Numerical study on a new forming method for manufacturing large metallic bipolar plates

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1 Abstract

Fuel cell technology offers a sustainable power supply solution for heavy-duty vehicles, aviation and shipping as well as stationary application. Manufacturing of metallic bipolar plates (MBPP) as a key component of fuel cells is nowadays one of the main topics in production-based research and processing industry. One reason for this is that although stamping of thin stainless-steel foils enables an economic large-scale production of metallic bipolar plates, tooling and press technologies required for embossing and shear cut operations are highly demanding and thus continuously being developed. Particular challenges are posed by the embossing of the complex flow field structure, which can cause forming defects and pronounced springback phenomena. Moreover, multiple embossing operations and high press forces are needed to plastify the metal foils as homogeneously as possible and thus form the desired channel geometry. Accordingly, future demand for large metallic bipolar plates is likely to exceed the limits of current press technologies in terms of force capacity and stiffness. Similarly, rolling is also not suitable for forming such large plates due to severe wrinkling and springback. Therefore, this paper proposes the so-called TIP-Form as a new forming process with a tilting forming kinematic of one or both tool halves as well as a crowning of the active surface. In this regard, a numerical study is presented, in which the new forming approach to decrease the force demand and improve the formability when embossing bipolar plates was investigated. Explicit forming simulations of a flow field section were performed using LS-DYNA and forming forces as well as formability were evaluated. Compared to conventional embossing, the controlled tipping and crowning of the punch could reduce the simultaneous acting contact zone between tool and foil and therefore maximum forming forces have been reduced. In addition, thinning of formed channels decreased, as the tipping forming kinematics enabled a beneficial material flow. The promising numerical results motivate for further research work and emphasis the development of a new press technology with tipping ram or table for the manufacturing of large metallic bipolar plates.

2 Introduction

2.1 State of the art for manufacturing of metallic bipolar plates

The growing demand for e-mobility, microelectronics, and renewable energy technologies has led to a significant increase in the production volumes of thin and miniaturized components manufactured from metallic foils with thicknesses below 100 µm. This trend is particularly evident in the field of fuel cells. A fuel cell comprises two electrodes separated by an electrolyte – typically a membrane [1]. These membrane electrode assemblies (MEA) are subsequently combined with bipolar plates to construct fuel cell stacks. The primary roles of the bipolar plates are to establish electrical connections with the individual MEAs, facilitate the supply of reactant gases, and manage the discharge of resulting water. In modern fuel cells, stainless steel foils are predominantly used for metallic bipolar plates. The manufacturing process involves the creation of two halves of the metallic bipolar plate, referred to as bipolar half plates (BPP), by means of hollow embossing of thin metallic foils. Subsequently, these halves are welded to form an unified bipolar plate.

However, the hollow embossing of high-precision BPP represents a highly sensitive procedure, fraught with various challenges for the manufacturing process. Defects such as cracks, wrinkles, or inadequate dimensional accuracy caused by springback arise even with minor fluctuations in material and process parameters [2-5]. Moreover, the formation of narrow channels through hollow-embossing necessitates exceedingly high press forces, which not only limit the dimensions of the BPP but also curtail the overall performance and potential for applications of fuel cell technology. As such, the anticipated future demand for larger metallic bipolar plates is likely to surpass the capabilities of existing press technologies in terms of force capacity and stiffness.

Due to these difficulties and challenges inherent in the manufacturing of metallic foils, alternative techniques have gained traction alongside conventional hollow-embossing, and new methods continue to be developed [6]. The most common approaches for forming metallic BPP include hollow embossing, roll forming, and hydroforming [6,7]. A schematic overview of these methods, along with the newly introduced TIP-Form discussed in this paper, is illustrated in Figure 1 below.

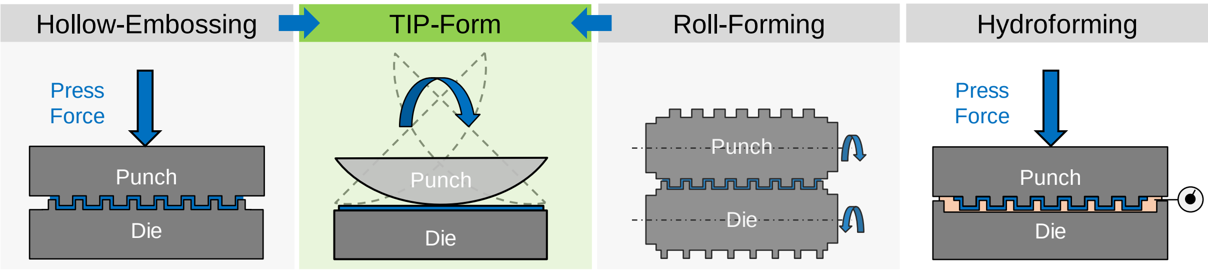

Fig.1: Schematic Representation of common forming processes and the proposed forming method TIP-Form for manufacturing BPP

