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A parameter-free strain estimation method to prevent occurrence of splits in sheet forming of complex CAD designs

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Abstract. Early detection of manufacturability issues in the design stage is key to avoid long lead times in product development. For various sheet forming processes a critical issue is the occurrence of splits, due to forming beyond the intrinsic formability properties represented by the Forming Limit Curve (FLC). Nevertheless, within industrial engineering practice a detailed manufacturing process simulation including forming limit prediction is not obvious. While commercial Finite Element analysis tools for sheet metal forming are readily available on the market, because of current limitations in availability of accurate data, companies may be rather inclined to choose experimental verification over process simulation analysis. For formability analysis, the required accurate data comprises both material data (hardening data, plastic anisotropy data, FLC data) as well as process data (e.g. non-linear friction data in lubricated system; static or dynamic tool elasticity properties).Therefore, we propose a first-order approximation of the forming deformation, without any parameter (e.g. for material, friction), based solely on conformal flattening of the CAD sheet surface. In this work, we show the usefulness of this method in hydroforming of complex-shaped, industrial parts (bipolar plates). It is shown that from the strain estimation, we can identify the most critically strained regions for individual categories of strain, as formability is known to be greatly dependent on strain mode. The tooling assists to compare design alternatives in terms of formability in the absence of FLC or even basic material data.

Challenges in Hydroforming of bipolar plates for fuel cells

Polymer Electrolyte Membrane (PEM) fuel cells require an intricate network of fine-mazed channels to guide gasses and coolant in-between sheets of MEA (Membrane Electrode Assembly). As illustrated in Fig. 1, such channels can be realized by bipolar plates, which are manufactured by stamping foils of materials such as 316L and Ti alloys. Common foil thicknesses are (75µm-500µm. The bipolar plate design determines the flow efficiency of gasses and coolant, and are therefore crucial for the fuel cell performance.

One of the commercial production technologies for bipolar plates is Hydrogate™, a continuous hydroforming process that delivers pressures up to 2000 bar, and that has been developed and patented by Borit NV. As all manufacturing processes, hydroforming has specific limits that may be translated in design practice by so-called manufacturing rules; a critical one of these is the occurrence of splits due to local deformation beyond the Forming Limit. However, experimental Forming Limit Curves are typically not available for commercial foils grades, and even basic material data to derive FLCs theoretically (see e.g. review article [1]), is usually lacking. In this industrial context, a strain estimation method for complex parts such as bipolar plates, offers a valuable tool to assess risk of splits.

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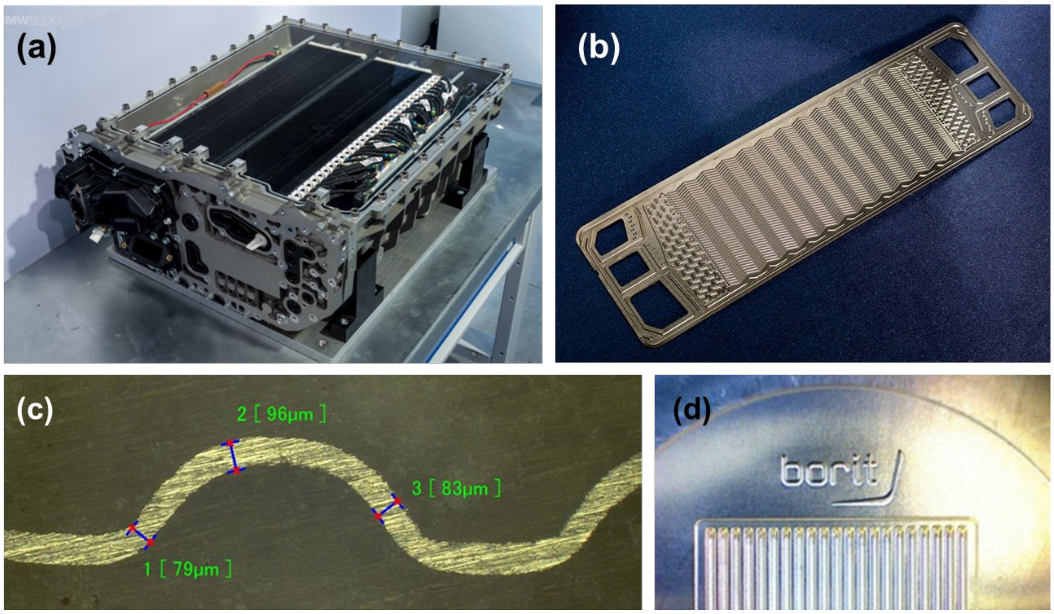

Fig. 1 (a) A fuel cell consists of stacks of (b) metal bipolar plates with intricate designs of channel-like features. Typical dimension: 80mm width. (c) shows a cross-section of these channels. (d) A hydroformed test plate showing the Borit logo and a series of channels.

