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12.4 Resource-saving manufacturing of more dimensional stiffened sheet metals with high surface quality and innovative lightweight products

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Abstract
Vault-structured sheet metals are produced in a unique material and surface preserving way. Hexagonal structures evolve instantly and energy-minimized with lowest strain hardening when a curved material is partially supported and loaded with very low external pressure. Synergetic properties are a reduced weight by increased rigidity, reduced droning of vibrating components, increased thermal stability by avoiding wrinkling (e.g. by welding heat), enhanced crash-energy absorption, large reserves for secondary forming, and preserving of initial surface qualities. Structure conform secondary forming techniques are invented and realized such as a bending technique with additional enhanced rigidity and fine structures for joining with quasi planar edges.
Exemplary vault-structured light weight products are an automotive catalyst cylinder made of stainless steel (Emitec), aluminium back-panel (Daimler SLK), demonstrator of a vault-structured perforated sheet metal which is deep drawn to a 3D-shape (Graepel), coiler plate “CLEANcoil” for spinnery machines (Rieter), Miele washing drum and a vault-structured façade (Manhattan, USA) made of perforated stainless sheet metal.

Keywords:
Energy-minimization; Hexagonal structures; Lightweight products; Self-organization; Vault-Structuring

1 INTRODUCTION

In addition to reduced weight, innovative lightweight components often need to fulfil further requirements such as surface quality, acoustic properties and high crash energy absorption. Preferably these products should be manufactured with improved resource efficiency.

The stiffening of sheet materials is usually accomplished by conventional forming operations such as rolling, embossing, and hydroforming (Figure 1).

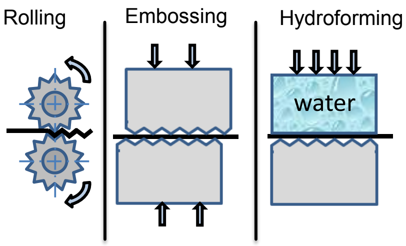

Figure 1: Conventional forming operations for production of stiffened secondary design elements (e.g. structures)

These conventional forming techniques can result in several disadvantages:

- The material is highly plasticized and partially thinned.
- A large work hardening of the material allows only low deformation degrees for secondary forming as well as low crash energy absorption.
- Large forces during forming operation lead to significant energy consumption.
- The surface quality is often affected by tool contact.

One approach in the design of sustainable products is to transfer evolutional principles of nature into technical applications. The comparison of the traditional technical way (Figure 2, top) of producing products with the biological way (Figure 2, bottom) for producing similar products demonstrates the potential of learning from nature.

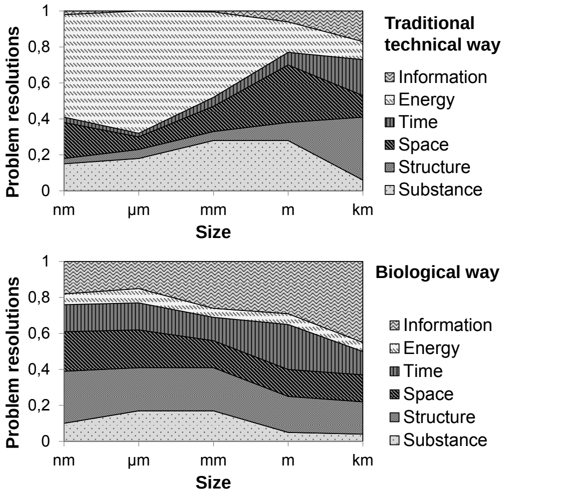

Figure 2: Problem resolutions (e.g. resources) according to size (product) by traditional technique and biological way [1]

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Following question can be asked: “How is it possible that processing learnt by nature is usually much more sustainable and beneficially utilized than traditional technical processing?” As shown in figure 2 for products generated by the biological way the substance is reduced approximately to 50% and at least only 1/10 – 1/20 of the energy consumption is needed. Here the “Structure” and the “Information” which can be interpreted as the intelligence to generate the structures play a significant role.