Hollow Embossing stands out as perhaps the most widely employed technique for fabricating metallic bipolar half plates. In this process, a thin metallic foil is embossed between two rigid counter dies under high press forces. Optionally, a blankholder can be introduced to reduce wrinkling in the outer regions of the BPP. Hollow embossing is distinguished by its high technological maturity and short cycle times, and it is currently utilized reliably in series production with relative rapid cycle rates of 1 – 2,5s per BPP [7]. However, the relatively high force requirement, which scales with an increasing size of BPP, presents a significant limitation. In contrast to hollow embossing, the so-called Roll-Forming is a method for manufacturing characterized by a low force demand and good scalability. The linear engagement of the two rotating tool halves, which encompass the plate geometry in an unwound form, significantly reduces the engaged tool contact area and thus force needed. This approach has the potential for very short cycle times and high quantities, yet limitations arise in the geometric design of the BPP, and excessive wrinkling and springback remain significant challenges in this process [6,7]. Especially, since a blank holder cannot be utilized in such tool constellation. Another widely used approach for forming BPP is the so called hydroforming. The advantage of this approach lies in the fact that a material's forming capacity can be more effectively utilized, enabling an extension of forming limits compared to, for instance, single-stage hollow embossing under cold forming conditions. Also only one active tool surface is needed. However, the considerable drawback of the relatively low production rate due to required hydraulic components becomes significant when high quantities are needed [6,7]. The newly proposed forming method TIP-Form combines the benefits of both hollow embossing and roll-forming methods in an appropriate manner.

2.2 New forming method TIP-Form

The new forming method TIP-Form consist of a tilting forming kinematic of one or both tool halves as well as a possible crowning of the active surfaces. This forming process can be classified between the conventional rolling with rotatory tool movement and the embossing with translational tool closing in vertical direction. Due to current limitations and challenges in the manufacturing of metallic bipolar plates, the new forming kinematic can overcome existing limits. Rolling of large foil parts cause tremendous springback and wrinkling as well as an expensive manufacturing of high precision mills. Furthermore, conventional embossing with a simultaneous acting tool and workpiece contact increases the force demand and often exceeds the capacity of existing press machines. Future trends for large-scale fuel cell systems are challenging manufacturers and will require new forming methods to ensure the production of large metallic bipolar plates. Presented study will focus on an exemplary large-scale bipolar plate and a state-of-the-art channel geometry, shown in Fig. 2.

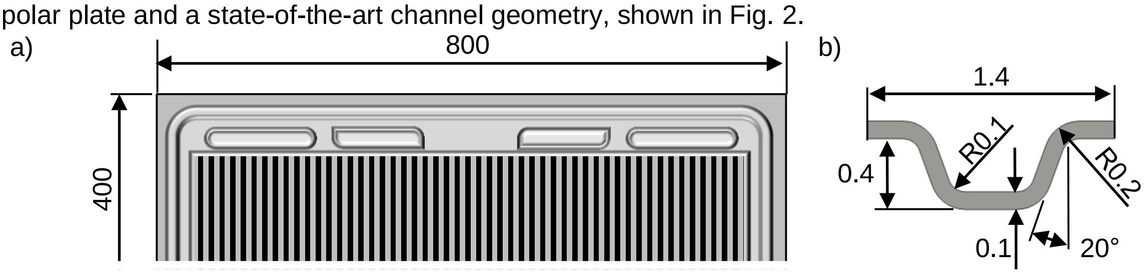

Fig.2: a) Dimensions of an exemplary large-scale metallic bipolar plate with b) the corresponding channel design.

The basic idea behind this new forming process Tip-Form is a reduction of the simultaneously acting contact area between tools and workpiece to decrease force demand and enhance formability. It can

be achieved by a combination of rotational and translational movement of tool halves, driven by a tipping press ram [3D] or additional actuators on tool base. Here, the benefits of rolling processes with reduced loads can be extended to large and variable punch crowning radii and an implementation of surrounding blankholding devices for wrinkle prevention.
For this purpose, a preliminary analytical study was conducted to investigate the relations between tool dimensions and kinematics as well as the reduction of simultaneous acting contact zone between tools and workpiece. The amounted tool setup is shown in Fig. 3 and is developed according to the exemplary large-scale metallic bipolar plate (Fig. 2). A variation of the crowning punch radius R will affect the tool dimensions and the kinematics, resulting in a change of tipping angle, horizontal and vertical tool translation and finally the contact zone between tool and workpiece. Therefore, a parametrized tool and kinematic model was built in CATIA V5R20 to identify the correlations between given dimensions and movements.

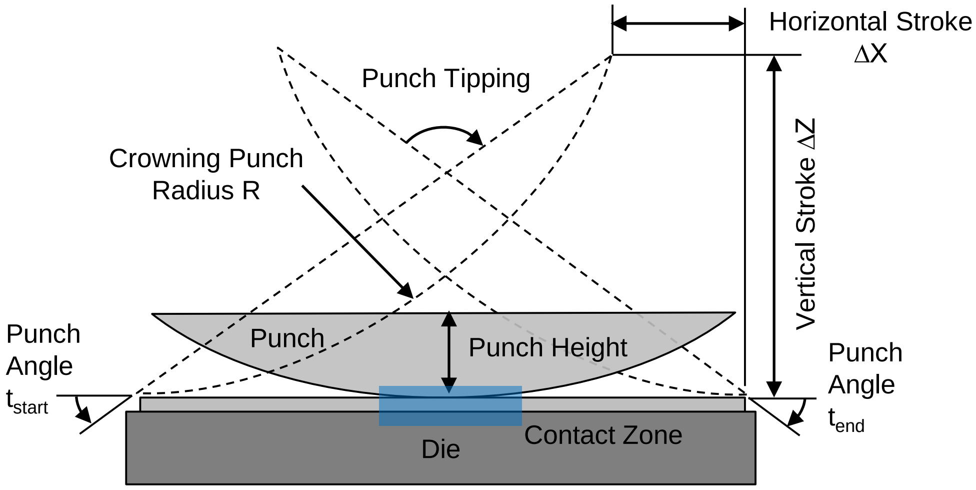

Fig.3: Geometry and kinematic of the Tip-Form process setup for manufacturing of large scale metallic bipolar plates.

