Impulse Hydroforming Method for Very Thin Sheets from Metallic or Hybrid Materials

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Abstract

Forming of very thin metallic and hybrid material foils is a demanding task in several application areas as for example in food or pharmaceutical packaging industries. Narrow forming limits of very thin sheet metals as well as minor process reliability due to necessary exact tool manufacturing (small punch-die clearance), both, causes abiding interest in new and innovative forming processes.

In this contribution a new method using high pressure pulses will be introduced to form small geometry elements into very thin metal foils or into hybrid polymer-metal foil. It will be shown how the acting pressure pulse will be generated by electromagnetic acceleration of a certain mass, which initiates a pressure wave within a working media. The effect of different pulse lengths has been compared and evaluated by the forming result. Finally, an outlook concerning suitable pulse power equipment and its industrial capability will be given.

Keywords

Manufacturing Equipment, Sheet Metal, Impulse Hydroforming

Introduction

New and more demanding forming tasks as well as the search for innovative forming methods, which extend or complement the number of conventional production processes, caused a steadily growing interest in high speed forming processes during the last years. Especially, Electromagnetic Forming (EMF) is actually on the way from laboratory use to industrial mass production.

Another group of high speed forming processes also using discharge impulses from a pulse power generator is the group of Electrohydraulic Forming (EHF) processes. In that process typically the sudden discharge through an underwater spark gap with or without ignition wire is used to initiate a pressure wave in a working media. This pressure wave acts on a tubular or sheet metal workpiece which is located in a certain distance to the spark gap (pressure source).

For both processes, EMF and EHF, the similar type of pulse generator can be used, but typically not with the same electrical parameters. Both processes have benefits and drawbacks related to the possible application spectrum: for example, EMF is easier to handle because no additional working media is required, on the other hand it is limited to workpiece material with good electrical conductivity. Other reasons to prefer the use of an acting fluid can be the workpiece accessibility or limiting workpiece properties, like a diameter which is too small for electromagnetic expansion or a wall thickness which is too thin for EMF, and so on. There is a lot of potential of EHF, quite similar to the benefits of "conventional" hydroforming processes.

Actually, the main application of underwater shock waves is in the area of kidney stone lithotripsy or other direct medical application. As part of a forming process they are not commonly used, but from time to time applications arise such as surface cleaning of casted parts [1] or calibration of preformed sheet metals [2].

Motivation and Demands of a Forming Example

Forming of very thin metallic and hybrid material foils is a demanding task in several application areas as for example in food or pharmaceutical packaging industries. An example of a typical aluminium blister for pharmaceutical packaging is shown in Figure 1: The material is a multilayer foil consisting of some plastic layers and a 45 µm aluminium layer in between which is an important barrier to light and gas diffusion.

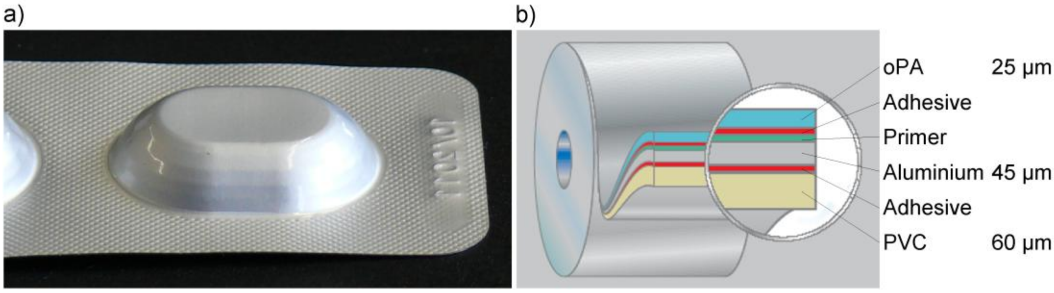

Figure 1: *a) Conventionally formed aluminium blister for pharmaceutical packaging b) composition of the standard multilayer material [3]*

The die cavities are typically 3 to 5 mm deep, depending on their diameter, and produced by a multi-step deep drawing process. This process is very demanding due to narrow forming limits of the very thin sheet and a necessary exact tool manufacturing which is caused by the required small punch-die clearance. An improvement of this manufacturing process can be achieved by reduction of process steps as well as by increasing the cavity density and a corresponding reduction of blister dimension. This can be achieved by small gaps between the cavities, but most by realization of steeper sidewalls.