That is a great stimulation and challenge for technical processes to learn from the biological way. Nature reveals that it is possible to generate highly stiffened structures with little plastic deformation of the material without tool dependent forming operations. Thereby the principles of self-organization and energy minimization play a decisive role. Paul Green [2] has shown in his fundamental work that stiffening macrostructures such as plant or animal shells can be traced back to physical principles of self-deformation of thin plates or shells (Karman equations). During growth of plant or animal shells compressive stresses are built up in membrane direction which leads to instabilities. By overcoming these instabilities new stiffening structures evolve ("buckling propagation" [2]). In industrial technology, usually no growing materials are available. The Dr. Mirtsch Wölbstrukturierung GmbH has traced a different path to generate compressive membrane stresses with resulting stiffening structures: a partially supported, curved sheet material buckles to staggered structures when a moderate external pressure is applied. Thus, a multidimensional stiffening of thin materials of different kinds can be achieved. The buckling process with a commonly negative interpretation receives here a different significance.

2 VAULT - STRUCTURING TECHNIQUE

2.1 Basic process and further development of the Vault – Structuring Technique

The basic process of vault-structuring is based on a self-organized buckling phenomenon (Figure 3) of a pre-curved, thin-walled material [3]: A supporting spiral serves as a "tool". A thin-walled cylinder is put over the spiral so that the spiral is in contact with the inner face of the cylinder. By applying a comparable low external pressure quadrangular staggered structures evolve spontaneously and energy minimized. The approximately horizontal structure folds are generated by forming against the supporting spiral. The vertical folds however evolve by themselves without an underlying tool contact.

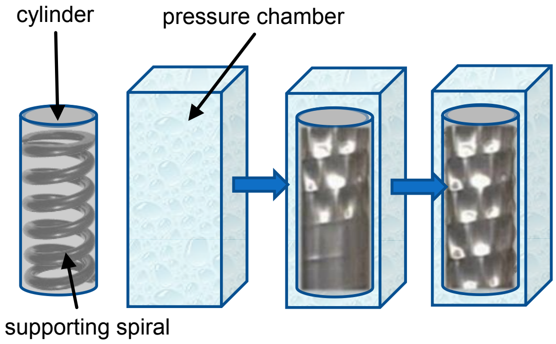


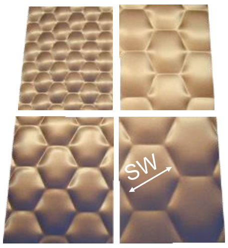
Figure 3 : Basic Vault-Structuring process with rectangular structures

This forming process is particularly gentle on the material because the resulting structure depth is mainly generated by dominant compressive membrane stresses with additional moderate bending stresses. In that way material thinning doesn’t occur. Additionally the energy consumption to generate the structures is drastically reduced compared to conventional forming (e.g. embossing) of structures.

A rectangular structured cylinder shows after straightening to a planar sheet one significant disadvantage: In the direction of the previously horizontal folds the bending stiffness is increased; in the transverse direction however the bending stiffness is low (similar to corrugated card board).

Using a supporting spring, which is not rigid but slightly flexible, a more complex self-organized structure formation occurs: At first (at very low pressure) the self-organized forming process is initiated. Afterwards the approximately horizontal structure folds develop by themselves to “zig-zag” shaped structure folds, resulting in the hexagonal vault-structures of the Dr. Mirtsch Wölbstrukturierung GmbH. Simulations of Prof. Böhm (Institute of Mechanics, Technical University of Berlin), indicated that compressive membrane forces spread out from the structure folds in the direction of the structure moulds. In this way the material obtains gentle force flows both during the structuring process itself as well as during the utilization phase of the component. These hexagonal vault-structures result in a more uniform bending stiffness in different directions than the rectangular structures.

The vault-structuring process of thin walled cylinders is limited to few applications, because large sheet panels and coils are often required. Additionally, slightly irregular structures caused by material inhomogeneities can occur when the basic vault-structuring process is applied. Therefore research and technical implementations were carried out to invent and realize a semi-continuous or continuous vault-structuring process to produce sheet panels and coils with exactly uniform structure geometry (contour of the hexagonal structure in top view). The process of structure formation is here assisted by partially acting, corrective supporting elements. Standard vault-structures for sheet metals or coils with different structures widths (SW = wrench size of the hexagon) of Dr. Mirtsch Wölbstrukturierung GmbH are shown in Figure 4.