An exemplary evaluation of the results for the analytical tool dimension and kinematic model are shown in Fig. 4. Here, only the crowning punch radius R was varied and the effect on the tipping angle at the beginning and end of the forming process was plotted. With an increase of the crowning radius of the forming punch, the necessary tipping angles of the punch can be significantly reduced. On contrary, the contact zone between tool and workpiece is exponentially increased up to 100 % for conventional embossing. For example, a constant crowning of the punch with a radius of 10,000 mm will result in a punch tipping from +2.3° to -2.3°. It will cause a maximum translational movement of the punch of 0.9 mm in horizontal and 32.0 mm in vertical direction. In doing so, the contact zone will be reduced by more than 80 % compared to conventional embossing with a simultaneous acting forming contact.

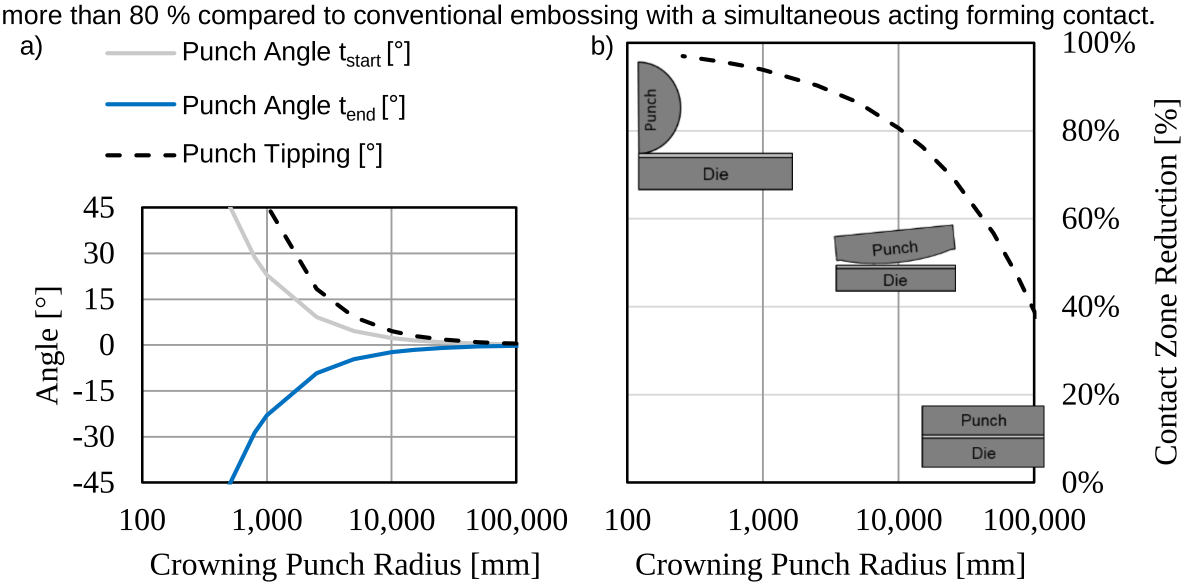

Fig.4: Analytical results for the examination of a) punch tipping angle and b) contact zone reduction as a function of the crowing radius of the punch.

3 Material characterization and modelling

For the presented numerical investigations, stainless-steel foil (1.4404) with a thickness of 0.1 mm was used. To determine the material parameters required for the forming simulation, uniaxial tensile tests according to DIN EN 6892 were first carried out using DIN 50125 Form H 20 × 80 specimens prepared in 0°, 45° and 90° rolling directions. The material properties obtained are listed in Table 1. In addition, bulge tests according to ISO 16808 were carried out allowing to gain data until a true strain value of 0.5 as shown in Fig. 5 a). For both tests, a strain measurement with GOM ARAMIS was carried out. Due to the high achievable value for true strain and expectedly low strains during the embossing of metallic bipolar plates, no further extrapolation of the flow curve was needed. The flow curve thus was fitted directly with a polynomial approach to achieved experimental data [5].

Table 1: Material properties of stainless-steel 1.4404 / X2CrNiMo17–12-2.

Material	t [mm]	Young's modulus [GPa]	Yield Strength [MPa]	UTS [MPa]	n [-]	r_0 [-]	r_{45} [-]	r_{90} [-]
1.4404	0.1	200	238	556	0.43	0.72	1.06	1.22

The determination of the forming limit curve (FLC) of the considered steel foil based on a scaled and non-standardized Nakajima test. Experiments were carried out using a punch with a reduced diameter of 20 mm compared to the Norm ISO 12004. The downscaling of the punch and the specimen's geometry were necessary to reduce the risk of wrinkling within the measuring area of the specimen. To reduce friction between punch and specimen, a layer of silicone with additional three layers of Teflon film and M-100 forming oil proved to be the most suitable solution. In this way, friction could be reduced tremendously, allowing for linear strain paths and thus reliable data for determining the FLC. For measurement of strains the optical measurement system ARAMIS was used. Corresponding specimens as well as acquired FLC are shown in Fig. 5 b) [5].

