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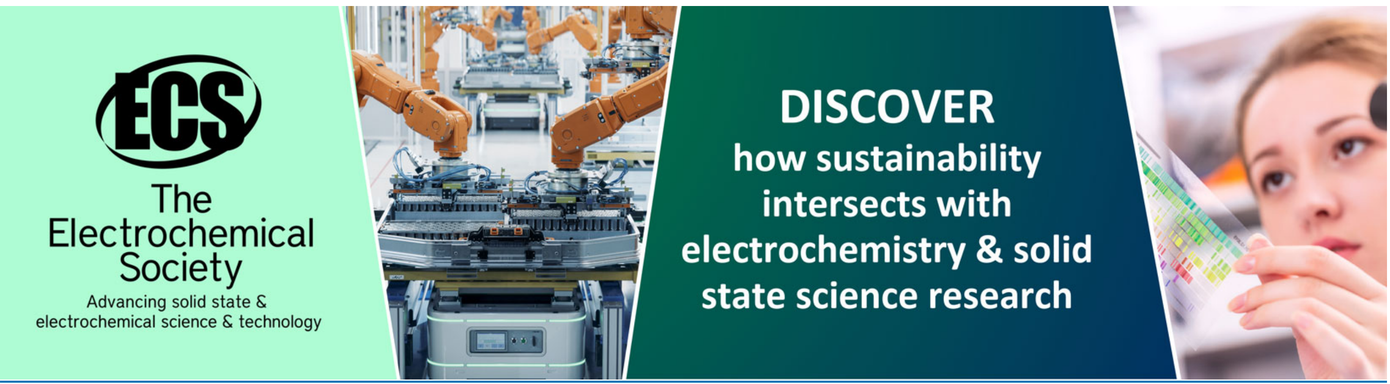

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Development of a Folding Tool for Miuri-Structures

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Abstract. Folding is the process of forming cellular structures out of a flat raw material. This technology makes it possible to create folded structures with high depths and multiple bending axes. Folding is part of technical origami and therefore is defined by:

1. its geometry, which is defined through folding and requires a folding algorithm,
2. the initial material, which has a negligible thickness,
3. the fact that there is no global strain or general plastic deformation in the workpiece.

Current research work focuses on applying this technique to metallic materials with non-negligible thicknesses. Such structures can be used for optical appealing cladding, heat exchangers or core materials of numerous sandwich panel designs. In previous projects with very thin raw materials, it was shown that it is necessary to pre-crease the bending axes on the flat raw material to achieve a defined folding shape. The folding was usually achieved manually. For sheet metal, embossing of grooves in particular appears as a promising approach for pre-creasing. General challenges for folding of sheet metals are the forming of radii and hardening effects on the bending axes as well as appropriate tool concepts for the process.

This paper deals with the development of a forming tool to form a complex Miuri-structure made of sheet metal having a thickness of 0.5 mm or more. In a first step a tool is designed and manufactured that is able to fold a simple zigzag structure with one single bending-line orientation. The folding with this tool is investigated experimentally and based on the observations the zigzag tool concept is enhanced to a structure with a tree bending-line orientated Miuri-structure. This paper shows that a complex bending of sheet metals with non-negligible thicknesses is possible if a proper tooling design is taken into account.

1. Introduction

Folding is the process of forming cellular structures out of a flat raw material just by local bending on defined multiple folding axes. This technology makes it possible to create folded structures with high depths and multiple axes orientations. This technology is originally part of the technical origami. The technical origami is based on the following definitions:

1. A foldable material has a negligible thickness.
2. There is no global strain or general plastic deformation in the workpiece. Deformation only occurs at the folding lines, which is negligible due to a negligible thickness (cf. Definition 1.).
3. The structure is defined through folding and requires a folding algorithm [1].

