Experimental evaluation of a feature based bipolar plate forming approach in a hybrid tool

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Abstract. The bipolar plate is a core component of a fuel cell and makes a decisive contribution to both system weight and cost. To reduce costs, metallic foils have been formed for several years to replace the conventional milled compound plates. The main challenge in forming is that the channel geometries must be produced with the highest accuracy requirements. Tolerances of a few micrometers should be maintained. The combination of high accuracy requirements with target production speed of less than one second and the complex geometric designs of flow fields pushes conventional forming technologies to their process limits. To meet this challenge, a procedure for feature-based forming has been developed (IDDRG2024) that enables multi-stage and hybrid forming. This allows bipolar plates to be manufactured independently of design but in a feature-specific production process. This previously developed theoretical process model will be physically validated and tested for effectiveness in investigations to be presented. For this purpose, a hybrid tool consisting of conventional stamping and rubber pad forming is set up, which is combined using precision workpiece transport. Using this tool, hybrid forming tests can be carried out based on previous numerical analysis to validate the procedure and derive an optimized process chain.

Keywords: Bipolar plate; Fuel cell; Feature based; Forming

1 Introduction

1.1 Motivation and previous work

The fundamental premise of feature-based manufacturing is that there exists a specific combination of one or more working principles that optimally addresses a forming task, ensuring the best possible results under the given conditions [1]. This assertion is theoretically supported by the understanding that various deformation mechanisms produce distinct stress states, which invariably affect the forming outcome. However, the assessment of how real production environments influence these results remains ambiguous. Therefore, alongside numerical analyses of the forming process, it is essential to evaluate whether this approach permits an acceptable level of abstraction error. To prove the validity of the approach, the hybrid tool already presented at the 43rd International Deep-Drawing Research Group Conference was tested with real bipolar plate geometries.

1.2 Tool setup and initialization

To validate the feature-based approach, a hybrid tool has been developed that integrates two distinct working principles within a two-stage manufacturing process. Additionally, three feature types have been introduced into the toolset. The primary challenges encountered during the development of the hybrid tool arise from the tolerances associated with the forming technologies employed. In a single step forming process utilizing rubber forming technology, the geometrical error of the finished plate is solely determined by the tolerance of the stamp. In contrast, conventional stamping technology requires precise alignment between the top and bottom stamps. In the hybrid process, the tolerance introduced during the transition between the two processes is also noteworthy. Consequently, the initial step in the development of the hybrid tool involves analyzing the tolerance chain within the experimental setup. Fig. 1 shows a sectional view of the hybrid tool, which is constructed within a four-column frame. The top part of the frame accommodates the top stamp for the conventional stamping process and the rubber pad for the rubber forming process. The bottom section features a base plate that supports the bottom stamp for both the conventional stamping and rubber forming processes, along with the sheet transfer system.

To reduce lateral positioning errors during the transfer phase, linear rails with adapted accuracy and stiffness are employed. Furthermore, the feature triplets on the stamp are oriented orthogonally to the feeding direction to mitigate the effects of any residual errors. Lateral accuracy is achieved by incorporating end stops for the carrier adjacent to both stamps. Any remaining lateral positioning errors are corrected using a micrometer screw to apply pressure against the end

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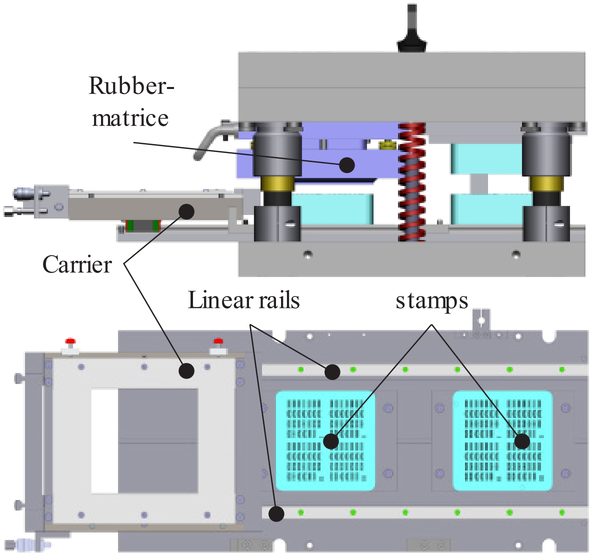

Fig. 1 Sectional and top view of the hybrid tool

stops. Additionally, the micrometer screw allows for the setting of a defined lateral offset to investigate the influence of positioning errors on the forming process. Prior to conducting trials, the hybrid tool was calibrated to establish the neutral transfer position of the micrometer screw, ensuring the elimination of any residual positioning errors. This calibration process was performed using a coordinate measuring machine (Zeiss Prismo), which offers a lateral accuracy of approximately 1.6 µm.