At the same time the requirements according to the cycle time in series production are high. Typically, production rate is in the range of 700 to 1300 per minute, which corresponds to an operation frequency of 10 to 20 Hz. Typically, high speed forming processes are used at much lower frequencies, although the forming rate is extremely high. Therefore a feasibility investigation has to include the potential of sufficient low cycle time. In case of pulse power equipment, it must be the intention to reduce load of all components significantly. This means, a strong reduction of discharge energy, discharge current, and if possible lower charging voltage are required.

Very first tests to form the above mentioned hybrid material foil have been performed by EMF due to the electrical conductivity of the aluminium layer. The skin effect and the extremely thin aluminium layer require a very high discharge frequency, resp. a very short current rise time. Figure 2 is shown that even with a discharge frequency of more than 100 kHz the material could not be formed because the aluminium layer is too thin. On the one hand depending on the skin effect the thickness is not enough to shield the magnetic field from diffusing through the workpiece, so that no pressure difference can be achieved. On the other hand the induced current causes a strong heating of the aluminium layer and melting of the plastic layer. These results lead to the development of a new method of pulse generation as described in the following.

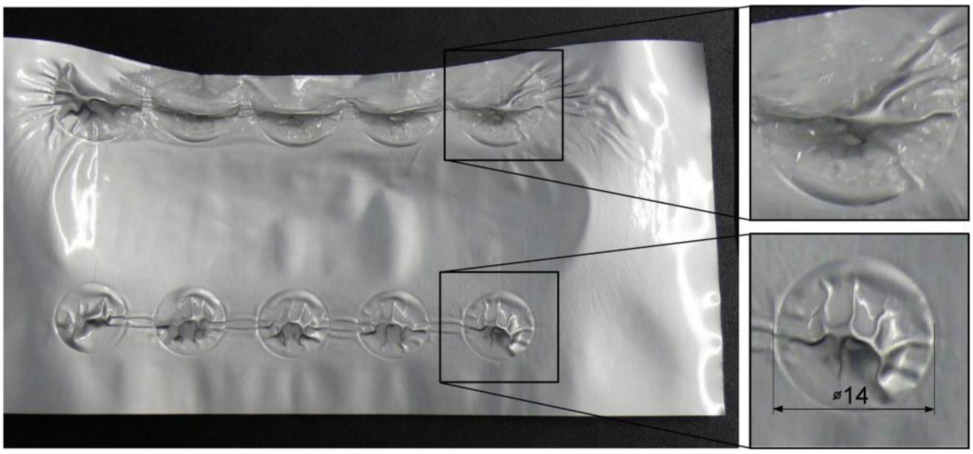

Figure 2: *First try to form aluminium blister foil by direct acting EMF with very short pulse duration (single turn coil, current rise time less than 3 µs)*

New Method of Impulse Hydroforming

Process Principle and Setup

With the intention to use high speed forming without induced current in the workpiece a kind of hydroforming process should be realized for the above mentioned forming task. As shown in Figure 3 a new method to initiate a pressure pulse in a fluid has been realized and tested. Different to EHF processes no spark gap is used, but the following setup:

A flat spiral coil is located below an aluminium or copper driver plate with a certain mass. This plate will be accelerated in vertical direction by electromagnetic forces of the sudden discharge of a pulse generator. It is fixed by a rubber membrane that allows the accelerated driver plate to move but brings it back into its initial position again. At the same time the membrane seals the water vessel above the plate. Workpiece and die are located in the water, but the vessel is “open”, with a free contact between water surface and the air above. There is no sealing required. However, the die cavity behind the workpiece must be evacuated as it is typical for high speed forming operations.