Current research work at the Institute for Metal Forming Technology (IFU) focuses on applying this technique to metallic materials with non-negligible thicknesses. Such structures can be used for several applications such as visually appealing cladding, heat exchangers or core materials of numerous sandwich panel designs. For the latter, the overall thickness of this core layer with multiple folding axes enables high levels of stiffness with a planar isotropic behaviour, comparable to

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honeycomb structures. Additionally, these cores result in open structures, and therefore, features like ventilation or functional integration can be applied without further machining operations. In Fig. 1, different folding structures with different numbers of major bending axes (MBA) are shown [2].

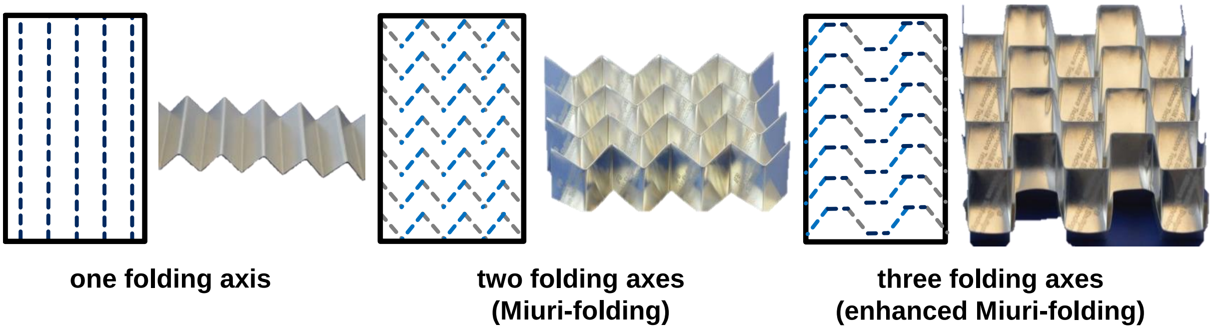

Figure 1. Different folding structures depending on their major bending / folding axes

2. State of the Art of folding processes

Until now, most research projects in the field of folding have focused on raw materials with low levels of thickness and strength such as non-metallic materials like polymers, aramid paper, cardboard, and fiber composites. Very few investigations dealt with sheet metal applications like pure aluminum / aluminum alloys with a maximum thickness of t = 0.2 mm – 0.6 mm [3,4] and steel sheet metal alloys having a thickness below 0.1 mm. In the works of Gattes et al. [3], different dies for gradually processing a 2-MBA structure are considered. However, this procedure is not a real folding process, because there is not only a bending at the bending axes, but also a stretching in the planar area of the cell. Schenk et al. [4] perforated two blanks along their bending axes (Fig. 2 (a)) in order to prescribe position of the bending axes and to reduce local bending forces. In this case, spacers were aligned manually along the perforated bending axes between both blanks (Fig. 2 (b)). Using a vacuum (Fig. 2 (c)) both blanks are then folded by twisting the aligned spacers (Fig. 2 (d)). This process provides good results with regard to the structural shape, but only materials having low yield strength levels are suitable for being folded in their manner.

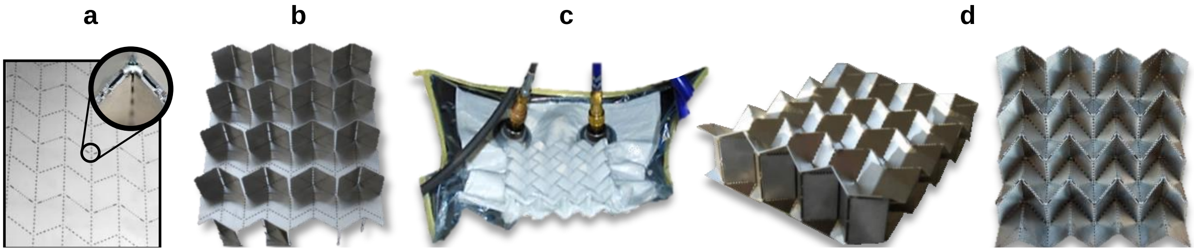

Figure 2. (a) Pre-crease by shear cutting; (b) alignment of spacers; (c) folding by evacuation; (d) folded structures with twisted spacers [4].

