# Investigation of Tailored Pressure Distributions by Vaporizing Tailored Foils

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## Abstract

*The rapid vaporization of thin metallic conductors can be used for innovative high speed forming processes. Metal wires or foils are vaporized when a high current is applied. The generated metal gas or plasma expands very rapidly with high pressure and impacts on an intermediate polyurethane plate near the wires or foils. A shock wave is induced into the polyurethane plate and provides the pressure pulse to the sheet metal, leading to a deformation of the sheet. This process requires no expensive tool coils and no electrical conductivity of the workpiece, which makes it attractive to multiple fields of application such as forming and impact welding. In this study, the basic process parameters that influence the shock pressure were experimentally identified including the charging energy of capacitor bank, foil geometry (thickness and width) and thickness of polyurethane plate. Based on the experiments of the parameter investigations, different new foil designs were investigated in order to acquire a tailored pressure distribution. The results show that the shock pressures can be located at different positions in a discontinuous way. Besides, the pressure amplitudes and areas at different positions can also be varied, which depends on the vaporized foil geometries at those positions.*

## Keywords

Impact forming, Vaporizing foil actuator forming, Sheet metal forming

## 1 Introduction

Electromagnetic forming is currently the most common high speed forming method that can improve the forming limit and reduce the spring back as V.Psyk et al. detailly reviewed [1]. The basic principle of electromagnetic forming is to utilize the induced Lorenz force on the workpiece in a changed magnetic field produced by a tool coil when the discharged current by a capacitor bank passes through it. Therefore, it is required that the formed workpiece in electromagnetic forming should have high electrical conductivity. The Joule heating effect of current on the tool coil and strong mechanical loads can greatly reduce the lifetime of the coil. In addition, it is also difficult for electromagnetic forming to produce the forming part with graded heights because of the rebound effect. However, vaporizing thin conductors like metal wires or foils could be an alternative to solve the challenging problems in electromagnetic forming process. This process requires no electrical conductivity of forming workpiece and expensive tool coil.

## 2 State of the Art

Vaporizing thin conductors has been originally used to research the physical process of plasma such as the electrical resistivity and conductivity of plasma and other physical problems [2]. An intensive research about this topic is concentrated between 1959 and 1962 which is concluded as the conference proceedings [3]. The basic principle of this process is to utilize the Joule heating effect of current to heat the thin conductor in the circuit until it is vaporized. The electrical circuit basically consists of the electric pulse generator and the thin conductor which is connected with the electric pulse generator to form a whole electrical circuit. The pulse generator can be described as an oscillating circuit characterized by its capacity C, the inductance L and the resistance R. The vaporizing process is initiated by triggering the high current switch of the pulse generator leading to a sudden discharge of the energy stored in the capacitor C. The discharge results in a damped sinusoidal current I(t) (see Figure 1b) running through the thin conductor which is then heated by the deposited electrical energy into it. The thin conductor is firstly melted and finally vaporized. The burst time of current which denotes the termination of the energy deposition into the thin conductor has been demonstrated to be the moment when the voltage begins to collapse (see Figure 1b).

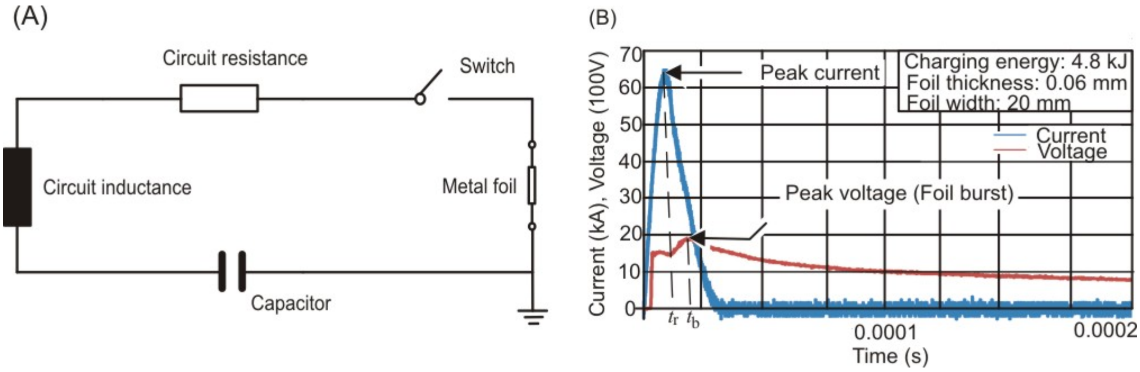

Fig. 1 (A) Schematic drawing of vaporizing foil circuit. This circuit is not necessarily the same as the one used in this study. (B) Current and voltage curves during vaporizing foils