Fig. 2. The Borit Hydrogate^{TM} process: a continuous sheet and foil hydroforming process by applying water pressure against a single-sided die.

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Strain Estimation by Conformal Projection

Methodology.

Referring to Fig. 3, we use a conformal flattening method [2] to recover the initial position (undeformed state) of discrete points onto the design (final positions). As points, we choose the corner points of a discretized format of the CAD design by triangulation. A conformal map minimizes the angular distortion. The resulting projection has most distortion as areal distortion (scaling). This type of mapping is similar to the deformation in sheet forming processes, which tends to "smear out" the deformation in a homogeneous manner (at least until localization of deformation occurs). The physical link with elastic deformation of sheets is discussed extensively in [3].

Originating from cartography, conformal projection has been originally applied to map the spherical glob onto a (flat) surface. The mathematical principles can be generalized to project points and shapes from any non-flat surface onto a flat surface. In this application within sheet metal plasticity, the undeformed (flat) reference state forms the (a priori unknown) map. It can be shown that conformal projection or flattening is in fact equivalent to minimizing the Dirichlet energy or membrane energy of map $f:\ \mathcal{M} \to \mathbb{R}^{[0,1]\times[0,1]}$:

$$E_{memb} = \int_{\mathcal{M}} |\nabla f|^2 d\mathcal{M} \quad (1)$$

This problem is typically discretized with the Laplace-Beltrami operator, with cotangent weights:

$$\Delta_{\mathcal{M}} f(v_i) = w_i \sum_{v_j \in N(v_i)} w_{ij}(f(v_j) - f(v_i)) \text{ with } w_i = \frac{1}{A_i},\ \mathrm{w_{ij}} = \frac{1}{2}(\cot\alpha_{ij} + \cot\beta_{ij}) \quad (2)$$

with v_i the vertices of $\mathcal{M}$, $N(v_i)$ the 1-ring neighbourhood of a vertex v_i. The vertex area A_i is one third the area of all triangles incident on the vertex and α_{ij}, β_{ij} are the opposing angles of an edge ij. A minimizer of the Dirichlet energy is given by solving the following Laplace problem, as a sparse linear system:

$$\Delta_{\mathcal{M}} f(v_i) = 0,\ \begin{bmatrix} \Delta_{\mathcal{M}} \\ \mathbf{1} \end{bmatrix} [u \quad v] = \begin{bmatrix} 0 & 0 \\ b_u & b_v \end{bmatrix} \quad (3)$$

with b_u and b_v the coordinates of the boundary vertices.

In hydroforming, it is assumed that the (flat) area of the foil that stays in contact with the (flat area of) the die throughout the process does not undergo any deformation, due to the "clamping" action of the water pressure. This flat area can be readily identified numerically and effectively provides boundary conditions for the solution of (1)-(3).

In a next step, from the initial and final positions of the 3 corners of any discrete triangular surface element, the deformation gradient tensor **F** is derived, in a similar way as is common for linear, 3-node shell elements in large-strain continuum mechanics. We assume triangles can be considered small enough so that we can find **F** by solving

$$\mathbf{F}[(u_2 - u_1) \quad (u_3 - u_1)] = [(v_2 - v_1) \quad (v_3 - v_1)] \quad (4)$$

with u_i, v_i vertices of undeformed and deformed state respectively. We can choose the reference frames aligned the triangle normal and the first edge, so that $u_i, v_i \in \mathbb{R}^2$ and $\mathbf{F} \in \mathbb{R}^{2\times 2}$. A polar decomposition of $\mathbf{F} = \mathbf{RU}$ (with **R** unitary and **U** positive semi-definite symmetric) reveals the right stretch tensor. We can find the principal stretches, i.e. the eigenvalues of **U**, by computing the eigenvalue decomposition of $\mathbf{F^T F}$ since, $\mathbf{F^T F} = \mathbf{U^T U}$

This in turn defines the (large-strain) strain tensor $\boldsymbol{\varepsilon} = \mathbf{U} - \mathbf{I}$ with **I** the identity tensor. The tensor $\boldsymbol{\varepsilon}$ is characterized by its principal values, namely the minor and major in-plane strain and thickness strain, together with their respective principal directions (Fig. 3).