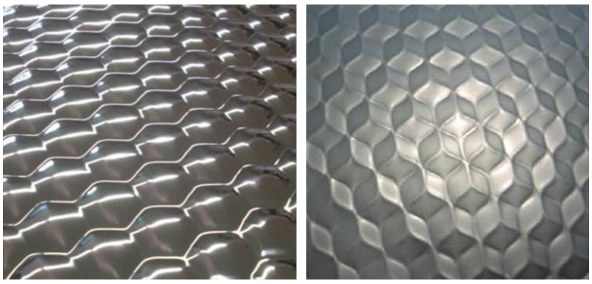
Standard Structure Width (SW):
SW 17; SW 33; SW 40; SW 50

Maximum wall thickness:
Steel: up to 1,0 mm
Aluminium: up to 1,2 mm

Maximum Dimensions:
Plate: 4.000 x 1.200 mm (l x w)
Coil width: up to 1200 mm

Figure 4: Standard vault-structures of Dr. Mirtsch Wölbstrukturierung GmbH

As further developments of vault-structures Dr. Mirtsch Wölbstruktureierung GmbH invented the structure types WaveHex® and MiCubix® (Figure 5).



WaveHex® MiCubix®

Figure 5 : Vault-Structures WaveHex® and MiCubix®

WaveHex® is characterized by particular smooth curves in the structure folds (waveform). Thus, the local plasticization in the structure folds is further reduced. The spatial facet structure MiCubix® is – compared to the hexagonal vault-structure – arranged with three additional folds for every single structure. The result is an optical appearance of regularly arranged 3D-cubes. The bending rigidity is more homogeneous in different directions compared to the hexagonal vault-structures.

2.2 Material spectrum of vault-structures

Vault-structures are applicable to a wide range of materials (Figure 6).

Metals Polymers/ Fibre reinforced plastic Paper/Cardboard

Figure 6 : Spectrum of vault-structured materials

Vault-structures can be applied on all thin walled metals such as steel, stainless steel, aluminium, titanium, magnesium or platinum. As part of a funded project (funding by the German Federal Ministry of Education and Research) [4] numerous studies on vault structuring and secondary forming of perforated sheet metals were conducted in close cooperation with the project partner Friedrich Graepel AG. Perforated sheet metals allow only comparable small degrees of deformation, since the notch stresses in the bars (between the holes), can rapidly result in fracture. Since the vault-structuring process is very gentle, even perforated sheets with very large free cross sections (up to 80%) and thus very thin bars can be vault-structured. Vault-structured perforated sheet metals with a high rigidity at low weight may be used as semi-finished products for several applications.

The preserved formability of vault-structured perforated sheet metal allows a secondary forming to 3D-shaped components [4] (Figure 7). Additionally fibrous materials like paper/ cardboard and fibre reinforced plastics can be stiffened by vault-structures even though their formability (especially the elongation) is very limited [5] (Figure 6).

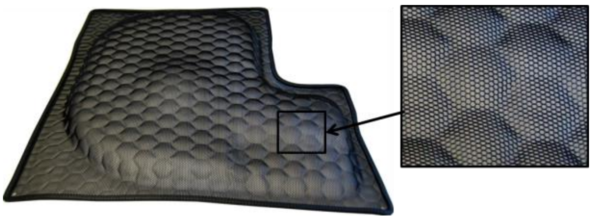


Figure 7 : Demonstrator of a 3D-shaped, vault structured, perforated sheet metal (Graepel AG) [4]

3 PROPERTIES OF VAULT-STRUCTURED MATERIALS

Vault-structures advantageously enable synergetic properties for sheet materials. In addition to the increased bending and buckling stiffness further synergetic performance characteristics occur:

The increase of bending stiffness and consequently the material savings potential can be quantified by 3-point bending tests. The deflection of the sheet metals and the corresponding forces are shown in the diagram of Figure 8. Compared to the unstructured sheet metal of same grade, and wall thickness, the bending stiffness of a vault-structured sheet in the preferred direction (corresponds to the zig-zag direction of the hexagonal folds) is up to seven times higher (stiffness factor). Perpendicular to the preferred direction the stiffness factor is about ½ or ⅓ compared to the preferred direction. A comparison with conventionally structured sheets (Knobbed) shows that the bending stiffness of vault-structures is increased in the preferred direction by a factor of approximately three (Figure 8). This ratio turns out even more positive for the vault-structures in case of high strength and brittle metals, because by conventional embossing only significantly shallower structures (with less increased bending stiffness) can be produced compared to the gentle vault-structures.