The rapid vaporization of thin metallic conductors can be used for innovative high speed forming processes. Metal wires or foils are vaporized when a high current is applied. The generated metal gas or plasma expands very rapidly with high pressure and impacts on an intermediate polyurethane plate near the wires or foils. A shock wave is induced into the polyurethane plate and provides the pressure pulse to the workpiece, leading to a deformation of it. In consideration of the specific form of shock wave, vaporizing wires is normally used for tube forming and vaporizing foils is applied to sheet metal forming. Vivek et al. investigated several metal forming processes by vaporizing thin conductors such as tube expanding [4] and perforated sheet forming [5]. For tube expanding, aluminum and copper wires with diameter 1.524mm were chosen as the vaporizing material which was surrounded by a urethane rod with hardness 80 A. It was found that aluminum wires are better than copper wires for this process. The perforated sheet forming process was conducted with changed charging energies as well as foils with different thicknesses. By qualitatively analyzing the trends regarding the pressure magnitudes and distributions, the effect of foil thickness on efficiency of energy conversion was acquired, which showed that thicker foils kept generating higher pressures with increasing energy than thinner foils. It can also be seen that the pressure magnitudes and distributions were different with changing the thickness of foils, which implies that the foil thickness has an influence on the induced shock pressure. However, the process parameters that can influence the shock pressure including the foil geometry and the thickness of polyurethane plate have not been investigated yet. Besides, in consideration of reducing rebound effect which is a common problem in electromagnetic forming, the possibility to realize tailored pressure distribution by vaporizing tailored foils should be also explored.

# 3 Experimental Procedure

## 3.1 Parameter Investigations

### 3.1.1 Effect of the Thickness of the polyurethane Plate

With the aim of identifying the effects of the process parameters on the forming results the free bulging height was chosen as the scale variable to indicate the amplitude of the shock pressure. Three different polyurethane plates with a thickness of 3 mm, 5 mm and 10 mm respectively were used as the intermediate plate to transmit shock waves. For each polyurethane plate, three charging energies were investigated: 3.2 kJ, 4 kJ and 4.8 kJ. The minimum charging energy was required to vaporize the whole active part of the foil. For example, the foil area with a thickness of 0.06 mm, a width of 20 mm and a length of 40 mm can be vaporized by applying a charging energy of 3.2 kJ. Based on this minimum value the charging energy was increased by 25% and 50%. Each parameter set was repeated three times. The free bulging height of the final part was measured by GOM Atos optical system, which can be seen in Fig. 3. For each thickness of polyurethane plate, the points show a linear distribution with respect to changing charging energies. As shown in Fig. 4, the final bulging height increases with increasing the charging energy. It is also clearly shown that, for each individual charging energy, the final parts formed with 3 mm polyurethane plate always exhibit highest bulging height while the parts formed with 10 mm polyurethane plate have the smallest bulging height.

The electrical energy deposition into the foil before the voltage collapses determines the final shock wave pressure on the sheet metal. With an increase in charging energy, the current through the foil gets bigger as well as the voltage drop across the foil. As a result, the deposited electrical energy into the foil which can be expressed as the integration of the current and voltage is also increased. As the thickness of the polyurethane plate gets bigger, the dissipation of the shock amplitude is increased because the shock wave must travel a longer distance until it reaches the interface of the polyurethane plate and the sheet metal. The increased number of internal interfaces enhances the scattering effect on the shock wave, which results in an attenuation of pressure amplitude.