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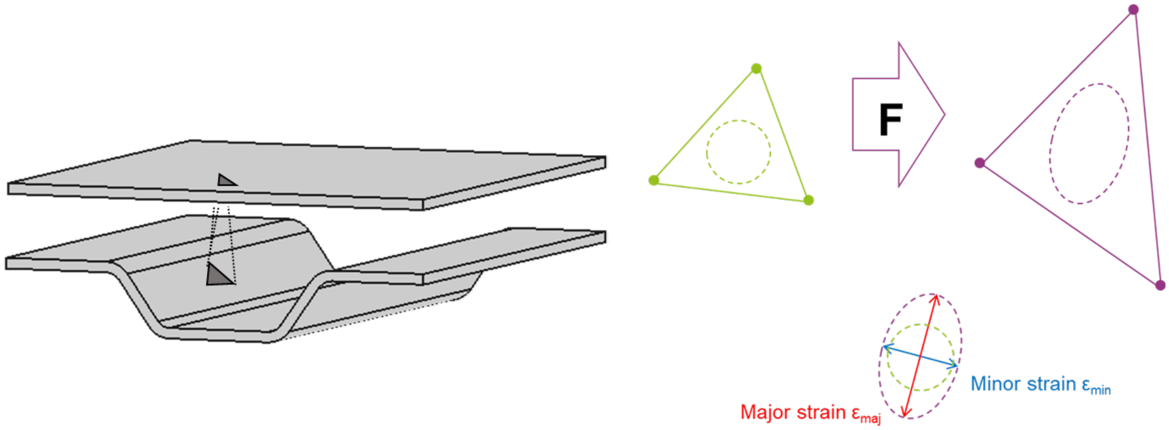

*Fig. 3 (left) Example of the projection of a discrete triangular element from undeformed (flat) state to the side of a channel in the deformed state. (right) This transformation is mathematically described by the deformation gradient tensor **F**, which can be constructed from the initial and final coordinates of the 3 triangle corners. From F, the strain of the triangular element can be derived, characterized by the major and minor strains with their respective principal directions.*

Implementation.
The methodology described above has been implemented as base functions within CameCAD, a prototype manufacturability assessment software tool for CAD designs. As outlined in [4], CameCAD interpretes intricate manufacturing knowledge that has been formalized by the Knowledge Formalization Editor. The KFE is conceived to describe manufacturing knowledge as geometry-based manufacturing rules within a generic formalism, meaning it is conceived to be applicable to *any* manufacturing process for which geometric manufacturing knowledge may be formulated; the strain estimation method as outlined in this paper just being one example among many [5].

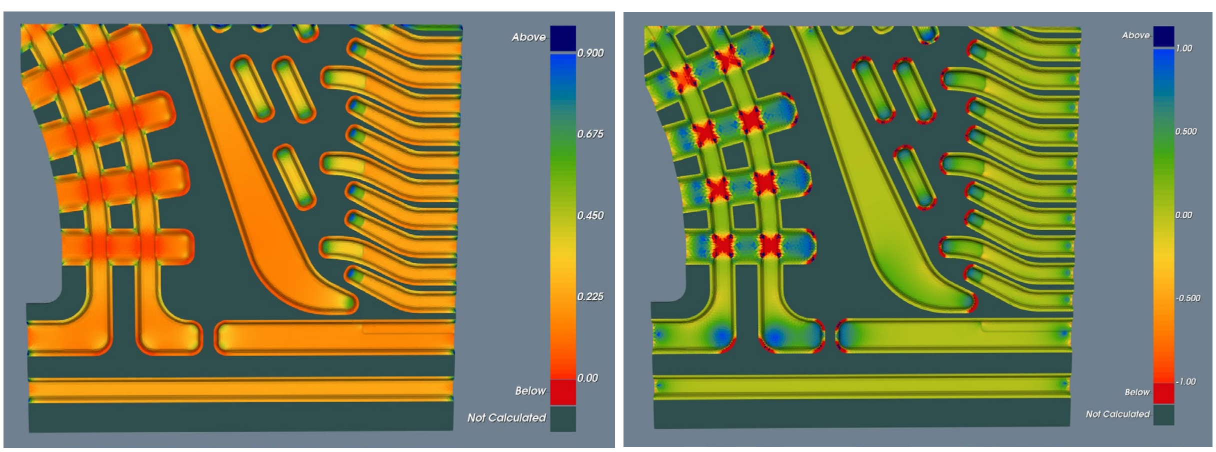

Fig. 4 Example of strain estimation by conformal projection, showing (left) the (dimensionless) von Mises equivalent strain and (right) the (dimensionless) strain mode, defined as the ratio of major over minor strain. The flat, undeformed area is shown here with label "Not Calculated". Plots generated by CameCAD UI [4-5].