This setup was designed to show the feasibility of the method, but also to vary important process parameters, to exchange the die geometry, and to achieve accessibility for measurement systems. To get some information about the moving plate during the process an optical shadowing principle has been adapted to the setup. Therefore, a laser beam will be detected by an analogue position sensitive photodiode (PSD), when the driver plate moves so that a free distance h_{pl} between coil and driver plate is growing linear with the vertical position of the plate. A second information is the discharge current which causes the very first acceleration forces acting on the driver plate (and on the coil as well). It will be measured by a kind of Rogowski coil in the HV output of the pulse generator / current input of the coil. The third aspect of investigation is the pressure impulse initiated in the fluid and acting on the workpiece. To detect the pressure wave at the workpiece position a PCB pressure transducer ICP M109B11 with a measurement range of 550 MPa and a rise time of 2 µs was integrated into a special die insert without cavity, see Figure 4d). In that way the pressure impulse will be measured instead of a forming operation. Therefore, the pressure signal does not include the interaction with the workpiece deformation. Finally, the workpiece deformation behavior over process time has been detected by a contact pin which could be mounted in the central die cavity and fixed in a certain distance to the workpiece. The time of contact at this certain distance was detected, in relation to the coil current over time.

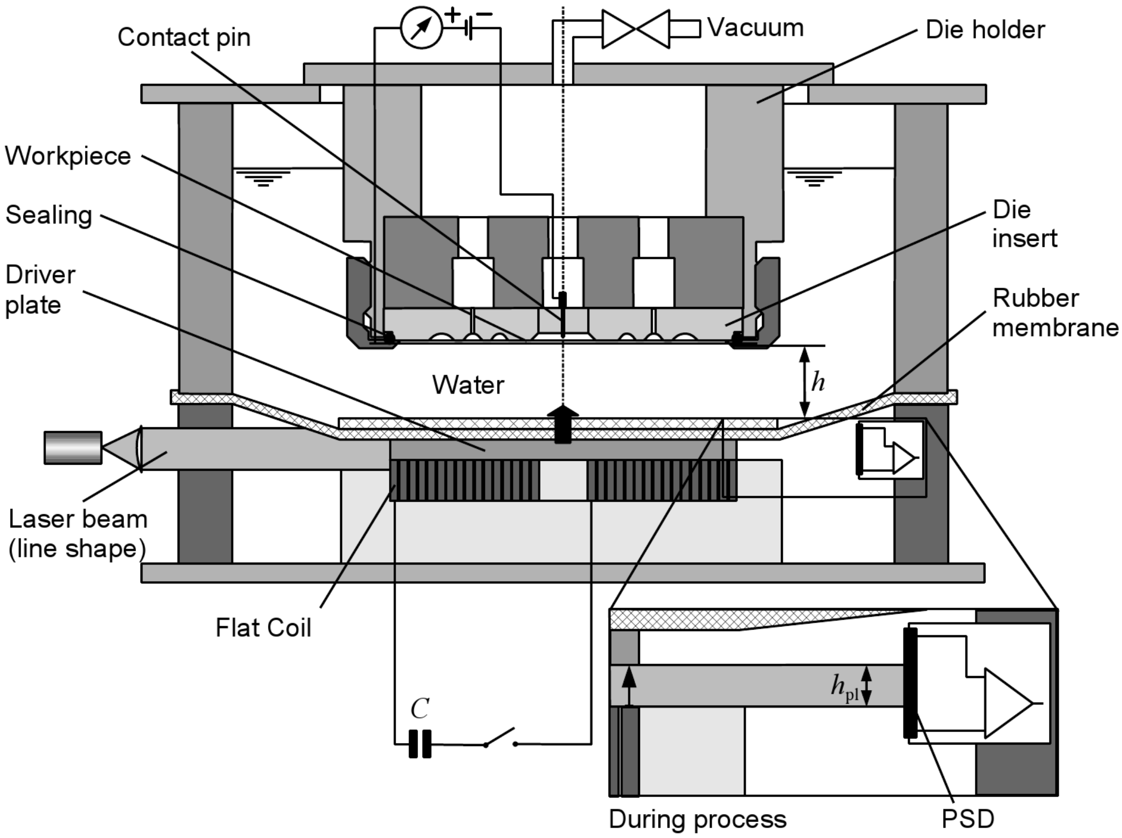

Figure 3: *Principle of new impulse hydroforming method*

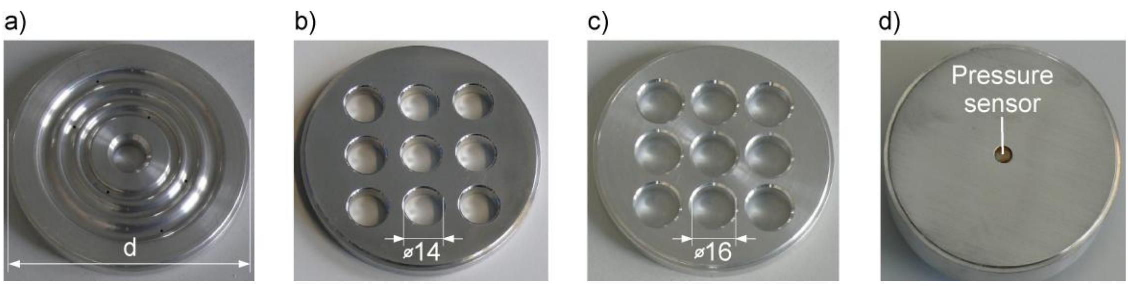

Figure 4*: Used die inserts (d= 90 mm) a) wavy cavity with 2 mm depth; b)-c) cavities for blister forming (depth is adjustable in range of 0 – 5 mm by additional inserts; d) position of pressure transducer in the centre of an insert without cavities*

Feasibility of Forming Pharmaceutical Packaging Foils

With the intention to introduce short and sharply rising pressure pulses in the water, the mass of the accelerated driver plate has been chosen as small as possible. On the other hand, the plate must not be deformed and should be reused over a lot of cycles. Finally, the weight of aluminium driver plate and rubber membrane was about 100 g. The water volume was kept constant 2.5 litres, as well as a distance h of about 10 mm between the moving bottom and the workpiece. Using this setup of the impulse hydroforming process the aluminium blister could be successfully formed, as shown in Figure 5.

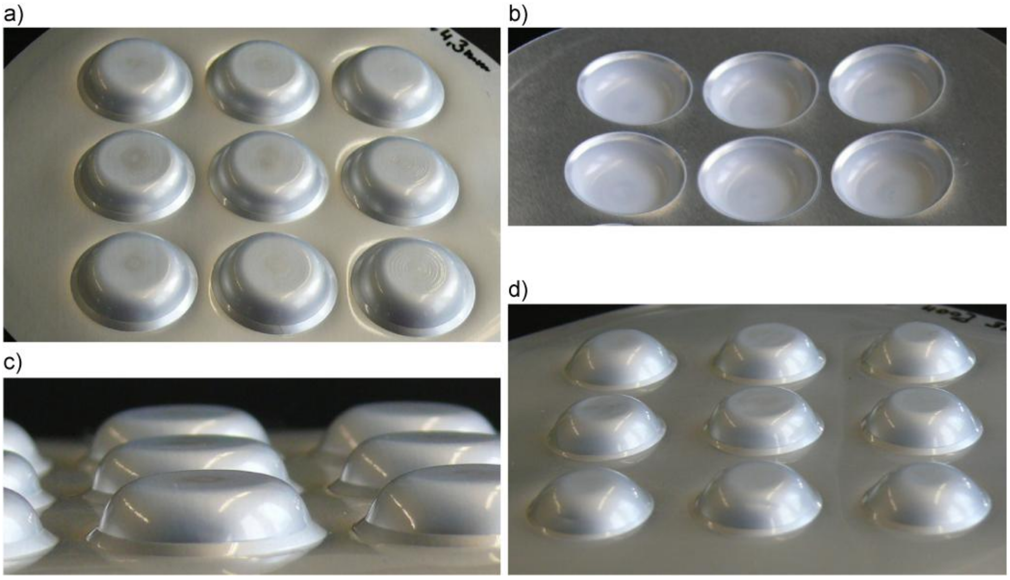

Figure 5: *Forming results for blister diameters d= 16 mm (a)-c)) and d= 14 mm (d)); discharge energy of 450J at 3.2 kV*