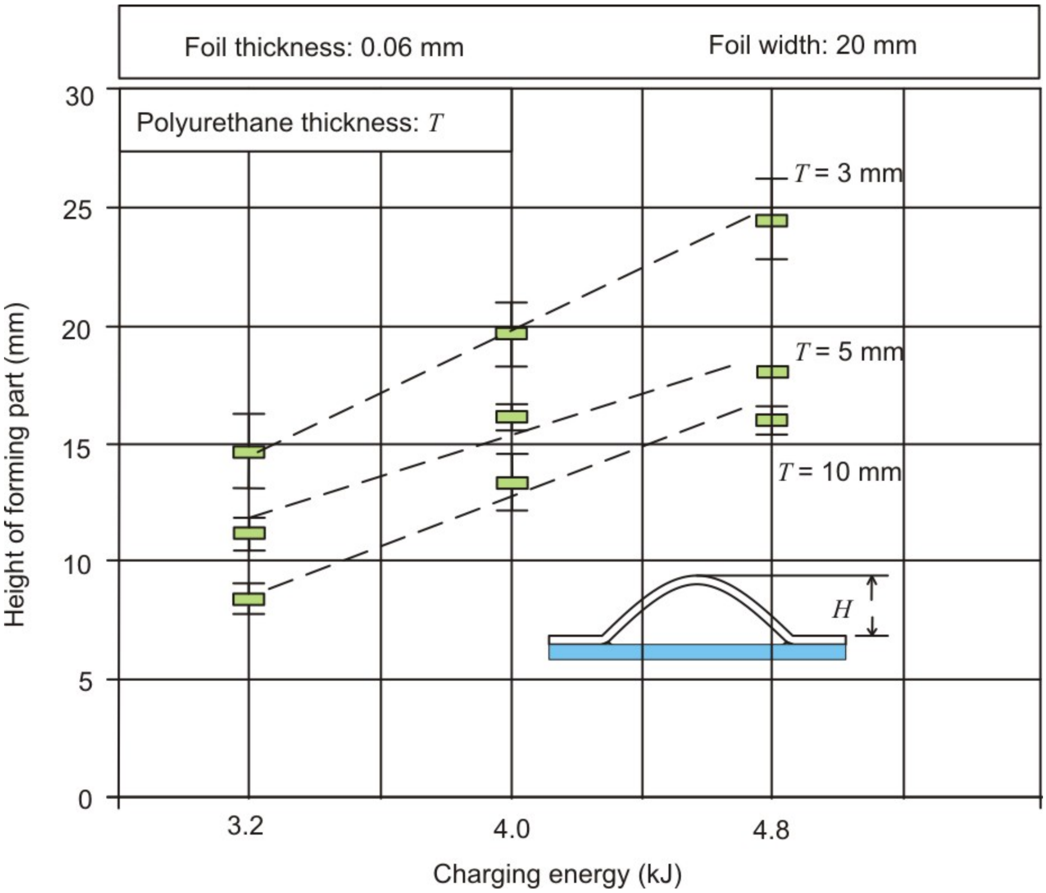

Fig. 4 Bulging heights with respect to charging energy and different thicknesses of polyurethane plates

### 3.1.2 Effect of the Geometry of the Foil

The influence of the geometry of the foil on the shock wave pressure was investigated by varying the thickness and width of the foil respectively under the constant charging energy 4.8 kJ and the same polyurethane plate thickness 3 mm. This resulted in two sets of specimens: 0.03 mm, 0.06 mm, 0.08 mm and 0.1 mm in thickness; 6 mm, 12 mm, 16 mm and 20 mm in width. For each set of specimens, the point distributions again show a linear relationship between the thickness or width and the bulging height. As shown in Fig. 5, the final bulging height decreases with increasing the thickness or width of the foil. In the case of the foil with thickness 0.03 mm, the formed part was cracked, which means the shock wave pressure was much bigger than in the cases with the other thicknesses.

The influence of the foil thickness or width on the shock wave pressure could be attributed to the fact that the current density across the foil section is increased when the thickness or width of the foil decreases. This results in a more intensive deposition of electrical energy into the foil. As the induced plasma reaches a higher temperature and has greater ion and electron densities, the internal energy of these particles is improved to a higher degree and thereby triggers a more intensive shock wave into the polyurethane plate.

