Materials Research Proceedings 25 (2023) 11-18 https://doi.org/10.21741/9781644902417-2

Proof of concept for incremental sheet metal forming by means of electromagnetic and electrohydraulic high-speed forming

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Keywords: Incremental Sheet Forming, Aluminium, High-Speed Forming

Abstract. The combination of incremental sheet metal forming and high-speed forming offers new possibilities for flexible forming processes in the production of large sheet metal components of increased complexity with relatively low forming energies. In this paper, the general feasibility and process differences between the pulse-driven high-speed forming technologies of electrohydraulic and electromagnetic forming were investigated. An example component made of EN AW-6016 aluminum sheet metal was thus formed incrementally by both processes and the forming result evaluated by an optical 3D measurement system. For this purpose, a forming strategy for electromagnetic incremental forming (EMIF) was developed, tested and adapted to the electrohydraulic incremental forming process (EHIF). The discharge energy, the tool displacement and the pressure field of the forming zone were determined as relevant parameters for the definition of an adequate tool path strategy. It was found that the EHIF process is less affected by larger distances between the tool and the blank, while this is a critical variable for force application to the component during EMIF. On the other hand, the more uniform pressure distribution of the EMIF process is advantageous for forming large steady component areas.

Introduction

The global trends towards individualized and regionally adapted products are leading to new challenges for production technologies due to the significantly higher number of variants and simultaneously decreasing batch sizes [1]. In addition, the reduction of greenhouse gas emissions and the sustainable use of resources are currently significant requirements for both manufacturing processes and products. Lightweight structures, for example, are a possible solution for addressing these challenges. The use of lightweight materials and more differentiated geometries leads to increasingly complex sheet metal components with the aim of saving materials and reducing CO_2 emissions. These demands on forming technology result in the need for flexible and cost-efficient production of complex components in small batch sizes. It is therefore necessary to develop innovative manufacturing processes that can meet these requirements in a good way.

Incremental sheet metal forming is one approach to the economical production of sheet metal components in small batches. In conventional incremental sheet metal forming a universal tool is used to create the desired workpiece shape. This universal tool (stylus) rotates and is moved by a CNC-machine or robot in paths along the desired geometry. The dimension of the mandrel is typically very small in comparison to the size of the workpiece and thus the part is formed gradually and locally. The small deformation zone of the tool makes it possible to dispense with at least one half of a forming tool such as those used in conventional forming processes like deep drawing. Incremental forming technologies therefore offer a high potential for increasing process flexibility and reducing tooling costs due to the decreased shape retention rate. A disadvantage of incremental sheet metal forming is that the production of large complex parts with fine details is only possible with long machining times. The process is also of limited accuracy for small radii and demanding geometries [2, 3].

High-speed processes, by contrast, offer a solution for manufacturing complex geometries with a high accuracy. These processes are characterized by high forming-speeds (e.g. 400 m/s) and strain rates (e.g. $10^4 s^{-1}$) which lead to increased formability for many materials. Sharp-edged shapes and small radii, in particular, can be produced more accurately than with quasi-static processes [4, 5]. Due to the short process times, inertia effects can be exploited in tool design. The required clamping forces are thus significantly reduced and the tools are more cost-effective [6]. Electromagnetic forming (EMF) is an active-energy-based high-speed forming process, which was first mentioned in the 1960s [7]. Electrohydraulic forming (EHF) is a working-media-based high-speed forming process. A limiting value for both methods is the size of the part to be formed, because they are usually only suitable for small or medium sized components or just for individual areas of a component due to equipment limitations. In the case of large components, very high capacitor charging energies are required, and the load on the tools increases significantly [8]. Other working principles for high-speed forming include the use of explosives and pneumomechanical compression [9].

In EMF the loads acting on the workpiece are generated using the energy density of pulsed magnetic fields. For this purpose, a transient current is imposed on the active tool (inductor), which generates a magnetic field (see Fig. 3 left). This in turn induces an eddy current in the workpiece, which flows in the opposite direction to the inductor current. Based on the fundamental principles of electrodynamics, so-called Lorentz forces are produced in this way. More simply, the acting loads can also be calculated as magnetic pressure according to Eq. 1 [10]. To obtain appropriate results, it is necessary to know the magnetic field intensity H_{gap} between the inductor and the workpiece, the penetrating magnetic field intensity H_{pen} on the other side of the workpiece and the permeability μ. As soon as the magnetic pressure reaches the yield strength of the material, the deformation of the workpiece begins. A detailed description of the process principles, equipment and applications is given in [11].