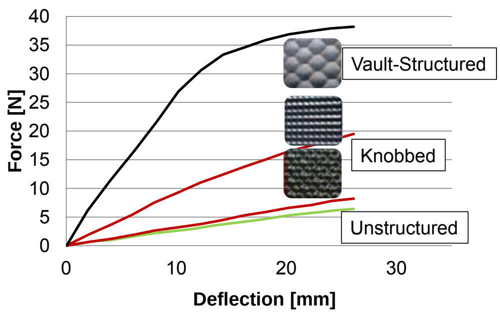


Figure 8 : Results of 3-Point-BendingTests (Steel DC04)

To quantify the local plasticisation in vault-structures a correlation of local Vickers-hardness and elongation (obtained from tensile test) was used. Due to the strain hardening during forming, the Vickers-hardness increases with larger strains. A boundary for the minimum and maximum local Vickers-hardness/ plasticisation is obtained by the Vickers-hardness of the unstructured sheet metal (no deformation; lower horizontal green lines in Figure 9) and the Vickers-hardness of the unstructured sheet after fracture in the tensile test (maximum deformation, upper horizontal red lines in Figure 9). A stainless steel sheet metal with embossed hexagonal structures of a competitor was used for the comparison of vault-structuring and embossing relating to plastic deformation. A vault-structured stainless steel sheet metal of the same thickness and material grade was manufactured with an equivalent structure depth for comparability. For both types of structured materials, the Vickers-hardness distribution was measured several times (HV 0.2) along the paths A and B (Figure 9). The averaged values are shown in the diagrams of Figure 9. For both types of structures the maximum Vickers-hardness occurs in the region of the fold and a local maximum in the region of the mould. For the embossed sheet metal, however, approximately 85% of forming reserves are already locally used, in the case of the vault-structured sheet only about 30% of the forming reserves are locally used [6]. It is shown that vault-structured materials preserve large reserves of formability which can be used for secondary forming operations, crash energy absorption or as a reserve for fatigue strength.

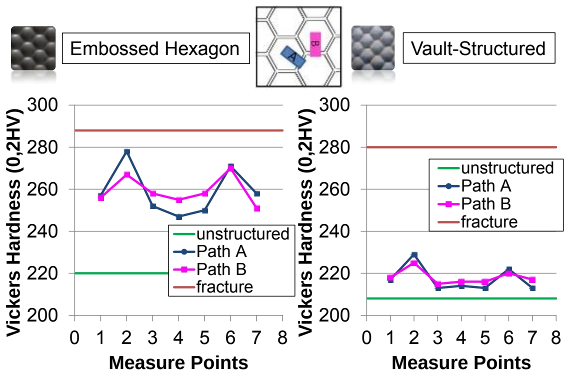


Figure 9 : Distribution of Vickers hardness of vault-structured and hexagonally embossed stainless steel sheet metal

Further synergetic properties of vault-structured materials which enable additional customer benefits are described below:

Reduced clanking and droning of thin-walled components: In vault-structured materials the low eigenfrequencies caused by acoustic excitation are shifted to higher frequencies compared to the unstructured materials. Additionally vault-structured materials also exhibit an increased logarithmic decrement, so that an acoustic vibration is much faster fading out compared to an unstructured sheet metal, as experimental studies have shown.

Preservation of surface finish: Raw materials can be economically coated with a functional layer (e.g. painting, anodizing) before the vault-structuring process. The gentle forming process doesn't reduce the surface quality.

Quasi glare-free light reflection: Used as a light reflector, each vault of the vault-structures acts as a small, curved mirror so that a diffuse, glare-free light is reflected (used in product: Hexal Lamp by Osram former Siteco).