2 Design of experiments and numerical characterization

The methodology for feature-based forming, as well as the test tools and forming test benches for validating the methodology, were developed as part of the “H2GO” research project [1]. The project was funded by the Federal Ministry for Digital and Transport Affairs (BMVD) as part of the National Innovation Program Hydrogen and Fuel Cell Technology Phase 2 (NIP II) (funding code: sub-network R2HP: 03B11027B). Accordingly, the geometries to be investigated are derived from the central bipolar plate geometry, which was used in the project to innovate the forming technologies.

2.1 Design of experiments

In the experiments Stainless Steel (1.4404) sheets with a thickness of 0.1 mm and the chemical composition given in Table 1 are used.

Table 1. Chemical composition of the metal sheet

C	Si	Mn	Ni	P
0,021	0,571	1,039	10,46	0,033
S	Cr	Mo	N	Cu
0,004	16,679	2,056	0,016	0,228

The metal sheets are formed using the hybrid tool, which is placed in a hydraulic press (Lauffer VAH850). During the forming process, the press can be configured to adjust and monitor the forming force, forming time, and force application rate. The conventional stamping stage of the hybrid tool is utilized as outlined in the tool's design. For the rubber forming stage, a rubber with a hardness of 60 Shore A and a height of 25 mm is employed. The blank holder springs in the rubber forming stage have a spring rate of 480 N/mm, providing a force of 13.4 kN at the working height.

For each forming process, a pre-cut metal sheet was prepared and secured within the carrier unit of the tool. The carrier unit ensures precise relative positioning between the forming stages. The plates are removed from the carrier only after the second forming operation and subsequently prepared for examination. Prior to each forming operation, the forming steps, tool stamps, and raw metal sheets are cleaned with acetone and compressed air.

2.2 Numerical characterization of feature-based forming

Forming simulations are conducted using an explicit solver, whereas hydrostatic deformation is analyzed with an implicit solver to efficiently simulate the deformation of the rubber cushion in a shorter time frame. All finite element models comprise three components: the upper mold, the lower mold, and the sheet metal. The components may vary based on the manufacturing technology, and each requires distinct characterization.

To optimize the model's composition, a rigid body representation is utilized for the metal components of the tool, including the punch of the upper tool and the die of the lower tool. The metal plate and the rubber pad of the lower tool are modelled as deformable elements. A visualization of the two simulation models is shown in Fig. 2.

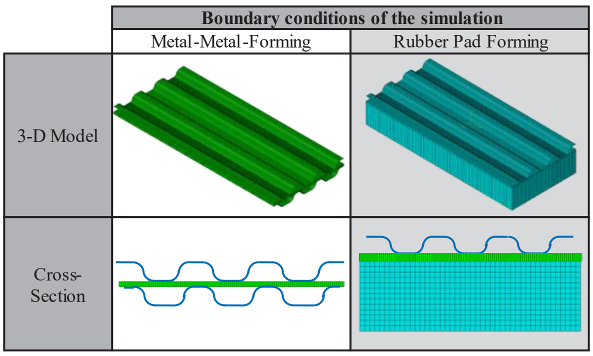

Fig. 2 Visualization of the manufacturing methods metal-metal-forming (left) and rubber pad forming (right)

The plastic behavior of the sheet is characterized by tabular data derived from experimental tensile tests conducted on the original material EN1.4404, which has a thickness of 0.1 mm. Material properties for the sheet such as density, Young’s Modulus and Poisson’s ratio are 8e-09 tons/mm^3, 200000 MPa and 0,28, respectively. The incompressible and non-linear hyper-elastic behavior of the rubber pad is defined by the Mooney Rivlin model. For that, only two constants are provided (C_{10} and C_{01}), their values are 0.736 and 0.184 [2]. Mesh elements for the deformable sheet, rigid bodies and rubber pad are SC8R, R3D4 and C3D8RH [3]. Mesh size is defined with the aid of energy balance analysis, where the ratio between ALLAE (Artificial Strain Energy) and ALLIE (Internal Energy) was kept below 1 % in all simulation models used [4]. Other variables were evaluated for convergence, such STH, Stress and Strain. All the mesh size values used demonstrated accuracy in the evaluation.