By the use of a 26 turn flat coil and a 90 µF capacitor bank, the required energy could be reduced down to a few 100 J. At the same time the coil current is only 8 kA and the charging voltage of this existing pulse generator (SMU1500, Poynting) is 3.2 kV. The very promising forming results demonstrate that it is possible to form a depth of e.g. 4.3 mm without fracture at a cavity diameter of 16 mm, Figure 5a)-c), as well as of 14 mm, Figure 5d). Only one single forming step is needed. Also an improved angle of the sidewall can be realized and allows an increased number of cavities per cm^2 or a smaller size of blister pack when the number of cavities will be kept. The only undesired effect is that the polymer-layer of the backside becomes opaque from stretching as shown in Figure 5b). Failure, like cracking, occurs when the maximum draw ratio of the aluminium layer is reached, or in case of the examples in Figure 6, when the die cavities are not completely dry. Even very fine water droplets on the backside of the workpiece material can cause cracking as shown.

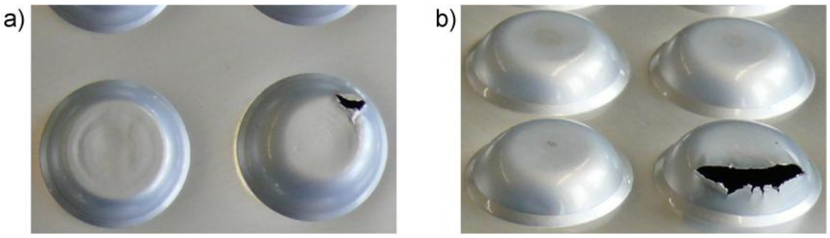

Figure 6: *Formed blisters with cracks caused by small water drops inside the cavities (a) blister diameter d= 14 mm, b) blister diameter d= 16 mm)*

Influence of Current Impulse Length

Due to the high mass of the driver plate it was expected that the current pulse should not be too short to work efficiently against mass inertia. This assumption comes along with the state of the art in electromagnetic riveting machines, as manufactured and described by Zieve et al [4]. The intention of Zieve also is to reduce costs of machine components by significant voltage reduction and longer pulse duration at the same time. In that case the impulse duration is in the range of milliseconds instead of microseconds, of course depending on the mass to be accelerated.

In order to find out which discharge time works best, first, the temporal interaction between coil current, membrane displacement and acting fluid pressure pulse had to be investigated. Exemplarily, in Figure 7 the measured curves for two typical experiments at 600 J discharge energy are shown.