A two-stage manufacturing process is considered to be the best solution for to bring a folded core into effect. In the first step, the folding axes are defined (the so-called “pre-creasing”) by a local reduction of the bending stiffness along the axes, in the second step, the structure is folded. For the first stage, different manufacturing technologies like embossing, beading, perforating e.g. by shear cutting, milling, etc. are applicable [5]. Klett [6] describes the analytical, kinematic relations of the geometry parameters of the folded structure to each other, which are given in Equation (1) to (3). These equations may be used for the definition of the geometrical run of the pre-crease of blank. Fig. 3 shows the parameters for a single 2- and 3-MBA structure.

There are different challenges for folding sheet metal, like the forming of defined bending radii, the hardening effects along the bending axes, and the design of an appropriate, novel tool concept. In Schneider and Liewald [7], a FEA for mono cells was conducted to investigate the folding behaviour of specimens which have embossed pre-creases. In this paper, triangular embossing shapes showed the most promising results regarding bending radii and hardening along the bending axes. In a further step, it is necessary to develop a new tool concept in order to fold entire cell structures, not only mono cells.

$$V(H) = \frac{L_0 \cdot V_0}{\sqrt{L_0^2 - H^2}} \quad (1)$$

$$S(H) = \frac{\sqrt{L_0^2 \cdot S_0^2 - H^2 \cdot (S_0^2 + V_0^2)}}{\sqrt{L_0^2 - H^2}} \quad (2)$$

$$L(H) = \sqrt{L_0^2 - H^2} \quad (3)$$

V	length of the front rectangular of a 2-MBA cell
S	width of half a 2-MBA cell
L	length of half a cell
H	height of cell
B	width of the centre part of a 3-MBA cell (const.)

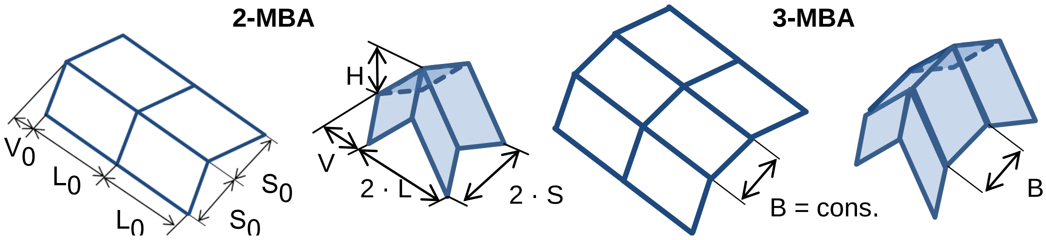

Figure 3. Fold kinematics of a 2- [6] and 3-MBA mono cell

3. Definition of cell geometry and tool concept

A major challenge of forming a Miuri- or a Miuri-like-structure (cf. Figure 1) is that the structure cells move (linear / rotational) relative to each other during the forming process. Due to this movement, a single rigid tool shape cannot be used. A promising approach to find suitable tool concepts is to have multiple tool components, which have limited and defined degrees of freedom (DOF) for their movement. For such a tool, the workpiece itself could serve as part of the tool. By folding the workpiece, it constrains different tool part movements in a defined manner and therefore ensures proper shaping of the folded core structure.

