping was thus considered. In this case, the material is prevented from flowing on at all, and the forming behavior corresponds to that of a stretch forming process. In this latter case, the material flows completely out of the sheet thickness, and the sheet thickness decreases as a result of the increase in surface area. Under these boundary conditions, the blank exhibits a higher forming resistance. Case III constitutes the most accurate representation of the displacement boundary conditions for incremental forming. There is also a difference between the attainable drawing depths of the two extreme cases for both processes. For the EMF process, the difference between the attainable drawing depths for case I and III is slightly smaller compared to the EHF process. This can be explained by the fact that, compared with quasi-static forming, the material flow is impeded by the high forming speeds due to the inertial forces. In the EHF process, this difference between case I and III is more pronounced due to the comparatively lower forming speed.

In conclusion, it can be said that the workpiece size and the mechanical support are thus a key influencing variable in incremental forming. In Section 3, the influence of the blank holder distance is also investigated; this also constitutes an essential characteristic of the mechanical support.

4. Discussion

The subject of the investigations was a comparative experimental and numerical comparison of the EHF and EMF processes against the background of their application as an incremental processing technology. A new type of EHF tool head, sealed by a membrane, was used for the investigation into the EHF process. This eliminates the need for a time-consuming change of the working medium after each forming process and thus makes an incremental process possible at all. For purposes of comparison, the resulting pressure distributions, the attainable forming depths, and the resulting forming speeds of the two processes were analyzed in a free forming process. The basic investigations were first carried out on a single discharge process (i.e., in a single forming increment).

In EHF, the maximum pressure and the pressure distribution depend on the electrode distance x_E and the discharge energy E_{EHF} . It was found that, in EHF processes, the highest pressure occurs in the center of the forming zone underneath the axially aligned electrodes. In EMF processes, depending on the inductor system used, and including the fieldshaper if applicable, the pressure maximum is located further out in the forming zone. In the specific case considered, it turned out that, compared to EMF, EHF is characterized by a considerably lower energy consumption. Comparatively large forming depths can thus

be achieved with low discharge energies E_{EHF} when using EHF. At the same time, the forming speed is significantly higher in the case of EMF. In this study, a discharge energy of $E_{EHF} = 2.5$ kJ was required to achieve a forming depth of approx. 15 mm in EHF. The maximum forming speed in this process was 50 m/s. The corresponding EMF process required an energy of approx. $E_{EMF} = 16.5$ kJ and reached a forming speed of up to 150 m/s.

Due to lower capacitance of the pulsed power generator for EHF, faster current rise times are produced. Furthermore, the low electrical conductivity of steel as well as the additional fieldshaper lead to an inconvenient efficiency of the EMF process. Because of this, much higher capacitor charging energies are necessary for EMF to deform the workpiece in the same manner. However, the fluid and the elastomer membrane slow down the shockwave and thus cause lower workpiece velocity for EHF.

Future investigations will be aimed at understanding the influence of the membrane materials and thicknesses t_M on the resulting forming speed and depth in the EHF process variant presented here. Following this, the transferability of the results obtained to incremental patch strategies will be analyzed. For this purpose, simple, linear forming strategies based on a strip-shaped geometry will first be investigated and then transferred to two- and three-dimensional contours. Viewed particularly against the background of the different forming speeds, these two processes offer different potential when it comes to attainable forming depths, radii, and the necessary path strategies for achieving the desired geometries.

FE modeling of both the processes constitutes an important tool for the implementation of these investigations. In this paper, a reduced simulation model was presented for simulating the EHF process. This model was examined in more detail here with respect to its validity and application limits because, unlike the numerical model of the EMF process, it is not a widely validated model. It was shown that this model is able to depict the free-forming process well at the ideal blank holder distance. For large blank holder distances ($x_{bh} \leq 5$ mm), however, which are also common in incremental forming, the reduced model reaches the limits of its validity and overestimates the attainable drawing depth. The following points must therefore be implemented and investigated in the simulation model:

- Inclusion of the active medium with adequate discretization (e.g., by means of ALE formulation)
- Modeling of the electrical discharge and the plasma channel
- Consideration of the reflection of the pressure wave
- Modeling of the membrane

For these enhancements to the simulation model, it will also be necessary to model the energy introduced into the discharge channel according to [7,58], i.e., as the experimentally determined resistance of the channel as a function of time or as the experimentally determined electric current and voltage of the electrodes.

5. Conclusions

In this paper, important process parameters of the high-speed forming processes EHF and EMF were investigated and compared both experimentally and numerically, with the aim of highlighting their differences and similarities. These investigations on the basis of a single forming step included free forming tests, the current course, the attainable forming depths, the speed in the process, and the analysis of the pressure distribution during forming into a perforated plate. In addition, the influence of the component size and the blank holder distance was analyzed. The results of these comprehensive investigations were examined comparatively in the discussion. The analyses were carried out with the motivation to prepare both high-speed forming processes for their application as incremental processing technologies. In addition, necessary subsequent objects of investigation were highlighted for this purpose.

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