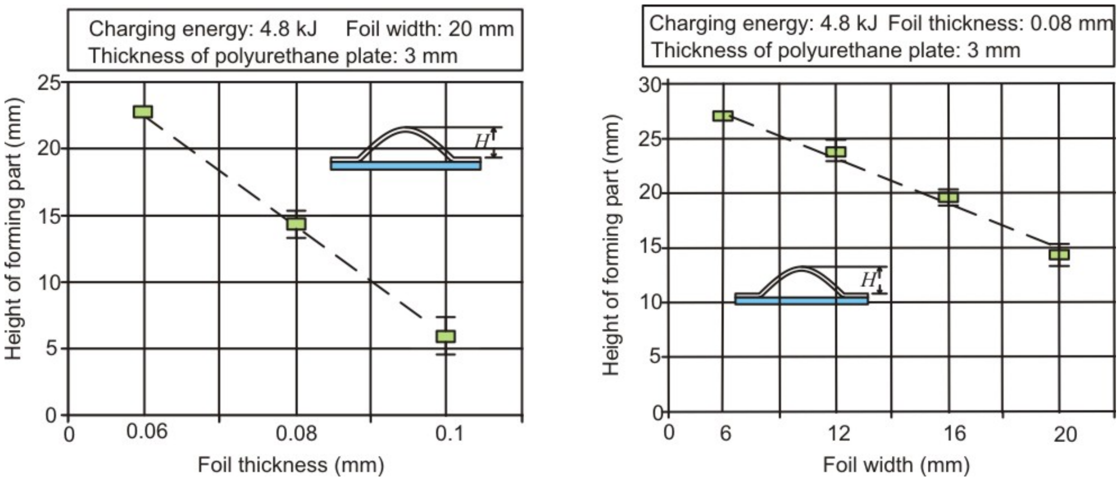

Fig. 5 Bulging heights with respect to thickness and width of foils

## 3.2 Perforating Sheet Forming under Tailored Pressure Distribution

Based on the results of the parameter investigations, the shock pressure induced by vaporizing foils is affected by the charging energy and geometry of the foils. In this section, the foils were cut in tailored shapes in order to acquire pressures at different positions in a discontinuous way. Therefore, there are mainly two aspects to be noted. One is if the two thin areas at different positions of the foil can be completely vaporized. The other is how the pressure amplitudes and pressure areas at these two positions change with different charging energies and geometries of the vaporized areas. Hence, three sets of foil specimens were prepared as shown in Table 1.

| | Length at position 1 (mm) | Length at position 2 (mm) | Charging energy (kJ) |
|---|---|---|---|
| Set 1 | 30 | 30 | 4, 5, 6 |
| Set 2 | 30 | 30 | 5 |
| | 60 | 60 | 5 |
| | 90 | 90 | 5 |
| Set 3 | 30 | 90 | 5 |
| | 50 | 90 | 5 |
| | 70 | 30 | 5 |

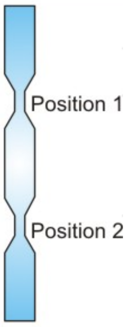

Table 1 Sets of specimens for vaporizing tailored foils

### 3.2.1 Tailored Pressure Distribution under Different Charging Energies

In this section, the geometry of the foils (see Set 1) was kept the same for all specimens with length 30 mm at two vaporized positions. The charging energies were chosen as 4 kJ, 5 kJ and 6 kJ respectively to examine its effect on the pressure distribution. The pressure area was indicated by the bulged points on the sheet after the perforating forming process.

The results in Fig. 6 show that the length of the pressure areas is close to the length of the vaporized parts of the foil. With increasing the charging energies of capacitor bank, the width of the pressure areas is enlarged. Meanwhile, the pressure amplitude is also improved under more charging energies, which can be seen from the bigger bulging heights of points or sheared holes. However, the pressure is not uniform over the whole pressure distributed area. It can be seen that the pressure within the original vaporized dimension of the foil is bigger than the surrounding areas.