The different folding structures according to Fig. 1 show different edges, which can be used for an application of a bending force and therefore for bending. These edges exhibit different kinematics during the folding process and thus they have different degrees of freedom (DOF). In Fig. 4, the folding structures of Fig. 1 are pictured with a focus on their edges. The edges of the three different cell types are arranged by their DOF. Five different types can be identified, and corresponding DOF are listed in Table 1. With N (DOF) = 4, Type III and V have the highest number of DOF, which makes such a tool solution more complex and hence not suitable. Type III has N (DOF) = 3, but also a rotational DOF, like Type III and V. In this case the tool parts, which apply requires bending force onto the blank, move translationally to each other and rotate in the same time. Therefore, these parts collide easily with each other. To avoid such a collision, such tool components theoretically might have no dimension i.e. negligible thickness. But for the transmission of the required bending force, a certain thickness is necessary. Due to these arguments, a tool solution with rotating parts should be avoided. Taking edge Type I and II into account, Type I seems more beneficial due to only two degrees of freedom. For a single 1-MBA cell, folding by applying a force at Type I edges leads to good results (cf. Fig 4 b top) [7]. However, for multiple cells this approach reaches its limits. If a force is applied at this edge in x-direction, edge Type II has no defined path in z-direction, which leads to an uncontrolled overall bending of the structure (cf. Fig. 4 b bottom). To avoid such behaviour, further tool kinematics are necessary and results in an even more complex tool design. Therefore, in this study a tool was designed being capable to apply local bending forces according to edge Type II.

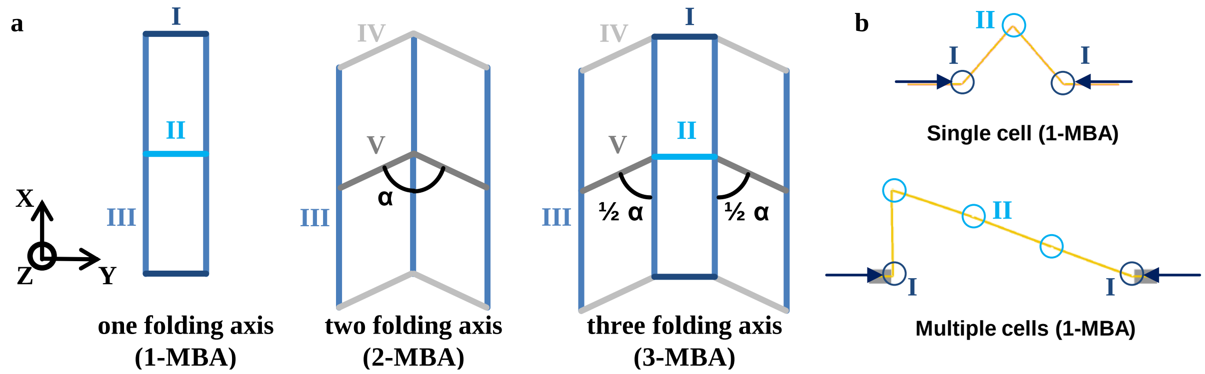

Figure 4. a) Edge configurations for different cell types and b) bending force / folding induced at Edge Type I for single and multiple 1-MBA cells.

Table 1. Degrees of freedom for the folding cell edges (cf. Fig. 4).

Edge Type	f_trans[1] x-axis	f_trans[1] y-axis	f_trans[1] z-axis	f_rot[2] x-axis	f_rot[2] y-axis	f_rot[2] z-axis	N (DOF)
I	+	+	0	0	0	0	2
II	+	+	+	0	0	0	3
III	+	+	+	0	+	0	4
IV	+	+	0	0	0	+	3
V	+	+	+	0	0	+	4

[1]f_trans: degree of freedom for translational movement
[2]f_rot: degree of freedom for rotational movement

Having non-rotational edges is the most important advantage of 3-MBA cells, which is an advantage for the corresponding tool design. From the production engineering point of view, another advantage is the angle α (cf. Fig 4 a). In a 3-MBA cell this angle is split, therefore the adjacent edge can only be bent to max. 90° degrees. Due to the missing middle part in a 2-MBA cell, this value can reach max. 180° degree, but this high bending angle unfortunately may induce failure during manufacturing.

4. Development and design of the folding tool

The fundamental design of the developed tool concept is based on the idea that the workpiece itself should act as a functional component of the tool and moves the different tool parts to a certain degree. Realized tool parts show a prismatic shape at the end and touch the Type II edge of the blank with their apex. The prisms are mounted on guide pillars, which enable only movements in the x- and y-direction. The movement in the z-direction is defined by the stroke of the press ram. Furthermore, the top and bottom prisms are placed on a lubricated plate. The blank has to be fixed to the outer bottom prisms to enable the pulling of the tool components by the blank. For the tools presented in this paper, the fixture was applied by the use of screws. These screws press the blank to the outer prisms and work as clamp.