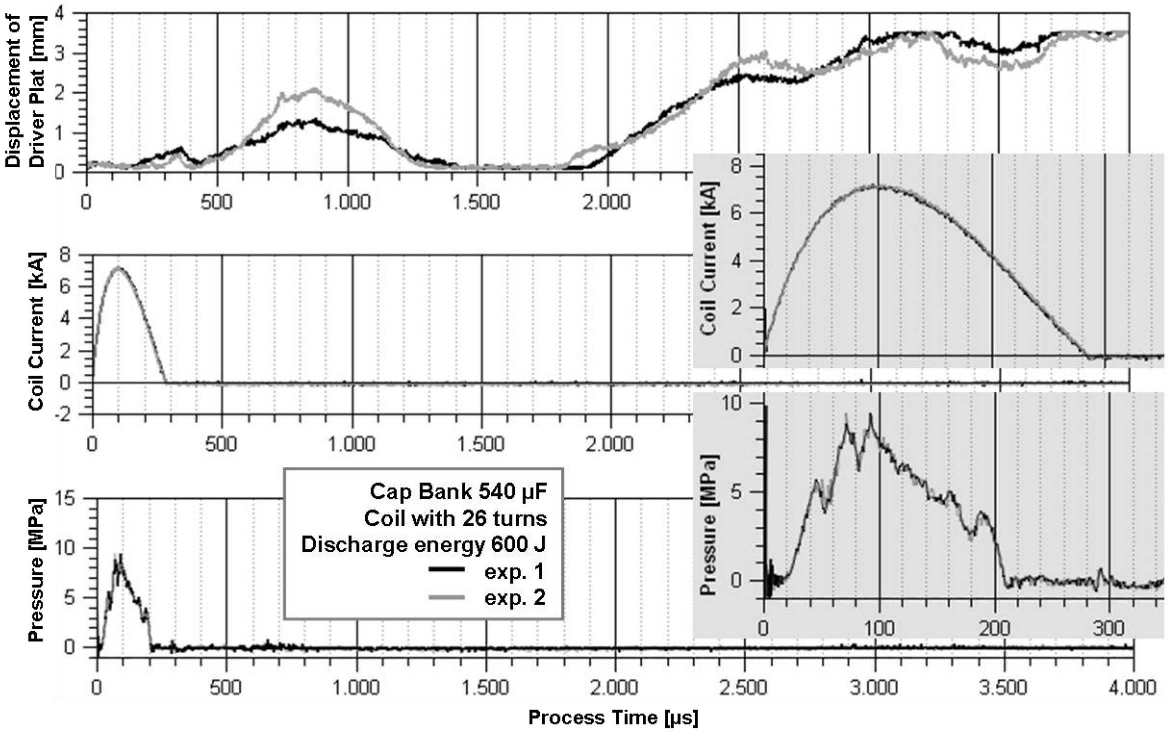

Figure 7: *Process- / Setup-specific time behavior of driver plate displacement, coil current, and pressure*

It can be seen that most of the aluminium driver plate displacement occurs a long time after the current pulse, but the fluid pressure acts only at the same time as the current discharge. This behavior was not expected but can be explained by the elastic membrane interacting with the "open" water volume obviously after the pressure pulse is finished. This comparable slow movement cannot cause a significant pressure because of the air above the water surface. So, the workpiece deformation can be achieved by the pressure pulse during the electrical discharge. A more detailed zoom into the time curves shows that the pressure rises after a short time delay. This delay depends on the distance between start position of the membrane and the position of the transducer, here h= 10 mm. If the distance will be decreased, the delay becomes shorter, with 0.7 µs/mm, which is in good correlation to the sonic speed in water.

To generate different current pulses at comparable amounts of discharge energy, the same setup has been used, but the capacitor bank has been changed [5],[6]. The charging voltage was adjusted for each setup to obtain the same discharge energy. In order to evaluate the process efficiency tin plated steel, 0.19 mm wall thickness, as it is used for can production for food packaging, has been formed into a die with wavy cavities of different width, Figure 4d). The measured current pulses and its forming results are shown in Figure 8. For experiment 4) a 16-turn coil was chosen instead of a 26-turn coil to further shorten the pulse length. In order to make the current curves comparable the current of the experiment 4) is normalized to a 26-turn coil. It can be seen that an optimum pulse length exist to form a workpiece with a sharp contour (experiment 3).