The contact interactions between the sheet and the rigid surfaces are defined such that the normal behavior is classified as ideal surface to surface contact, while the tangential behavior is modelled using a friction coefficient of 0.2 [5]. The interaction between the rigid components and the sheet metal is described as surface-to-surface contact, employing the kinematic contact method and finite sliding for the forming simulations. Additionally, the surface-to-surface discretization method is utilized in the hydrostatic forming models to address the contact interactions between the rigid and deformable dies and the sheet metal. All models are computed with a uniform step time of one second. Additionally, it is noteworthy that both displacement and load simulations exhibit comparable parabolic amplitudes, reaching a maximum value of 0.5 seconds.

2.3 Execution of the forming processes

To compare the two-step forming process with the single-step forming process, the stamps in the experiment are divided into quadrants. Fig. 3 shows a top view of one of the stamps and indicates the positions of the various areas. Each of these quadrants is assigned

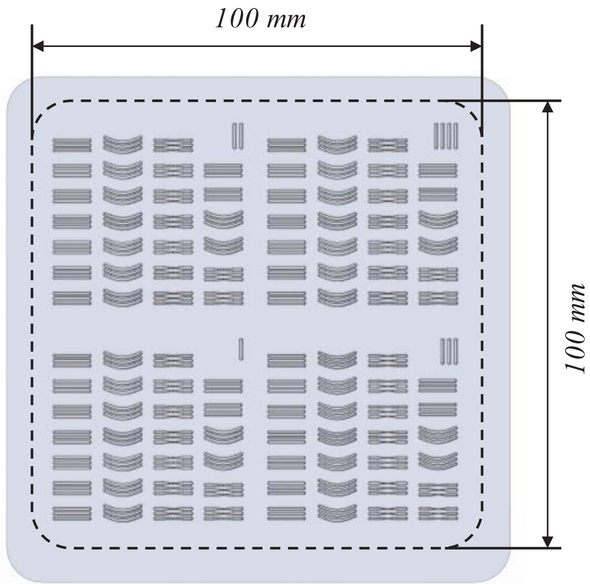

Fig. 3 Top view of the test stamp

to a distinct manufacturing configuration. Quadrant I is designated for 100 % conventional metal-metal stamping (MM), quadrant II for 100 % rubber (pad) forming (RF), quadrant III for hybrid forming with conventional followed by rubber (pad) forming (MMRF), and quadrant IV for hybrid forming with rubber pad forming followed by conventional forming (RFMM). In the hybrid forming operations, the desired geometry is formed to 90 % of the final dimensions in the first stage and to 100 % in the second stage. The value of 90 % is related to the final channel height. In the experiment, each manufacturing configuration is executed with three different forming forces and a constant neutral offset.

The forming force is based on previous research and calculated for the specific forming area. Pressures typically range from 20 to 150 MPa, depending on the hardness of the rubber [6-9]. With an active forming area of 100 mm x 100 mm, this corresponds to a maximum forming force of 1000 kN to 1500 kN. In the experiment, the maximum forming force is constrained by the rubber forming process to 800 kN. The fundamental geometrical features used in the test design include straight channels, theta bents, and horizontal tapered channels. These geometries are representative of the features and dimensions found in the H2GO bipolar plate design.

In Fig. 4 the dimensions of the Triplets are shown in a top view as well as in a cross-sectional view. The

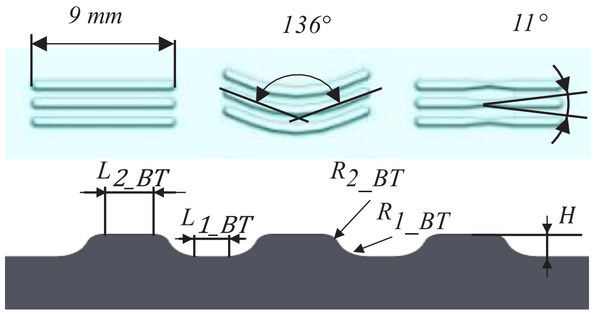

Fig. 4 Top-view and cross-sectional-view of the features used in the experiment

dimensions of the triplets are shown in the left part with all triplets having the same length. In the cross-sectional view, the parameters H, R1, R2, L1 and L2 of the bottom tool are defined. The parameters of the cross-section are varied across the surface of the test-stamp. For each feature, there are three different configurations per parameter in the design.