For the experiments, a steel (grade: 1.0312 (DC05); Tensile strength: 300MPa) having a thickness of t_0 = 1.0 mm was investigated. The bending edges are pre-creased by a triangular shape embossing

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(angle: 90°; depth: 0.5mm). At the corners of the bending edges, holes with a diameter of 2.3mm are shear cut prior to the folding process. The dimensions for the structure are L_0 = 35mm, S_0 = 26mm and B = 25mm. No lubricant was used for folding the blanks.

4.1. Folding tool for a 1-MBA-cell structure
At first, a simplified folding tool concept was utilized in order to perform fundamental investigations. Therefore, a 1-MBA-cell or rather a zigzag structure was manufactured having two DOF in the x- and z-directions. In Fig. 5 the built tool is shown. 5 prisms are positioned on the bottom plate aligned to simple guiding pillars and 4 at the top plate. Between prisms and plates lubrication grease Nigrin 74145 is applied. All prisms have a size of 25x360x75mm with an angle of 45°. They are adjusted to guide pillars, which allow a movement of prisms solely in x-direction, the initial distance of the prisms is d_0 = 45mm. The bottom plate is placed on the press table and the upper plate is assembled to the press ram. In stage 1 – 3 of Fig. 5, the blank (highlighted in white) is pushed down by the upper prisms. The flanks of the workpiece between the bending edges stay flat and pull the prisms at the top and bottom side towards each other. In the next section, the tool concept is enhanced by including a y-axis to form also 3-MBA structures.

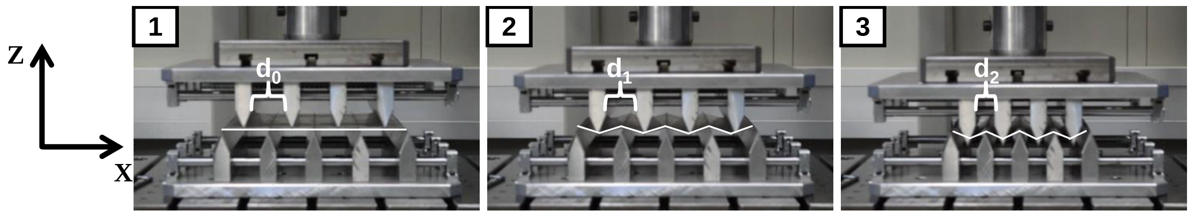

Figure 5 Prototype tool for a 1-MBA / zigzag structure folding induced at Edge Type II.

4.2. Folding tool for a 3-MBA-cell structure
The second tool is designed to fold a 5x5 cell structure (5 cells in width, 5 cells in length). In Fig. 6, the tool is pictured. In the x-direction, 6 prism lines are placed on the lower and 5 prisms lines on the upper tool side. The outer prisms of the lower tool side have a flat area each with tapped holes for M8 screws. Above these areas, small rectangular plates are placed, which can be fixed with a screw to fix the blank and the outer prisms to each other. In the y-direction, the prisms are not aligned in same direction. Due to the kinematics in the y-direction, only line A, C and E are oriented in one line, directions B and D are slightly shifted. Only some of the prisms are adjusted to each other by guide pillars in the y-direction.