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

In electrohydraulic forming, the workpiece is formed by a short but very high pressure pulse. This is achieved by applying a high voltage to an assembly of two electrodes inside a water-filled discharge chamber (see Fig. 3 left). The voltage is supplied by capacitors. For forming, these are short-circuited via a spark gap between the electrodes. As soon as the water resistance is overcome, a plasma channel is formed and expands at high speed in the working medium. The resulting shockwave accelerates the workpiece into the single-sided die. In conventional EHF setups, the blank is positioned between the die and the discharge chamber in direct contact with the working media. The insulation between the electrodes and the housing, and the sealing of the housing against high pressures are important for the stable operation of EHF tools [12].

The electromagnetic incremental forming process (EMIF), first proposed in [13], combines the advantages of high speed and incremental forming into a new forming process for larger sheet metal parts. The coil system is moved across the part and local deformation generated to shape the part incrementally. A process strategy for forming complex parts by EMIF was investigated in [6]. Discharge energy, tool displacement and the pressure field were found to be relevant parameters for defining a suitable tool path. In [14], a further approach to incremental forming technology was presented by combining it with the electrohydraulic forming process. The incremental application of the electrohydraulic effect for forming complex geometries with sheet metal has not, however, been proven as yet. This paper provides the proof of concept for the electrohydraulic incremental forming (EHIF) strategy and compares EMIF and EHIF on the basis of a specific demonstrator component. For this purpose, the EMIF forming strategy developed at the Fraunhofer Institute for Machine Tools and Forming Technology (IWU) in Chemnitz was transferred to the EHIF process by the Chair of Forming and Machining Technology (LUF) in Paderborn. The same geometry was considered for both technologies to allow a direct comparison.

Experimental setups

For EMIF, a flat spiral coil made of CuCrZr1 with a diameter of 120 mm is used as the active tool. It consists of 2.5 turns and each turn features a width of 10 mm and a height of 25 mm. The insulation distance between the turns is 6 mm. A pulsed-power generator of type Bluewave PS100/25 from PSTproducts, Alzenau, Germany, provides the electrical energy. The maximum capacitor charging energy is 100 kJ at a maximum voltage of 25 kV and a maximum capacitance of 330 µF, which can be changed incrementally. The sheet is positioned between the inductor and the tool via a clamping frame. The positioning is achieved by two orthogonally aligned linear axes. A more detailed description can be found in [6].

The tool used for the investigation of the EHIF process at the LUF consists of an electrode system with two CuCrZr12 electrodes arranged facing each other in a cylindrical discharge chamber. The discharge chamber has a diameter of 150 mm and a spherical reflection surface above the electrodes. The electrical energy is provided by an SSG-0620 pulsed-power generator from Poynting GmbH, Dortmund, Germany. The maximum capacitor charging energy is 6 kJ at a maximum voltage of 20 kV and a capacitance of 30 µF. In contrast to conventional EHF tools, the active medium (water) and the workpiece are separated here by an expandable membrane in high-grade NR-SBR (hardness = 40 Shore) with a thickness of 3 mm. This makes it possible to move and position the tool freely on the workpiece. A more detailed description of the process principles and the tooling can be found in [6, 14, 15].

The forming-tests were carried out using aluminum sheet made of the alloy EN AW-6016 with a thickness of 1 mm. In quasistatic tensile tests in the rolling direction, a yield strength $R_{p0.2}$ of 133 MPa and a tensile strength R_m of 241 MPa at a uniform elongation A_g of 16.1 % were determined.

Incremental manufacturing requires the development of a component-specific forming strategy. The pressure distribution in the forming zone must be taken into consideration here. Analysis of the membrane behavior is one possibility for achieving a qualitative description of the pressure distribution within the EHIF forming zone. Fig. 1 shows, by way of example, the evolution of free expansion of the membrane during a discharge with 3 kJ and 20 kV. The images were taken with a high-speed Fastcam SA1.1 camera from Photron at a frame rate of 5000 fps. Immediately after ignition, the membrane expands in a cone shape within 13.2 ms. The pressure maximum is at its center and the expansion attains a maximum of 134 mm. After the membrane has receded from the first expansion, the pressure waves reflected in the discharge chamber are superimposed and an annular expansion occurs. From this point onward, the membrane oscillates between conical and annular expansion with a rapid decrease in intensity. It can be assumed that, in the process of forming sheet metal, only the first two expansions contribute significantly to the forming, because the impulse is quickly absorbed by the damping of the membrane and energy dissipation during forming.