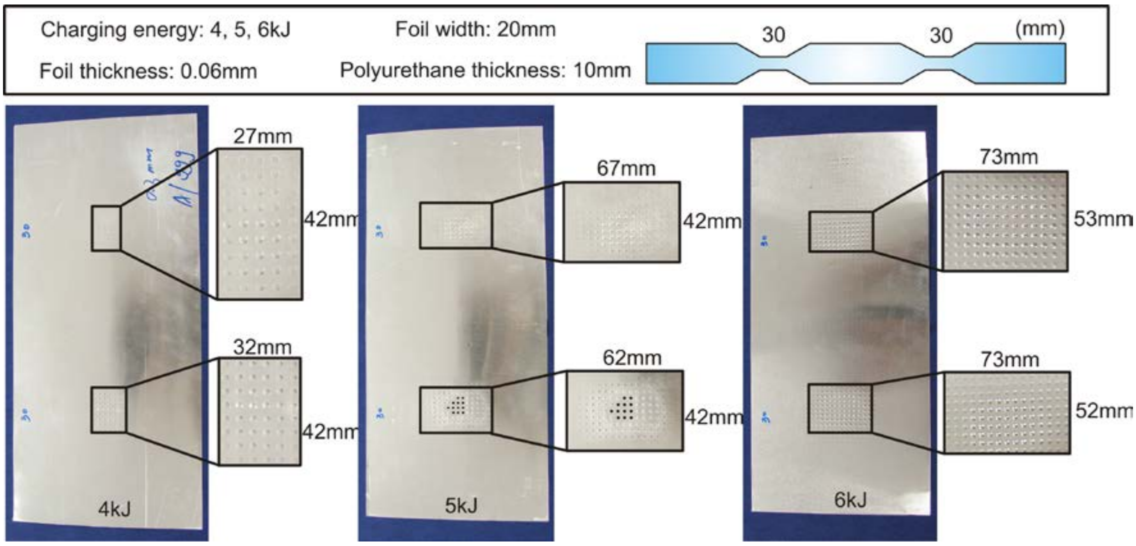

Fig. 6 Perforating formed sheets with respect to different charging energies

### 3.2.2 Tailored Pressure Distribution under Different Foil Geometries

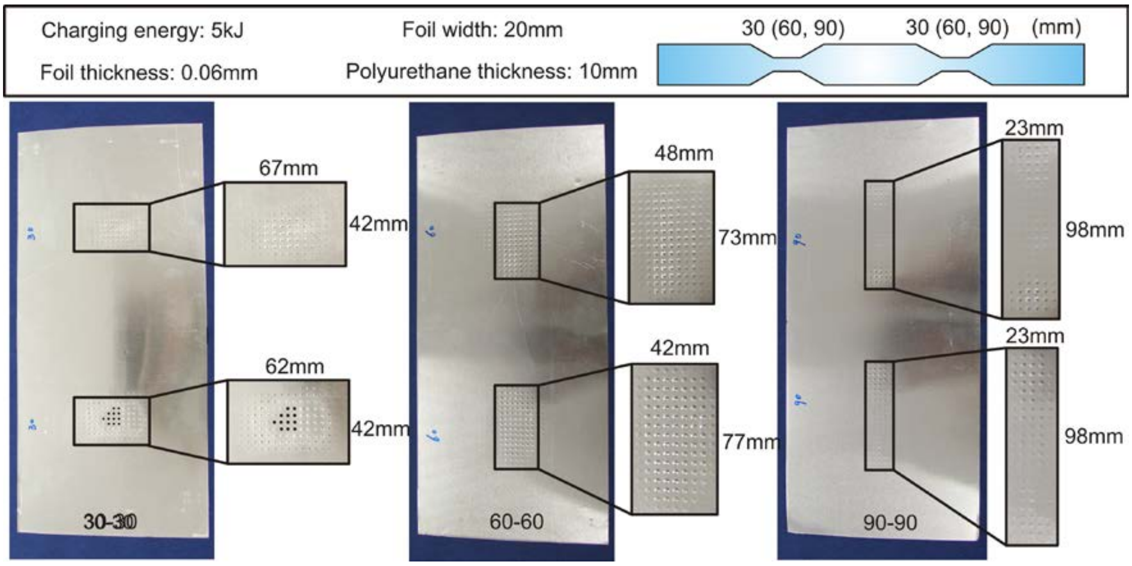

Fig. 7 Perforating formed sheets with respect to different vaporized lengths at tailored positions

Firstly the lengths of the vaporized areas at two positions (see Set 2) were varied which were 30 mm, 60 mm and 90 mm respectively. At the same time, the lengths of two vaporized parts of a specimen are kept the same with each other all the time. The charging energy of capacitor bank was chosen 5kJ for all the specimens. The vaporized results are shown in Fig. 7. It can be seen that all the tailored foils were successfully vaporized even when the length of the vaporized part was increased to 90 mm (180 mm vaporized in total). The pressure area on the perforating formed sheet in the case of tailored length 90 mm is almost the same with the dimension of the vaporized part of the foil. With regard to the tailored length 30 mm, the pressure area on the perforating formed sheet is extended in the transverse direction. Meanwhile, the pressure amplitude induced by short foil is also enlarged compared to that induced by long foil.

Secondly the lengths of the vaporized areas (see Set 3) were only changed at one vaporized position while the lengths of the vaporized areas at the other position were kept constant. The changed lengths at one position were chosen as 30 mm, 50 mm and 70 mm respectively and the constant length at the other position was chosen as 90 mm. The initial charging energy of capacitor bank was used as 5 kJ.