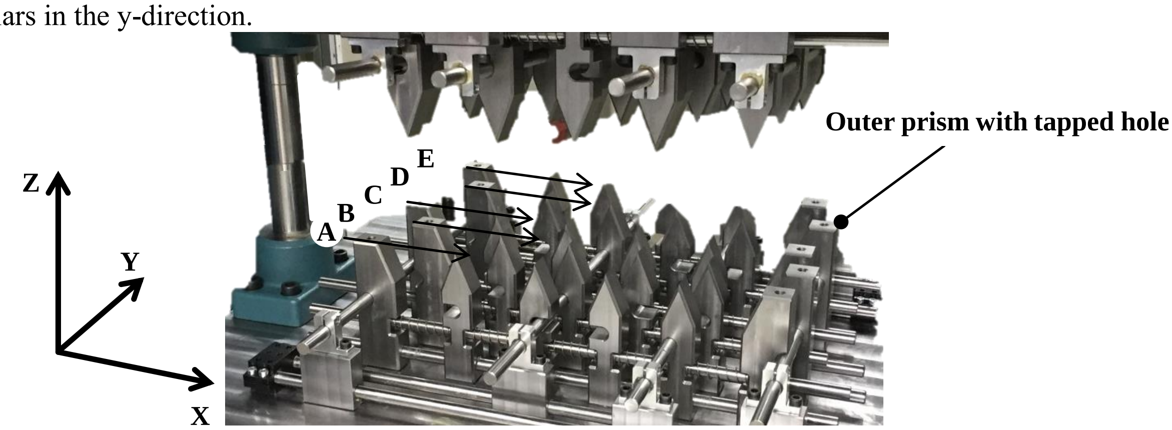

Figure 6. Prototype tool for a 3-MBA structure with marking of the prism lines in y-direction.

The achieved dimensions and shape quality of the fold structures manufactured by this tool design look promising. The prisms move to a certain folding depth as this depth is defined by corresponding

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DOF. A folding depth of about H = 18mm ($H_{max} \approx$ 31mm) was achieved, at which point the workpiece failed near a bending edge due to strong contact and tension conditions at one of the prisms. This failure was caused by the fact that not all prisms slide perfectly. A folding depth of t = 25mm should be possible in the near future after tool optimization. Fig. 7 shows two parallel folded workpieces after folding.

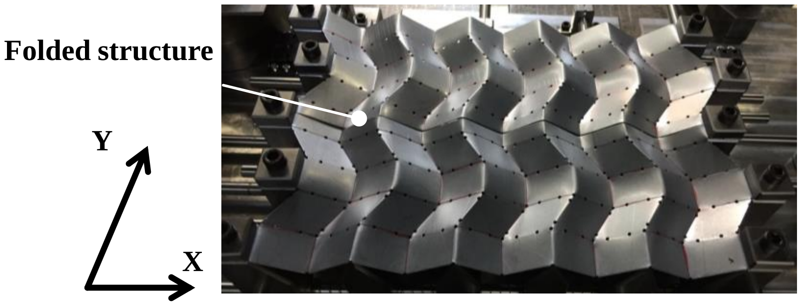

Figure 7. Folded 3-MBA structure after folding process (still fixed to the tool).

5. Summary and Outlook

In this paper, the development of a folding tool is presented. The concept of the tool is that the workpiece itself is part of the tool and its movement. First, the bending edges of the different folding cells were evaluated with regard to their suitability to apply a suitable bending force and thus a bending moment during the folding process. The selected bending edge was determined by analyzing the possible versus required DOF in order to keep the tool design as simple as possible. Bending forces are induced by prismatically shaped tool parts, which are restricted to their DOF by guide pillars. With the first tool design for folding a simple zigzag structure, an enhanced tool concept was developed. By means of a second tool construction, the concept was enhanced to a 3-major bending axes (MBA) structure, which needs a more complicated design of guide pillars in two different directions. The folded structures showed that the concept is suitable to fold / to bend structures made of sheet metal having a blank thickness much higher than the current / bend state of the art [4].

In the next step, the tool has to be improved with regard to its sliding abilities between guiding pillars/prisms and tool plate/prisms. Furthermore, the pre-crease design should be optimized. So far, the structure is tearing near embossing areas, where the material already shows high strain values and is probably damaged due to embossing. Therefore, heat treatment of workpiece between pre-creasing and folding might improve the folding depth as well.

In the further outlook, the gained experience should be taken into account for the development of a continuous folding process, e.g. by rolling, to enable a continuous production of folded structures.

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