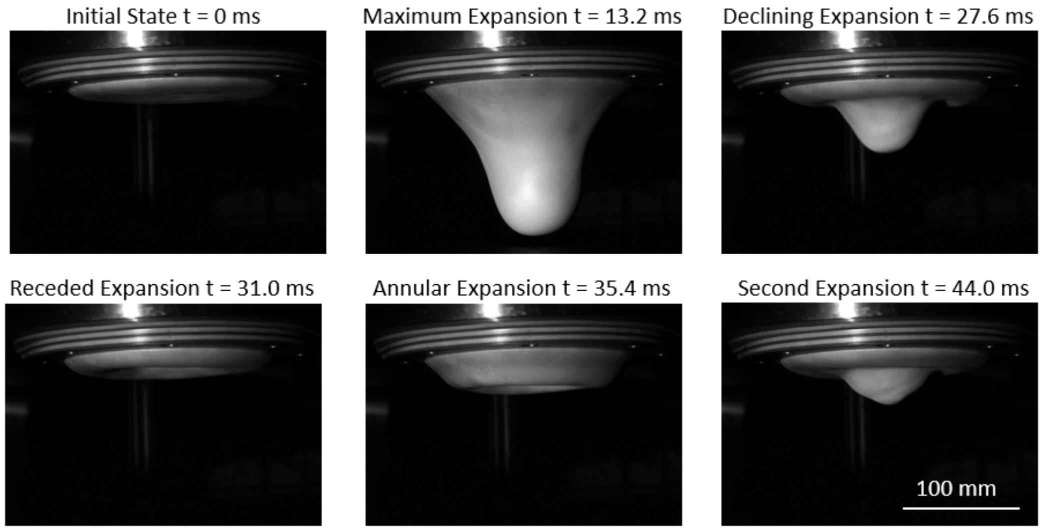

Fig. 1 High-speed camera images of the EHIF membrane at 3 kJ and 20 kV discharge parameters

Electromagnetic incremental forming of a chair seat

The concept for EMIF for large complex parts was already proven in [6]. For this, a small area of a chair seat, designed by elem design [16], was formed with different capacitor charging energies and distances between each step. Taking the experience gathered from these prior investigations on small sections of the part, a strategy for forming the full chair seat was developed in this work. It was found that the process parameters have to be adapted to the geometrical variations within the component. In detail this means that smaller relative displacements are necessary for fine structures. This in turn makes it possible to increase the displacement for large steady areas. In addition, as is familiar from single shot forming, sections with a higher depth of the die require higher capacitor charging energies. The forming strategy shown in Fig. 2 is the result of these findings.

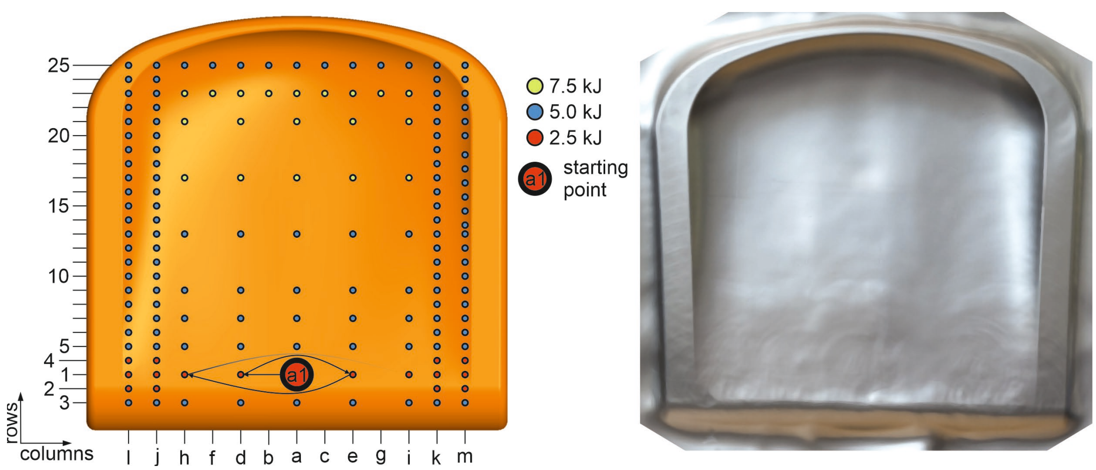

Fig. 2 EMIF forming strategy (left) and resulting workpiece (right)