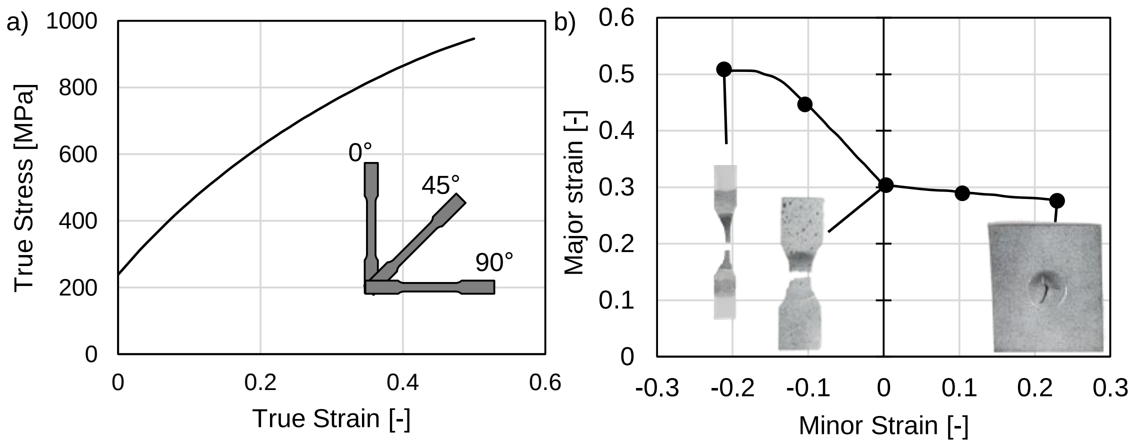

Fig.5: a) Flow curve based on uniaxial tensile and bulge tests and b) forming limit curve (FLC) based on scaled Mini-Nakajima tests.

The obtained material parameters were implemented in **`*MAT_PIECEWISE_LINEAR_PLASTICITY_2D`** for 2D-Simulation (Section 4) and **`*MAT_FLD_3-PARAMETER_BARLAT`** for 3D-simulation (Section 5). The latter was found suitable for the simulation of embossing processes with dominant stretch forming due to consideration of anisotropic material properties under plane stress conditions.

4 2D-Simulation study of new forming process

In order to verify the feasibility of new forming process Tip-Form, a 2D-Simulation study was conducted. Due to the fine channel structure and high number of channels, the problem was reduced to only a small section of the large-scale bipolar plate, shown in Fig. 6. Blank dimensions amounted 18.5 mm in length and 0.1 mm in thickness direction, discretized by 74,100 2D-shell elements with an edge length of 0.005 mm and a thickness in Y-direction of 1 mm. For a total number of ten channels, punch and die geometries were modeled according to the desired channel design shown in Fig. 2 b). The tool meshes were modelled by 12,010 2D-shell elements with an average edge length of 0.01 mm and a master contact definition towards the blank by **`*CONTACT_2D_AUTOMATIC_SURFACE_TO_SURFACE`**.

Boundary conditions like a symmetry plane were used to model only a section of the large part and process. In combination with the 2D-boundary conditions, the number of elements and calculation time was maintained on a low level compared to a full-size 3D model with approximately more than 1.7 billion of elements.

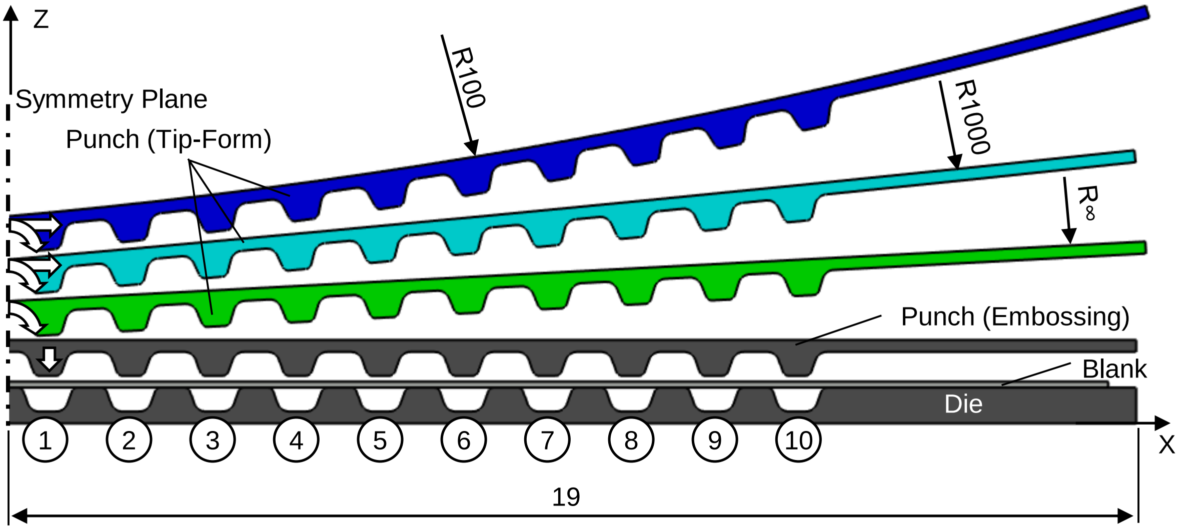

Fig.6: 2D-Simulation setup for the comparison of conventional embossing and Tip-Form process with a variation of crowning punch radius.