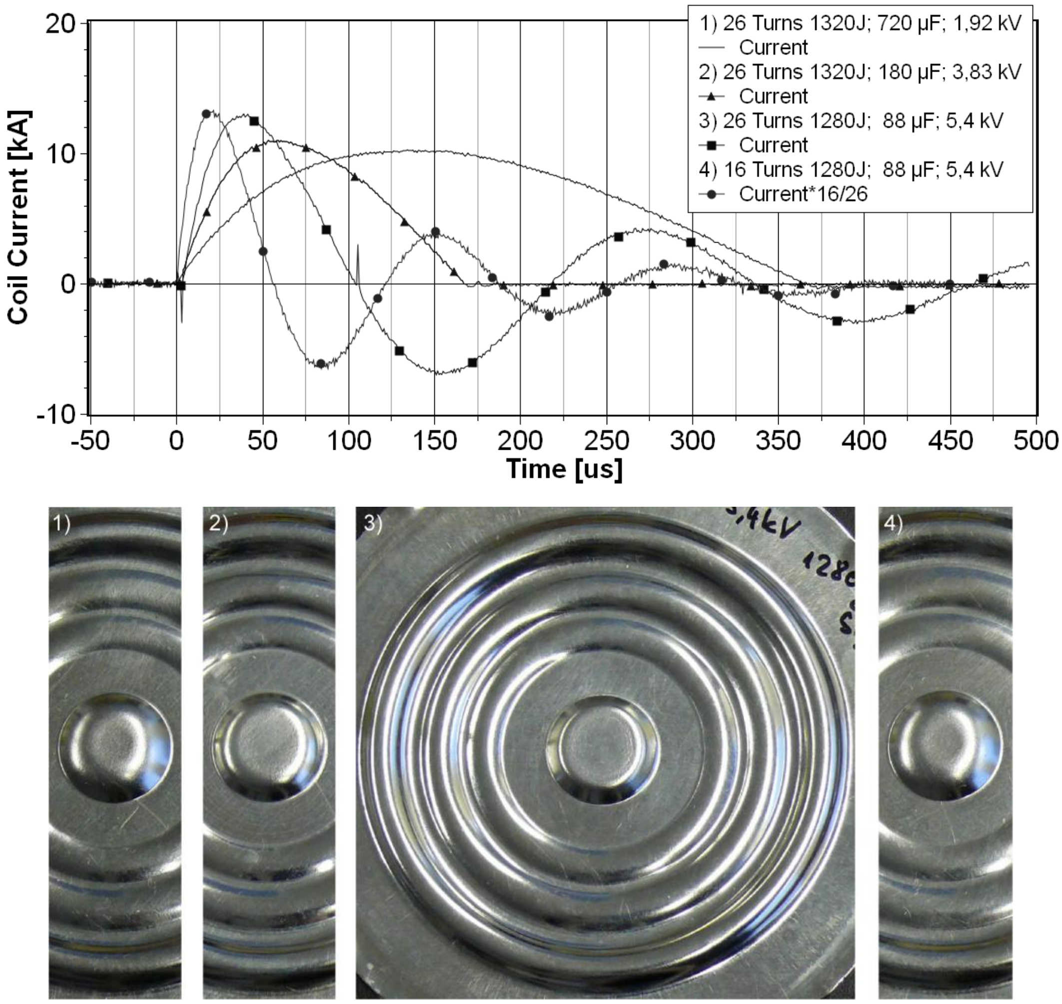

Figure 8: *Different current pulse lengths and corresponding forming results*

Additionally, the measurements with a contact pin in three distances to the sheet metal, 0.55 mm, 1.0 mm, and 2.0 mm, are shown as pictograms in the current over time graph, Figure 9, to give an impression of the sheet behavior related to the discharge pulse, whereas the first setup is the same as in experiment 3, Figure 8. This comparison shows the increased forming rate as advantageous effect of the more optimized capacitor-coil setup at experiment 3).