A suitable starting point for the forming process is the center of the front area of the chair seat (a1). Here, only minimal forming is necessary and hence a low capacitor charging energy is required. In addition, the gradient of the forming depth below the effective area of the inductor is very low compared to all other areas. The value was therefore set to 2.5 kJ. For the area with the largest forming depth, on the other hand, a capacitor charging energy of 7.5 kJ was used. For all other areas of the chair seat surface, it was set at 5 kJ.

In terms of the geometric boundary conditions, the workpiece is well suited to a discontinuous trajectory. As shown in Fig. 2 left, the process was first performed in columns (i.e. in the x-direction), alternating from the inside to the outside (letters a to m). Then the rows (numbers 1 to 25) were formed. The distance from one line to the next was 15 mm. Between the columns there was 30 mm in each case. Since small edge radii run all around the u-shaped flat surface, small displacements (i.e. 15 mm) were chosen at these points. In the center of the workpiece, only a few geometric details are present. A displacement of 60 mm was therefore used in this area. All other areas were produced with a relative displacement of 30 mm. Based on this, the positioning sequences of the inductor were a1, d1, e1, h1, …, j2, k2, l2, m2, a3, d3, …, a5, d5, e5 and so on. With the selected path strategy, 158 capacitor discharges were necessary to form the chair seat. 15 discharges were performed using 7.5 kJ, 17 discharges performed using 2.5 kJ and all the other (i. e. 126) discharges were performed using 5 kJ.

Fig. 2 right shows the result. The u-shaped plane, including the surrounding radii, is well formed. The areas with the lowest forming depths show visible imprints of the inductor for the individual increments, but these are only visible on the side facing the inductor. These imprints should be prevented by homogenizing the magnetic pressure through adjusting the inductor geometry. Furthermore, the complete forming depth has not been reached in the deepest section of the die. This is because the inductor was only moved parallel to the sheet plane. In general, it was shown that workpieces of a good quality can be formed by EMIF.

Proof of concept for electrohydraulic incremental forming

Next, the feasibility of EHIF was demonstrated too. For this purpose, the capacitor charging energies had to be adapted to the different technology (EHIF) and equipment. In order to identify the corresponding energy level – i. e. energy levels leading to the same deformation – in EMF and EHF, free forming tests, similar to [14] were carried out, i. e. metal blanks (ø220 mm) were formed by EMF and EHF into a drawing ring without restricting the forming depth (Fig. 3).

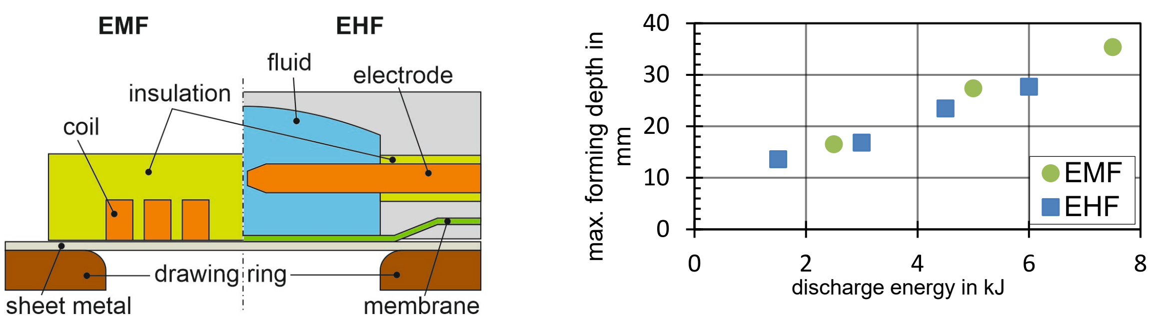

Fig. 3 Forming depth as a function of the energy levels for EMIF and EHIF

Achieving the same forming depth by EHF requires a slightly higher capacitor charging energy than EMF. However, the large number of increments required for forming at capacitor charging energies close to the power limit of the EHIF system at LUF significantly stresses the tooling system and hence the applied discharge energy was limited to 4.5 kJ. Fig. 4 shows the EHIF forming strategy. The starting point (a1) and the discontinuous trajectory were adopted from EMIF. The numbered row spacing in the y-direction (15 mm) and the alphanumeric column widths in the x-direction (30 mm) are identical to those for the EMIF forming strategy in Fig. 2 too.