The CameCAD User Interface produces, among others, color plots of the described manufacturing knowledge as evaluated over the surface of CAD designs. Fig. 4 shows a result of strain estimate by conformal projection.

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Use Case: Hydroforming Test Die

Experiments

Before ordering a production die suitable for mass-production of a new bipolar plate design, it is safe engineering practice to have try-out tests of the design using a smaller (and cheaper) 'test die', cf. Fig. 5. It is crucial in this practice that the test die features the critical regions of the overall bipolar plate, as missing such feature could result in splits that are noticed only at the start of full-scale production using the production die. It is in this respect that our strain estimation tool provides a practical and insightful engineering check, as is illustrated next with a real-life example of industrial practice.

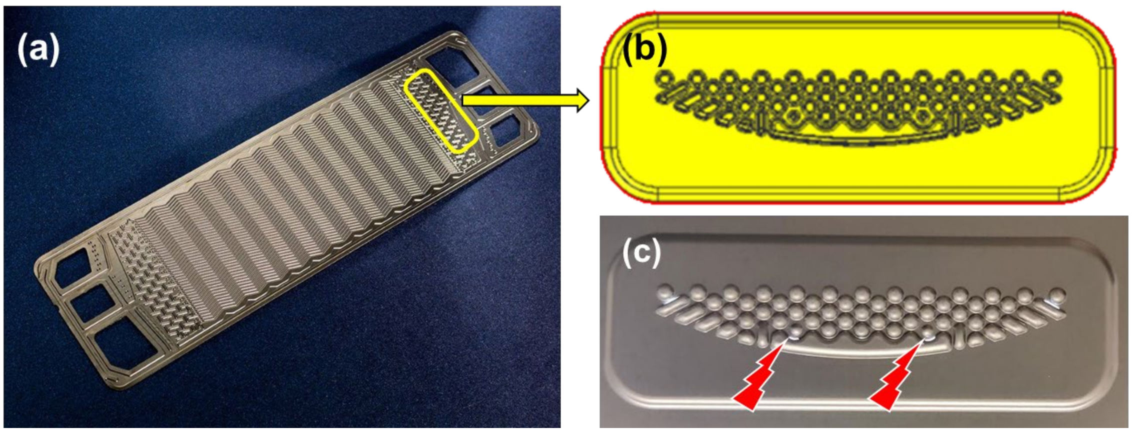

Fig. 5 Out of (a) a bipolar plate, a smaller region is selected for testing in a test die: (b) shows the corresponding CAD and (c) a forming test result with 2 splits.

Thinning estimation to improve the CAD design process

An existing customer to Borit wishes to design a next-generation fuel cell product, in which the bipolar plates are thinner and of a new alloy, in comparison to previous product version. However, preliminary testing with the available test die onto the new material, results in systematic splitting at the locations depicted in Fig. 5(c). This triggers an engineering discussion between Borit and its customer, resulting in 3 alternative design proposals. With the absence of formability data from material supplier, or even basic material data a detailed formability analysis is not an option.