Besides the conventional embossing process with a vertical translation of the punch in Z-direction and a fixed die below the blank, three process variants of new Tip-Form method were modelled. The punch was crowned by three different radii to reduce the contact zone between tool and workpiece. In doing so, motion of the punch had to be defined for each use case to ensure a proper forming of channel geometries by a defined gap between the engaged punch and die. Therefore, rotational and translational motions were added with the help of `*BOUNDARY_PRESCRIBED_MOTION_RIGID` to the rigid punch for crowning punch radius of 100 mm and 1,000 mm. This enabled the constant movement of the rotation axis in horizontal direction in combination with the defined rotation. The flat punch (R∞) was only subjected to a rotational movement around a fixed rotation axis outside of the part.

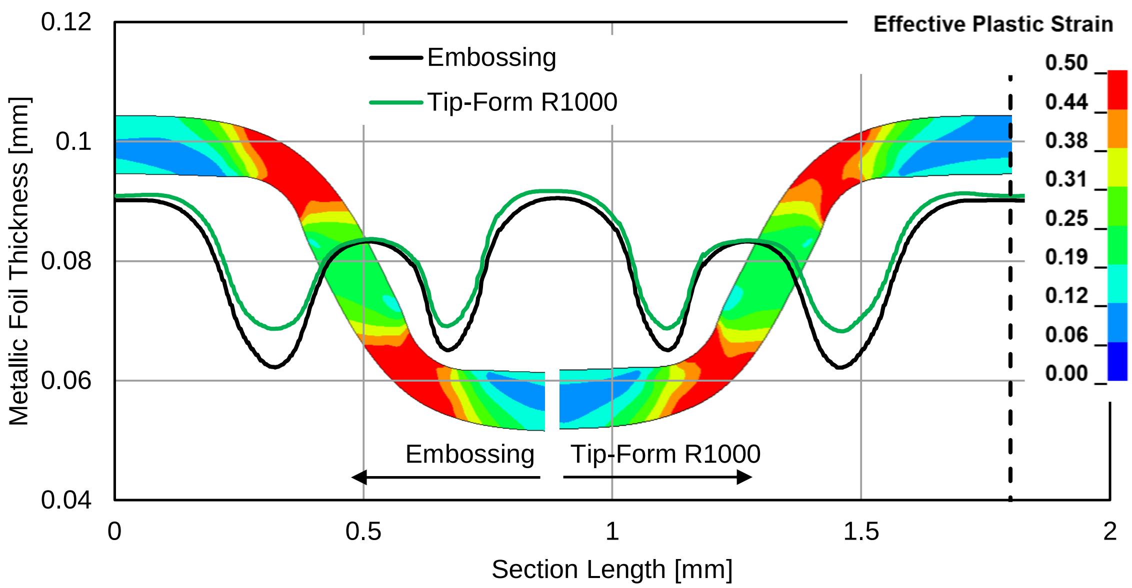

Fig.7: Local evaluation of metallic foil thickness and effective plastic strain for conventional embossing at channel 1.

Fig. 7 shows the evaluation of the effective plastic strain and the thickness of the metallic foil after forming in a single channel segment (1) for the conventional embossing process. Here, the simultaneous intrusion of the punch prevents the material flow in horizontal direction and results in high strains at the sharp tool radii and a corresponding thickness reduction. Exemplary shown results for Tip-Form R1000 show minor thinning of the metallic foil due to reduced plastic strains in radii and flat channel sections. A more global view on the apparent metallic foil thickness for all considered process variants over the ten channel segments are shown in Fig. 8. Here, the draw-in of the free blank edge affected the thickness distribution for all process variants. Conventional embossing and the simultaneous locking of all channels caused severe thinning of channel segments 1-8. As a conclusion, the material is locked at the third channel (8) from the direction of the free blank edge. On contrary, it can be stated that for all process variants of the new Tip-Form method, the thinning of the metallic foil was reduced. The increase of the crowning punch radius caused an increase of the metallic foil thinning. Smaller crowning radii enabled less thickness reduction in the channel segments next to the free edge (8-10).

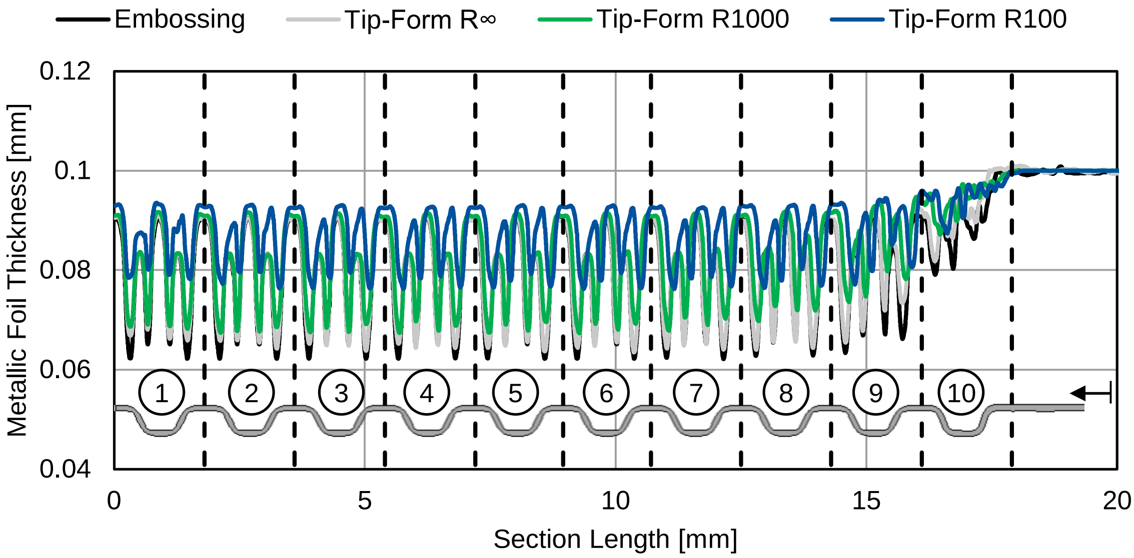

Fig.8: Global evaluation of metallic foil thickness after forming for conventional embossing and Tip-Form process with a variation of crowning punch radius.