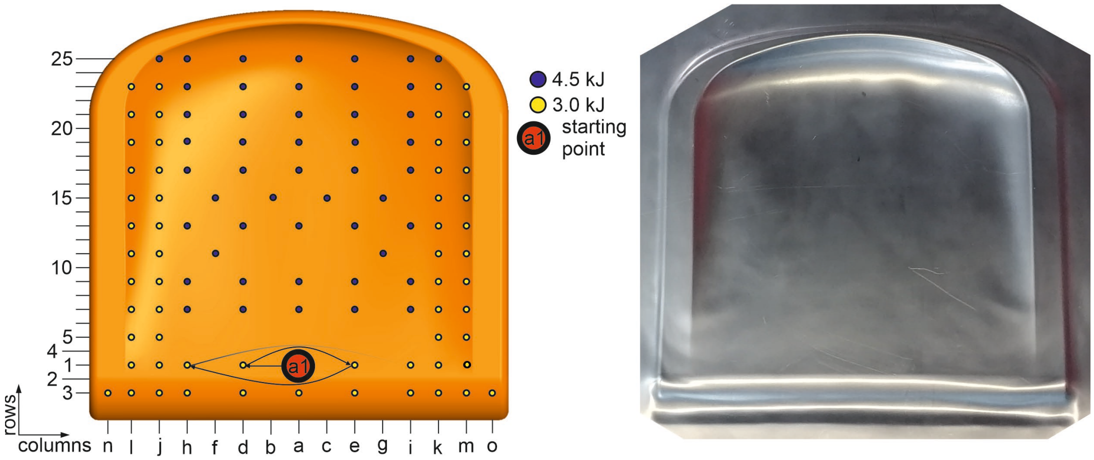

Fig. 4 EHIF forming strategy (left) and resulting workpiece (right)

In the same way as for the EMIF strategy, different capacitor charging energies were used for areas of different forming depths, but the energy level was adjusted to 3 kJ for the u-shaped flat area and 4.5 kJ for deeper sections of the die. While, for the EMIF forming strategy, a larger displacement of the tool could be chosen for successful deformation of steady areas without fine structures, the discharges in this area have to be distributed more evenly and with a smaller displacement for the EHIF forming strategy, because dents result in the seat surface if the displacements are chosen as large as those for EMIF. One possible cause is that the maximum pressure of the EHIF forming zone acts in its center, while in case of EMIF a ring-shaped area exists in the middle coil radius. In addition, discharges with high energies and large displacements caused already-formed areas to spring back or rebound. This effect was particularly pronounced for discharges in deep sections of the die. A smaller-step approach and staggered discharges in the middle section of the seat (see Fig. 4 columns 11 and 15) proved successful here. Overall, the displacement in y was changed from 15 mm to 30 mm. Previous forming tests showed that this did not cause any deterioration in the good forming of the radii for the u-shaped flat area. Two additional discharges (see Fig. 4 n3 and o3) were positioned in the bottom section of the seat to counteract wrinkling in the corner area. A total of 108 discharges were thus used for forming with this strategy, 60 of which were performed with 3 kJ and 48 performed with 4.5 kJ capacitor charging energy. The radii in the u-shaped area were well formed, while the front end of the seat is warped. This indicates subsequent deformation due to material being drawn into the deeper areas of the die.