3 Evaluation of the forming quality

To evaluate the influence of the manufacturing configuration on channel geometry, a comparative analysis is performed. This includes a visual inspection and measurement of the surface characteristics of the formed plates. Furthermore, a metallurgical analysis is conducted to investigate the thinning of the material.

3.1 Surface examinations

The formed metal sheets, along with the stamps, are examined using a Focus Variation Microscope (Alicona Infinite Focus G5). To facilitate the comparison of metal sheets produced by the different tool configurations, measurements are taken from the underside of the sheets for the analysis. To minimize measurement errors, the lengths L1 and L2, as well as the radii R1 and R2, are averaged across the triplet. The test series was not aiming for achieving an ideal target geometry through forming. Instead, the objective was to determine whether different manufacturing methods exert varying effects on the characteristic values of an individual forming feature under identical pressure conditions. Therefore, the forming surface quality, and the thinning of the straight channel feature are evaluated.

The following Fig. 5 illustrates the characteristic values of the straight channel feature as a function of the manufacturing strategies. In this evaluation, the values for the rubber (pad) forming (RF) alone were not included, as they deviated by more than 100 %, thereby distorting the overall interpretation. Additionally, only the absolute values of the deviations were considered in the evaluation, resulting in all percentage values being represented as positive. In determining the forming quality of bipolar plates (BPPs), the deviation from the target geometry is critical, regardless of the direction of the deviation.

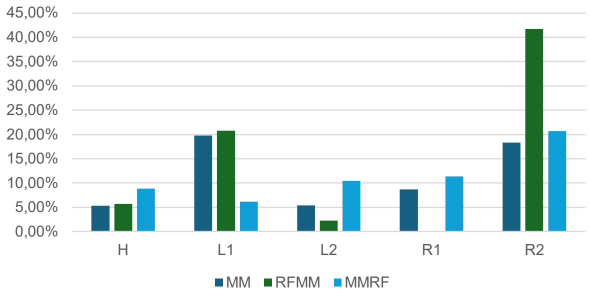

Fig. 5 Absolute sum of deviations per characteristic

It is evident that the various manufacturing methods yield distinct forming results. By calculating the sum of the deviations for each characteristic parameter, it is apparent that, the two-stage production process utilizing metal-metal forming (MM) followed by rubber (pad) forming (RF) in the second step represents forming process chain with the lowest overall absolute sum of deviation.

3.2 Metallurgical analysis

For the metallurgical analysis, the plates are cut at predetermined locations to obtain representative samples. These samples are then embedded in a resin matrix to facilitate handling and subsequently polished to achieve a smooth surface finish. An example of each process combination is illustrated in Fig. 6, with samples extracted specifically from straight channel triplets.

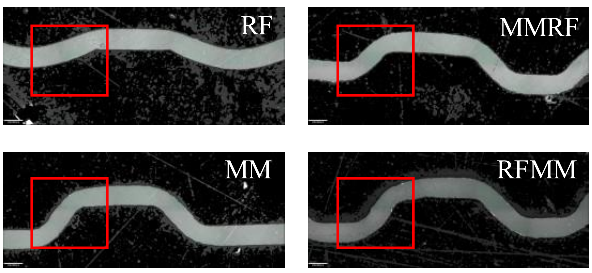

Fig. 6 Cross-Section of the formed metal sheets

To assess the extent of thinning in the samples, the polished specimens are examined using a microscope. This allows for precise measurement of the material's cross-sectional characteristics. The analysis focuses on identifying the thinnest regions within the R1 and R2 areas, thereby providing insights into the material behavior and the effects of the different manufacturing processes on the structural integrity of the formed features. The results were gathered as an average value measured in the central channel of a triplet over three formed plates with the same operating parameters.

Fig. 7 presents the normalized values for the two measurement points associated with each triplet. The

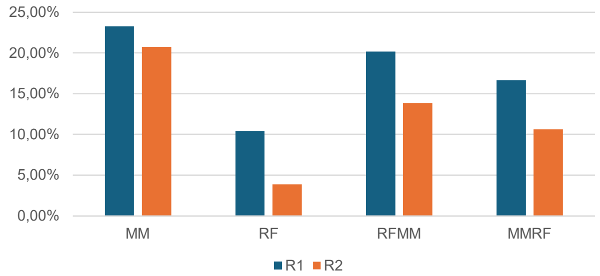

Fig. 7 Thinning percentage of the measured probes at different positions

normalization is using the actual thickness measured at a straight segment adjacent to the triplet, serving as a baseline for comparison. The extent of thinning associated with the rubber forming (RF) process is significantly lower than that observed in the other manufacturing combinations.