Cause and effect of the reduced thinning phenomena was found in an evaluation of the blank draw-in and longitudinal elongation, shown in Fig. 9. The smaller the radius of the punch crowning, the more blank material was drawn into the channel sections and the less blank elongation was observed. Due to the incremental engagement between tools and blank of each channel section as a function of punch crowning, the blank draw-in increased and the maximum thinning was reduced up to 14 %. Additionally, the thinning of the flat top and bottom channel sections was also reduced because of the lower blank elongation of the considered Tip-Form process.

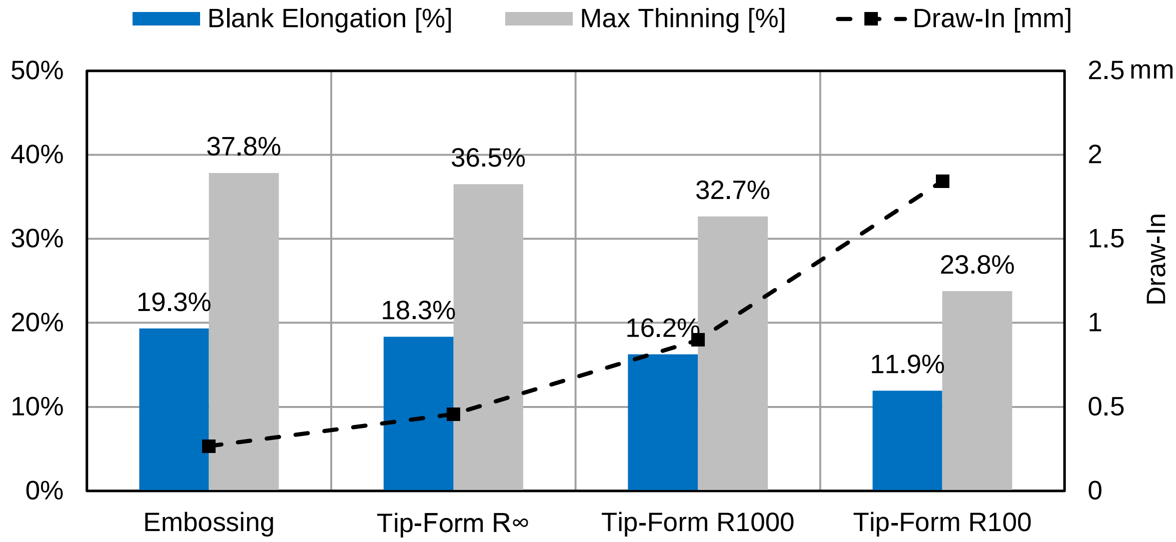

Fig.9: Evaluation of the free blank edge draw-in and the corresponding blank elongation and maximum thinning of the metallic foil.

Besides an evaluation of forming results and the promising potential for an increased formability, main focus of the present study was to decrease the high force demand of embossing processes for metallic bipolar plates. The evaluation of maximum total contact forces between the tools and the blank is presented in Fig. 10. A simultaneous intrusion of the punch and forming of all ten channel segments at once amounted in a maximum vertical force of more than 3,500 N for the considered 2D-section. Instead of a vertical translation of the flat punch for conventional embossing, the punch was rotated and therefore sequentially formed the channels by Tip-Form R∞. In doing so, maximum force demand was already reduced by 54 % to 1,617 N. An additional crowning of the punch together with an extended tool tipping kinematic caused even a more pronounced decrease of the force demand to form the ten channel segments. Here, the crowned and tipped punch with 1,000 mm of radius lowered the maximum load by more than 70 % to 1,002 N per considered 2D-section. Although the strong crowning of punch by a radius of 100 mm would only be feasible for a bipolar plate with a reduced length (<314 mm) due to the limited unwinding length of the half cylinder, the forming simulation revealed a tremendous forming force reduction potential of more than 86 %. In addition, Fig. 10 also shows the required computation times on an Intel Core i7-6700 3.4 GHz with a total of four CPU. It can be stated that the more complex kinematic of the crowned punch results in an increase of node displacements and therefore an exponential extended calculation time. Compared to the conventional embossing simulation with a calculation time of 851 s, the tipping of the punch as a combination of rotation and translation can increase the required simulation time up to 18 h. This may limit the transfer of 2D-simulation to more complex 3D-simulation due to limited resources and computational costs.