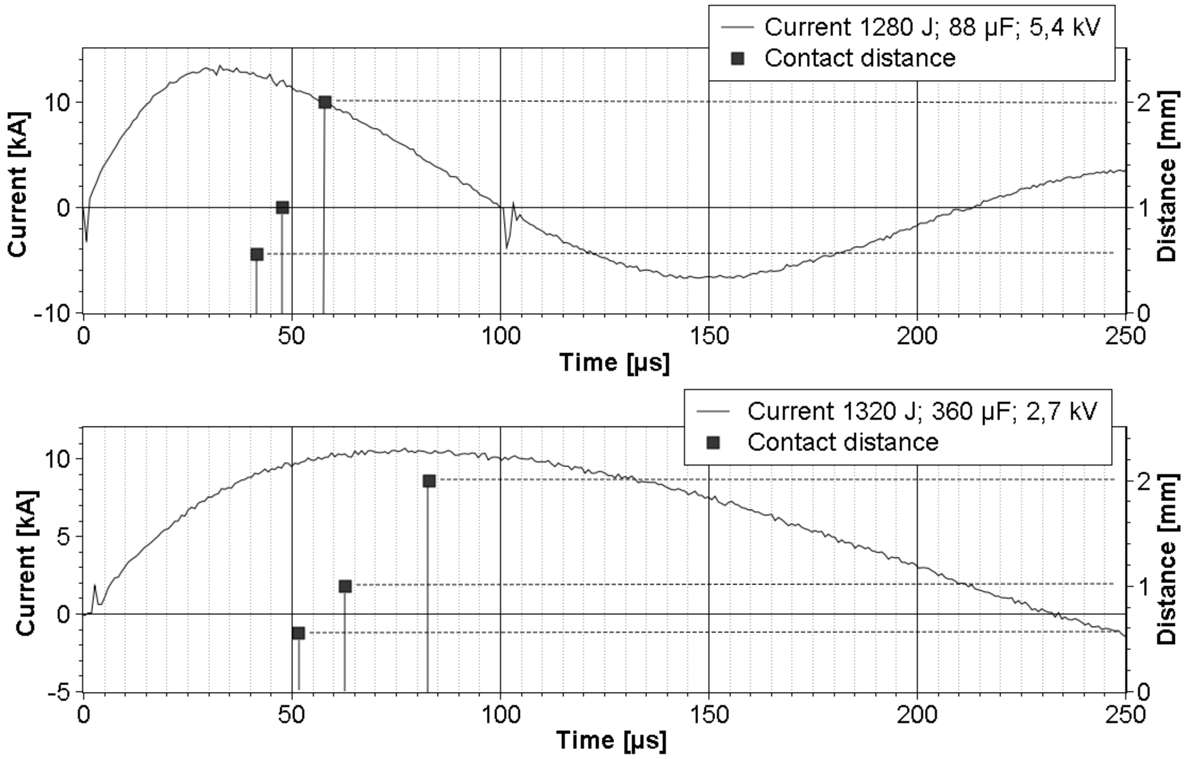

Figure 9: *Two setups with three contact pin measurements at different distances*

Outlook and Potential of the Impulse Forming Method

In this paper a new method for generating a pressure pulse in a kind of electrohydraulic forming process by using an electromagnetically accelerated driver plate is presented. This method is capable of forming very thin metallic and hybrid materials as used in pharmaceutical and food packaging industry [7]. In comparison to EMF the forming capability does not depend on the electrical conductivity of the workpiece material. An additional benefit comes along with the uniform pressure distribution caused by the use of an acting fluid. Especially, if the forming task means embossing of fine geometry details, most application geometries require the workpiece area to be uniform pressurized. Even with the un-optimized experimental setup blister packs can be manufactured in one step and with steeper sidewalls. This increases the usable area of the blisters and accordingly the packaging density. Additionally, the new process is more stable because it does not depend on such accurately manufactured tools as in a deep-drawing process.

In order to tap the full industrial potential of this impulse hydroforming process and to expand its application further development and a concrete design of the required equipment are necessary. Beside the suitability for forming very thin metallic and hybrid materials an additional intention is to keep the required energy and the coil current as low as possible to reduce load of the HV components, like capacitors and high current switches. The pulse generator, driver mass and the coil have to be optimized to minimize the required discharge energy down to only a few hundred joules. An application with e.g. 200 J discharge energy used at a production rate of 20 Hz would dissipate 4 kW. This would already be tolerable, but can be reduced again by recovering the swing back current by an additional circuit. The desired range of cycle time demands the use of long life components, which are usable for more than half a million discharges per day. One step in the right direction is the application of coils with a lot of turns because this allows a reduction of the required coil current below 10 kA. With a current below 10 kA, a dI/dt below 1 kA/µs, and a voltage below 3 kV the durability of the components, especially of solid state switches, can be considerably increased. A lower current and voltage also makes the selection of capacitors easier. The described experiments have shown that the rate of current change dI/dt already is in a range, which allows us to use phase control thyristors. Not to exceed the 3 kV limit helps to avoid serial connection of such power switches to reduce components and assembly costs. Furthermore, it will be possible to replace the specialized pulse power components partially with standard components which will also significantly reduce the machine costs and the long term process costs.

For the blister pack manufacturing the magnitude of voltage and current are already in the mandatory process parameter range of below 3 kV, 10 kA and a moderate dI/dt. This is not the case for the investigated tin plate, yet, but the values are not far away and the existing optimization potential is not exhausted so far. With such an optimized process the machines and coils can be built with a components durability which will apply to necessary time cycles of 10 – 20 Hz with acceptable machine costs and long-term process costs. Finally, the next step must be the redesign of the experimental setup to the requirements of a continuously working production line. A principle solution is described in [7] including the workpiece and die handling as usual in state of the art mechanical blister pack production.

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