Improved heat and mass transfer: The liquid flow over a vault-structured wall results in an alternating flowing of the boundary layer of the fluid resulting in improved heat and mass transfer of 50% to 90% in comparison to the unstructured wall. Since the vault-structures have got no sharp edges and further more the mean hydraulic flow cross-section of the pipe or channel is constant on all cross-sections (due to the evenly staggered arrangement of the structures), the pressure loss compared to the unstructured wall increases only comparatively moderate. In that way advantageous properties for apparatus of the heat and mass transfer, concerning heat or mass transfer performance, pumping energy, material costs and weight saving are generated.

4 FURTHER PROCESSING OF VAULT-STRUCTURED SHEET METALS

Vault-structured materials sometimes require a modified processing technology, so that the beneficial synergetic properties are preserved. For that reason the Dr. Mirtsch Wölbstrukturierung GmbH attaches significant importance in structure conform as well as material and surface preserving secondary forming processes. An important feature of the vault-structure conform secondary forming process is a substantially isometric deformation, which means that surface area before and after the secondary forming operation is quasi unchanged.

The 3D-contour of vault-structures is not obtained by increasing the surface area (which would result in partial thinning of the sheet metal), but by geometrical gathering, which means that surface area remains basically unchanged with no thinning of the material thickness (Figure 10, left). For secondary forming of vault-structured materials it beneficially needs to be ensured that in the areas of secondary forming an equivalent geometrical gathering is achieved as in the remaining areas. In this way, disturbing residual stresses and instabilities due to differences in lengths between the secondary-formed and initial areas of a vault structured material can be avoided.

4.1 Fine-Structures for Joining

A common requirement for the application of vault-structured sheet materials is the integration in existing constructions especially the joining in the edge regions. To design quasi planar edge regions the vault-structure conform fine-structures were developed and tested. The fine-structures are adapted to the geometry of the vault-structures in a way that a) the geometrical gathering of both structure types is quasi equivalent and b) the heights of the fine-structures is very small compared to height of the vault-structures (Figure 10, right). A simple local flattening of the edge regions of a vault-structured sheet material is not applicable. Local flattening of the vault-structured material would result in uncontrollable residual stresses and distortions caused by local geometrical stretching. Figure 10 (right) shows an example of fine-structures with a structure height comparable to the thickness of the initial sheet material.

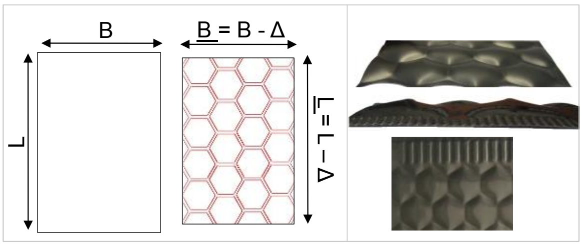


Figure 10 : Geometrical gathering of a sheet material by vault-structuring (left) and fine-structures on the edge region of a vault-structured sheet metal (right)

4.2 Bending Technique „BendHex“ for Vault-Structures

If conventional bending technique (with straight bending edge) is applied to vault-structured sheet metals, residual stresses and unwanted distortions can appear. The reason is - analogue to the local flattening of vault-structured sheet metals (see par, 4.1) – due to resulting length differences of the structured areas and the locally flattened and straightened bending edge.

A new vault-structure conform bending technique "BendHex" was developed and invented by Dr. Mirtsch Wölbstrukturierung GmbH. The curvy bend edge is designed in a way so that a) quasi no differences in lengths between the vault-structured area and the area of the bending edge occur and b) the shape of the bending edge is generated in a comparably material preserving manner (Figure 11).

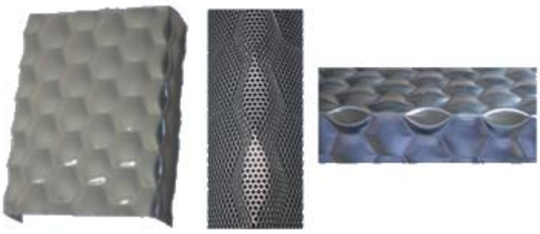


Figure 11 : Vault-structure conform bending technique “BendHex” of Dr. Mirtsch Wölbstrukturierung GmbH

Studies (experimental and FEM) have shown that the bending technique "BendHex" additionally results in a significant stiffening of the bending edge compared to conventional straight bending edges. This new bending technique can be applied on conventional bending machines equipped with special, patented bending tools (development and distribution by Dr. Mirtsch Wölbstrukturierung GmbH).