Comparison of EHIF and EMIF

The forming result of the workpiece was measured using the Comet L3D optical measuring system from Steinbichler. Following the measurement, the workpiece and tool geometry were superimposed, and their deviation determined. Fig. 5 shows the forming results for EHIF (left) and EMIF (right). The deepest region of the die (area A) was better formed by EHIF than by EMIF although free forming tests showed that single-discharge EMF achieved higher forming depth for equivalent capacitor charging energies (Fig. 3). The reason for the inferior forming of EMIF is the longer distance between the inductor and the blank in this area, which is caused by pre-deformations resulting from preceding forming increments. It is well-known that increasing this distance significantly reduces the magnetic pressure and hence the deformation in that region. A possible solution is to shift the EMIF tool in the z-direction in order to reduce the distance again. The membrane, or the active medium of the EHIF process respectively, can easily overcome this distance as a moving mass with less energy dissipation.

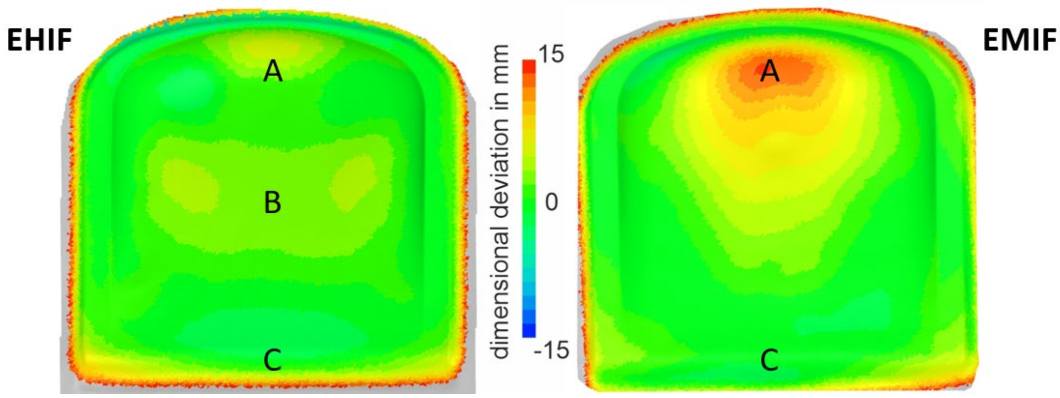

Fig. 5 Dimensional deviation between the workpiece and die for EHIF (left) and EMIF (right)

Furthermore, it is obvious that the middle section of the component produced by the EHIF process (area B) deviates from the target geometry. This might be due to the lever effect created by the point load on the sheet metal due to the pressure distribution of the EHIF forming zone. It may also be responsible for the dent formation in large steady areas of the component. The component produced by the EMIF process shows significantly less irregularities in this area due to the more uniform pressure distribution of the forming zone. The comparison of the seat edges (area C) in the lower part of the image shows, that the pressure in the outer area of the EHIF forming zone is not sufficient to achieve the set shape and therefore further discharges are necessary.

Based on these results, it is possible to make initial rough estimates of the economics of the process, especially with regard to the process time and the energy costs. As modern pulsed power generators typically allow a maximum discharging rate of four discharges per minute, the production of one full chair seat takes about 39.5 minutes in the case of EMIF and 27 minutes in the case of EHIF [17]. To estimate the energy cost for the forming process, the power consumption of the pulse generator was recorded at IWU as a function of the capacitor charging energy. For EMIF of the chair seat, the total energy consumption is 0.328 kWh. Taking an electricity price of € 0.15673/kWh, as averaged out over the last 10 years for industry in Germany, this energy consumption corresponds to electricity costs of € 0.0514 per component. Taking the same characteristic values, the electricity costs for the EHIF process are € 0.0265 per component.

Conclusion

This study has shown in broad terms that the incremental approach of electromagnetic and electrohydraulic forming can be used to form workpieces of a good quality. Nevertheless, there is still further potential for reducing the deviation between the set and the measured geometry. The process-related differences were mainly seen in the way the load is transferred to the blank. While in the EMIF process the distance between the die and the coil is a relevant factor for the forming depth, the active-media-based EHIF process can overcome larger distances. In terms of the evenness of the component surfaces produced, the more uniform pressure distribution of the EMIF process is advantageous. Further investigations should aim at improving the forming strategy. Adding a tool displacement in the z-direction in order to achieve greater forming depth as well as varying the number and distribution of discharges for a better fit of the desired geometries are possible approaches.

Acknowledgment

The authors would like to thank the German Research Foundation (DFG) for funding the research project “Incremental high-speed forming technologies" with reference numbers “HO 2356/17-1” and “PS 68/4-1”. The research work conducted in this project forms the basis of the paper.

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