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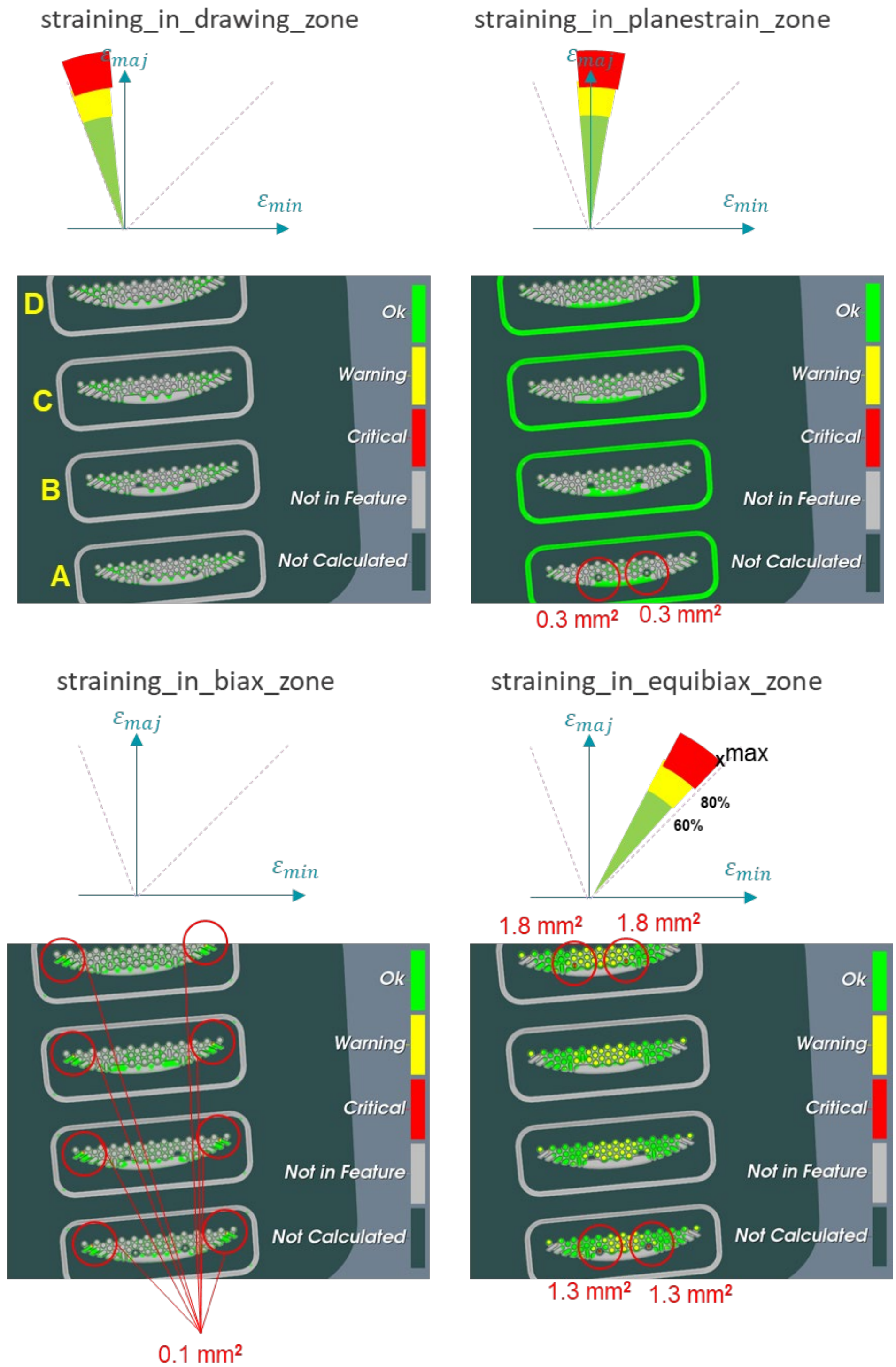

Fig. 6 Simultaneous analysis for the largest-strained regions for original design (labeled A) and 3 alternative test die designs (labeled B, C and D), each within 4 "categories of strain mode". The Forming Limit Diagrams shown indicate the respective strain mode category with colored pie-section (a strain mode category is defined here as a specific range of strain mode between a lower and upper limit). Per strain mode category, the areas that are less than 60% strained of the maximum value are colored green, more than 60% but less than 80% are colored orange, and more than 80% are colored red and are additionally encircled with an indication of the area size, in mm^2. Plots generated by CameCAD UI [4-5].

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In this context, the CameCAD tool provides valuable insights to steer the design selection in terms of manufacturability. Firstly, as Seen in Fig. 6, it confirms that the split location is a highly-strained region under (near-)equibiaxial deformation conditions. Secondly, referring to Table 1, it confirms that the strain level are significantly lower with the alternative designs, which explains why there are no splits observed for these designs. In the end, the most performant design that is manufacturable, is selected.

Table 1: Summary of test die designs, with strain data obtained by CameCAD [4].

Alternative Test Die Designs	*Max. equivalent strain (equibiaxial category)*	*Experimental outcome*	*Conclusion*
A (original)	1.04	Systematic splits (cf. Fig. 5(c))	Rejected: manufacturing issues
B	0.84	Manufacturable	**Selected design**
C	0.75	Manufacturable	Rejected (poor functional performance)
D	0.73	Manufacturable	Rejected (poor functional performance)

Summary

For intricate 3D designs to be manufactured by sheet forming, we propose a strain estimation method on the basis of conformal flattening. Given the limitations in accuracy of predictions, which is to date not yet sufficiently quantified, this methodology nevertheless forms a useful engineering tool in common industrial practice, notably since no material data is required and no process data is needed apart from the CAD design.

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