This finding is consistent with the deviations reported in the surface examinations and can be attributed to the insufficient forming capabilities inherent in the RF process when utilized independently. The reduced thinning may indicate that the RF process, while effective in certain contexts, does not achieve the same level of material deformation as the other combined processes, thereby resulting in a more favorable preservation of material thickness in the formed features. This highlights the importance of process selection in achieving optimal forming outcomes and suggests that the integration of multiple forming methods could enhance the overall performance in producing components with stringent geometrical and mechanical requirements.

3.3 Quality comparison between the features

The characteristics of channel geometries or features that are particularly important for specific designs must be evaluated on a case-by-case basis, with appropriate weighting. This option for weighting was already integrated into the methodology presented in 2024.
To illustrate how different manufacturing methods influence forming quality, the analysis focuses on the values of channel height (H) and radius (R2). The summarized values are presented in the following figure, providing a visual representation of the impact of manufacturing methods on these critical geometrical characteristics (Figure 8). The analysis includes the absolute sum of the deviations from the target geometry, providing an overview of the forming accuracy. Additionally, values for the three principal features, straight channel, theta bent, and horizontal taper, are presented to facilitate comparison.

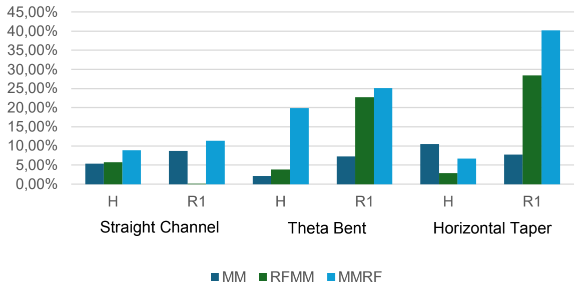

Fig. 8 Feature comparison with H and R1

The evaluation of total deviations shows that for the specific channel structures of both straight channel and theta bent, the two-stage process MMRF results in the most favorable forming outcomes. This indicates that this sequence effectively minimizes deviations from the desired geometry, thereby enhancing the accuracy of the formed features.

In contrast, for the horizontal taper, the single-step MM demonstrates the smallest sum of deviations. This suggests that this process is optimal for achieving the required geometrical specifications of the horizontal taper. Overall, these findings underscore the significance of process sequencing in optimizing manufacturing outcomes and achieving precise geometrical characteristics in the formed features.

4 Results and discussion

The analysis of three distinct triplets revealed the existence of an optimal process chain for producing the specified structure using a particular forming technique or combinations thereof. However, it was also demonstrated that the selection of the ideal forming technique may vary when different features are introduced into the scope of consideration.

This finding supports the hypothesis that optimal forming quality can be achieved by composing a process chain utilizing different forming technologies. It is important to recognize that this composition may require modification in the presence of different geometrical or functional characteristics. The proposed methodology allows for identification of optimized process chains for a diverse array of characteristics and technologies.

The necessity for conducting physical experiments before establishing production technology is significantly reduced, as the process chain can be predetermined with high precision forming simulations. However, the increasing complexity of the integrated production system, characterized by a growing number of tools and partial forming steps has to be considered as it may influence the overall cost effectiveness and quality of the manufacturing process.

5 Conclusions

This study shows that the theoretical framework for feature-based forming, is supported by experimental data. A combination of advanced numerical simulations and designed physical forming tests, conducted within a specialized hybrid tool setup, reveals that the mechanical characteristics of individual channels respond differently to various forming technologies. Additionally, these characteristics can be optimized through a feature-specific combination of processes or forming techniques.

The integration of two-stage hybrid processes with hydrostatic forming significantly reduces material thinning at channel radii, achieving a absolute decrease of up to 10 % compared to single-stage forming methods used in stamping. This reduction is crucial for enhancing the structural integrity and performance of formed components.

The research shifts the understanding of the bipolar plate, as a composite of distinct forming tasks that can be addressed with multi-technology strategies. Furthermore, the findings highlight the potential of hybrid forming technologies to mitigate thinning as a major limitation to BPP quality.

Future efforts should focus on automating this innovative approach to enhance its industrial applicability. A more detailed investigation into the physical interface definitions between the various forming stages is also necessary, as it will provide insights into the interactions and transitions in the hybrid forming process.

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