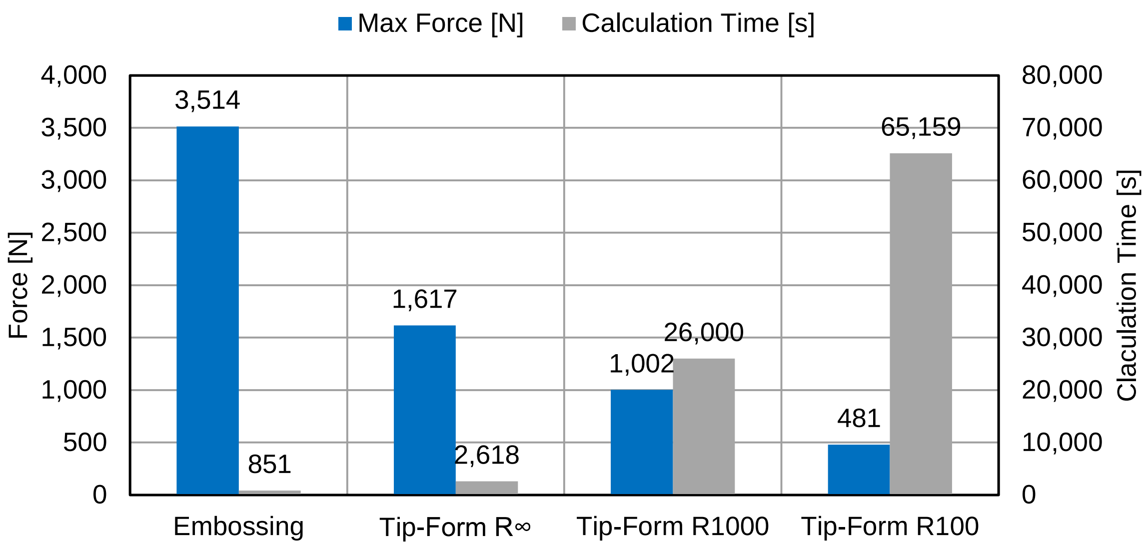

Fig.10: Evaluation of maximum forming forces and comparison of calculation time on 4CPU LS-DYNA SMP R11.0 solver

5 3D-Simulation of a metallic bipolar plate section

Based on conducted 2D-Simulation study, a transfer to a more complex and 3-dimensional channel design was made. Herein, the conventional embossing was compared with the new forming method Tip-Form using a flat punch and solely rotational movements. Due to the more enhanced calculation time for the crowned punch variants of Tip-Form, a consideration was not possible in presented study but will be investigated in future work. The exemplary designed bipolar plate section provides several channels, aligned in rolling and transversal direction as well as curved segments. In total, an embossed area of 152 mm² was analyzed for the two process variants with a vertical translational (Embossing) or a rotational punch movement (Tip-Form R∞). The blank was discretized by fully integrated shell elements with an edge length of 0.015 mm and the average element size of rigid tool mesh amounted 0.05 mm. Prescribed boundary conditions with two defined symmetry planes reduced the model size and prevented the material movement on two sides and enabled it on the respective opposite sides. Fig. 11 a) illustrates the designed setup with the initial positioned flat punch for b) conventional embossing with translational movement and c) Tip-Form with rotational movement.

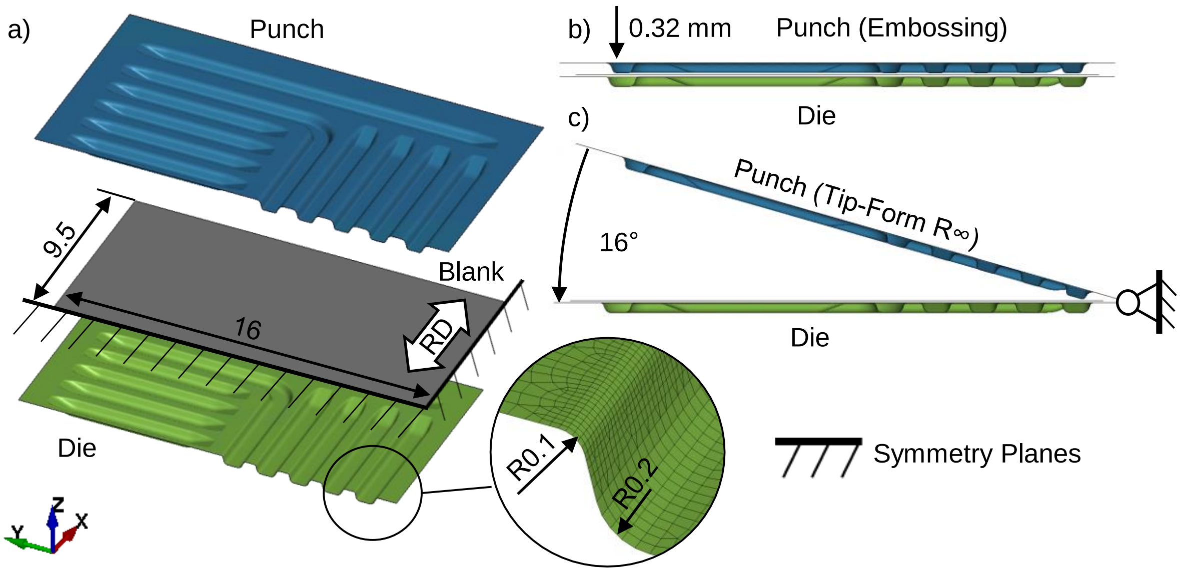

Fig.11: a) 3D-Simulation setup for the comparison of b) conventional embossing and c) Tip-Form process with a flat punch (R∞)