5 PRODUCTS WITH VAULT-STRUCTURES

Vault-structured products are applied in various industrial sectors. Preferably the product is enhanced by several synergetic properties of the vault-structures to increase the customer’s benefit.

5.1 Products in automotive applications

The lightweight catalyst of Emitec is equipped with vault-structures resulting in a reduction of wall thickness and thus weight reduction (Figure 12). Due to the vault-structured stainless steel cylinder a) the bending rigidity is improved (compared to cylinder with equivalent wall thickness) and b) mechanical stresses caused by rapid changes in temperature loads and thermal shocks are significantly reduced.

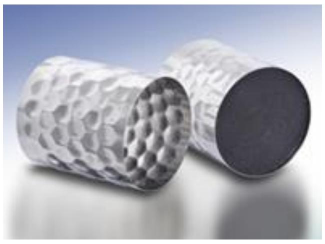


Figure 12 : Lightweight catalyst (Emitec)

The back-panel of the roadster SLK (Daimler) is equipped with vault-structures (Figure 13). The Dr. Mirtsch Wölbstrukturierung GmbH manufactures the pre-cut vault-structured sheets made from aluminium coil, which are pressed to the finished back-panel in a secondary forming operation (Gestamp). In addition to material savings the synergetic properties are a better acoustic damping behaviour and a reduced installation space needed.

Figure 13 : Back-panel of SLK (Daimler)

5.2 Product in process engineering and washing machine

With the vault-structured coiler plate CLEANcoil (Rieter) fibres like polyester are well defined placed in containers of spinning machineries at great speed (Figure 14). Using conventional coiler plates, cleaning cycles of 2-3 hours are required to remove disturbing dust or fibre particles. The vault-structures reduce the friction when the fibre is sliding over the smooth vault tops. Simultaneously unwanted dust or fibre particles are separated and collected in the folds of the vault-structures. Therefore the cleaning cycle is drastically increased from 2-3 hours to 1-7 days.

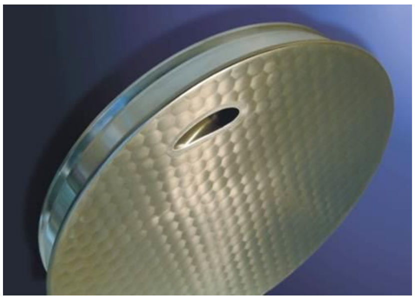


Figure 14 : Coiler plate CleanCoil (Rieter)

With the vault-structured washing drum (Miele) the laundry is particularly protected both during washing and during spinning: Due to the 3D-shape of the vault-structures a water film is generated between the textiles and the drum wall on which the textiles slide like on a cushion. Therefore, the mechanical stresses on the clothes during washing and spinning are reduced allowing a "more gentle, faster and more economical washing" (Figure 15).

Figure 15 : Miele washing-drum

5.3 Products in architecture

Vault-structured sheet metals are used in several architectural projects. Figure 16 shows a sports hall with a vault-structured roof (6.000m²) in Odessa, Ukraine. For this project the Dr. Mirtsch Wölbstrukturierung GmbH received the "German Material Efficiency Award". In a very ecological and economical way pre-coated aluminium coil material was continuously vault-structured and afterwards continuously roll-formed to standing seam profiles which were mounted on the roof. Due to the vault-structures the material thickness/ weight could be reduced, the pre-coated surface quality remained unchanged and possible dents caused by hail impact were optically camouflaged.

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Figure 16 : Vault-structured roof in Odessa (Böhme Haustechnik)

For a representative building in Manhattan, USA perforated stainless steel sheet metals with vault structures were used as façade elements as shown in Figure 17.

Figure 17 : Decorative façade in Manhattan (Roy, High Line 519)

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