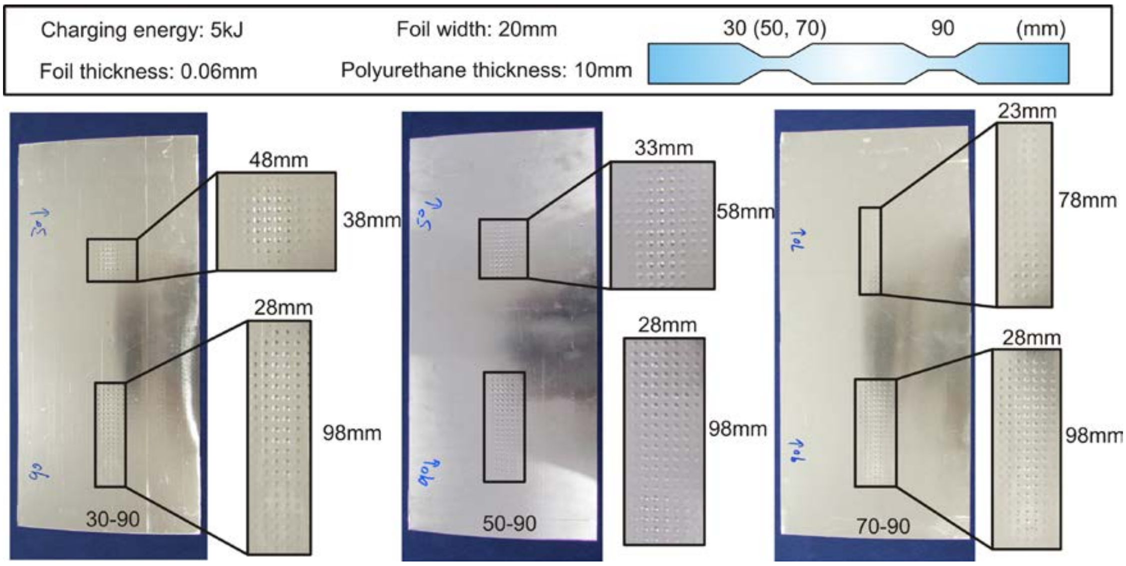

Fig. 8 Perforating formed sheets with respect to different lengths at two vaporized positions in a specimen

As Fig. 8 shows all the tailored parts of the foils were totally vaporized. The lengths of the pressure area are determined by the separated vaporized parts of the foils. The pressure amplitudes are decreased when the lengths of the vaporized parts are increased. Because the dimensions of the two tailored parts in a specimen are different, the pressure areas and amplitudes at two vaporized positions are different.

Based on the results above, the charging energies of capacitor bank and the dimensions of the tailored parts of the foils determine the final pressure areas and pressure amplitudes at two vaporized positions. Under the same charging energy short tailored parts tend to produce a pressure area in a stubby form which means the pressure area is extended to the transverse side while long tailored parts tend to generate a pressure area in a strip form due to the limited electrical energies for the large vaporized dimensions of foils. Therefore, it is important to choose a proper charging energy for a specific tailored geometry of foil in order to acquire an ideal pressure areas and pressure amplitudes.

## 4. Conclusion

The process parameters that can influence the shock pressure were experimentally identified through the free bulging tests by vaporizing foils. The charging energy, thickness of polyurethane plate and geometry of foils can greatly affect the final shock pressure on the sheet metal. Based on the parameter investigation results, the foils were cut in tailored shape which causes the foils vaporized at different positions. By varying the charging energies of capacitor bank, the pressure amplitudes at two vaporized positions were changed. In addition, the pressure areas and amplitudes were also dependent on the tailored part dimensions at two vaporized positions in a specimen. Therefore, by means of an appropriate combination of charging energy and tailored foil geometry, a tailored pressure distribution including the pressure amplitudes and areas can be realized at different positions in a discontinuous way.

## Acknowledgements

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## References

[1] *V. Psyk, D. Risch, B. L. Kinsey, A. E. Tekkaya, M. Kleiner,* Electromagnetic forming-A review, Journal of Materials Processing Technology, Volume 211, no. 5, pp. 787-829, 2011

[2] *A. W. DeSilva, J. D. Katsouros,* Electrical conductivity of dense copper and aluminum plasmas, Physical Review, Volume 57, Number 5, 5945-5951, 1998

[3] *Chace, William G.*, Exploding wires 1, Plenum Press, New York, 1959

[4] *Vivek, A., Taber, G.A., Johnson, J.R., Woodward, S.T., Gaehn, G.S.*, Electrically driven plasma via vaporization of metallic conductors: A tool for impulse metal working, Journal of Materials Processing Technology 213, 1311-1326, 2013

[5] *Vivek, A.*, Rapid vaporization of thin conductors used for impulse metalworking, Ph.D thesis, Ohio state university, 2012

[6] *Saveway Isolierstoffe GmbH*, www.saveway-isolierstoffe.de