The calculated contact forces between tool and workpiece are shown in Fig. 12 a). The conventional embossing of the evaluated bipolar plate section resulted in an estimated force demand of more than 0.21 kN/mm². Maximum force occurred at the very end of the forming process when the tools are moved in the final and closed position. It was found, that especially areas of wrinkling with a material thickening tendencies are responsible for high force demands. Closing of tools with a designed gap corresponding to the initial metallic foil thickness will result in a high load and contact pressure at areas of material thickening. Besides wrinkling and thickening at free edges of the part, severe thinning and cracks were observed for conventional embossing method, see Fig. 12 b). On contrary, the sequential forming of the channel geometries by the Tip-Form process caused an increased wrinkling tendency in channel transition zones, see Fig. 12 c). Nevertheless, the corresponding sequential forming and reduced contact zone between tools and workpiece resulted in a reduction of the maximum force demand by more than 70 % to 0.05 kN/mm². Additionally, severe thinning and risks of crack were reduced in channels aligned transversal to the tipping rotation of the punch. Cause and effect were found in the extended draw-in of the free blank edge in rolling direction of punch, which overall improved the formability of the part. Here, draw-in of the free edge in Y-direction was increased by more than 116 % and resulted in less thickness change of the foil material in the transversal channel sections.

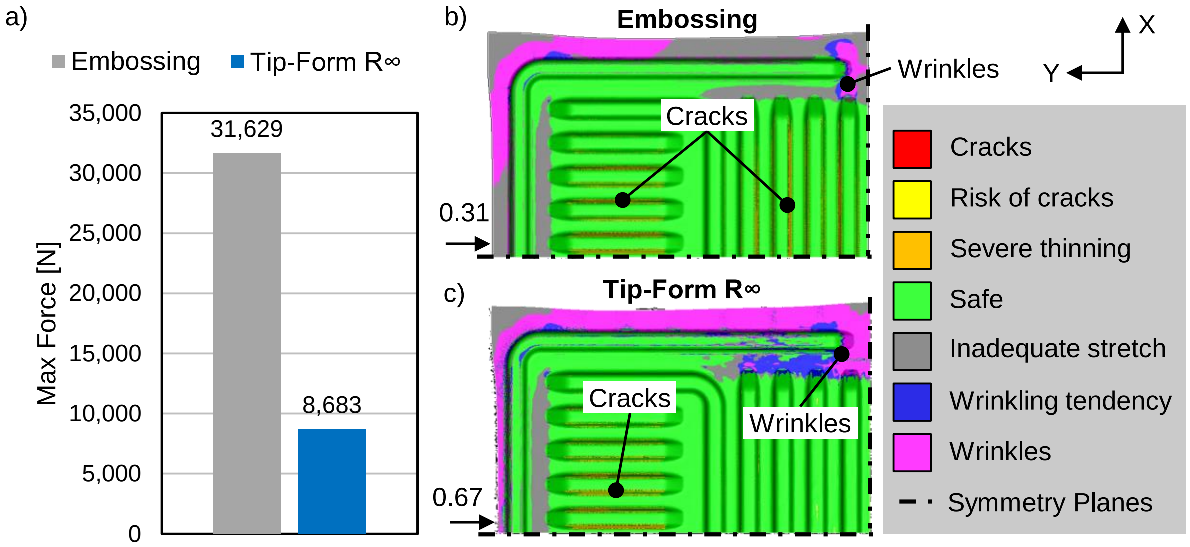

Fig.12: Evaluation of maximum forming forces and formability for conventional embossing and Tip-Form process with a flat punch (R∞)

6 Summary and outlook

Current challenges in the manufacturing of metallic bipolar plates by forming technologies provided the motivation for the development of a new forming process. High costs for tooling, steadily increasing demand for even higher press forces and forming of complex geometries under the observance of minimum tolerances lead to a production at the leading edge. The proposed new forming process called Tip-Form may overcome certain limitations and can be classified between the conventional rolling on mill stands or the embossing on press machines. A tipping movement of one or both tool halves during forming allows a reduction of the simultaneously acting contact area between tools and workpiece, resulting in a reduction of press load and an increasing formability. Therefore and based on newly developed material characterization, a 2D-Simulation study was conducted to evaluate the potentials for a reduction of forming forces and metallic foil thinning. It was found that the combination of rotational and translational punch movement in combination with a crowned punch can reduce the force demand up to 86 %. Moreover, the sequential forming of the channel segments enabled a single sided material draw-in and therefore, thinning was reduced up to 14 %. These results were verified on a bipolar plate section within a 3D-Simulation study, comparing conventional embossing with the Tip-Form process. Rotating a flat punch instead of the simultaneous intrusion via vertical movement reduced the total force demand by more than 70 % to 0.05 kN/mm². An extrapolation of the estimated force demand for conventional embossing a large-scale metallic bipolar plate would need a press machine with more than 6,600 tons of press force. New process Tip-Form can reduce the maximum of forming forces to 1,828 tons and further saving potentials can be achieved by an additional crowning of the punch or die.
Here, future investigations need to tackle current limitations in simulation technology. Material testing and modelling of thin stainless-steel foils with coatings will rise the demand for new technologies and standards. Large-scale models with fine channel structures lead to huge and complex mesh structures and FE-models with unpracticable simulation costs, where new complexity reduction methods need to be developed. In addition, the development of new tool and machine technologies are necessary to implement new forming kinematics and verify presented results.

7 Literature

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