APPLICATION OF INNOVATIVE MATERIAL CONCEPTS FOR SAFETY LIGHTWEIGHT INSIDE CARS USING ALTERNATIVE POWERTRAINS

Stefan Lindner[1]

[1] Oberschlesienstraße 16, 47807 Krefeld, Outokumpu Nirosta GmbH, Stefan.Lindner2@outokumpu.com, www.outokumpu.com

Keywords:

Material concepts, Lightweight, Electric mobility, Crash-performance, Composite structure

ABSTRACT

New megatrends in the automotive sector like alternative powertrains, autonomous driving or car sharing but also continuous improvements like increased safety regulations or CO_2-emission standards can be influenced directly but also indirectly by an application-orientated selection of the used material or material combination. Thereby a new generation of material concepts can help to fulfil the partly divergent requirements and conflict of objectives consisting of strength, stiffness, energy absorption or lightweight. Further, the materials must be suitable for volume production and easy to integrate into established manufacturing processes like cold or hot forming and assembling, especially joining. Of course, new materials should be cost-effective, recyclable and completely simulatable.

To reach those targets, material scientists have different approaches like developing a monolithic metal or a compound structure, varying by fundamental basics like alloying elements, microstructure, number of phases, homogeneity, anisotropy, cross-sectional profile but also layer set-up and order [1].

The present paper takes up the mentioned diversity and introduces into different further developed material concepts which can be differentiated into opportunities for creating tailored properties of austenitic cold-hardening stainless steels, surface structured thin steel sheets and steel-polymeric composite structures. For every development, the focus is targeted to the combination of strength, stiffness and lightweight with the question how to increase every single value of the combination by using one of the new material concepts.

The target application is thereby the field of alternative powertrains, especially the application area of electric mobility. Therefore, three different concept ideas are given for this strategic part of automotive development. One element is to use significantly cross-industry innovations to ensure a fast integration combined with reliable experience into this new application field.

1 INTRODUCTION

In 1886 Gottlieb Daimler with his invention of a motorised carriage and Karl Benz with his invention of a motor vehicle established the automobile as one new individual private transport technology for passengers [2]. Parallel to the development of the automobile with combustion engines, researchers also developed successfully on electric vehicles. As two substantial examples Werner von Siemens with his electrically powered carriage (1882) or the electric cars developed by Ludwig Lohner und Ferdinand Porsche for the world exhibition 1900 in Paris can be pointed out. Passenger cars with combustion engines dominate the 20th century because of their significant expanded range, availability and price of the fossil fuels as well as the quick refuel process. During the last years, the frame conditions like the increased price and limitedness of fossil fuels but also the social desirability and acceptance changed. Therefore, electric vehicles experience a renaissance [3].

Simultaneously staged megatrends like autonomous driving or car sharing reinforced this trend. Further, regions inside Asia and Africa show an increased need for transportation concepts. Especially the

K. Dröder et al (eds), *Technologies for economical and functional lightweight design*,
Zukunftstechnologien für den multifunktionalen Leichtbau, https://doi.org/10.1007/978-3-662-58206-0_17

topic of “last-kilometre” transportation for goods can be pointed out. In turn, the changing kind of mobility also results into demands for application-specific material concepts. As the main requirements for the mentioned application field of transportation, the key topics of lightweight, strength, stiffness and safety (resistance against impact) can be highlighted. At the same time, other important aspects like joinability, especially for multi-material-design, but also formability, corrosion resistance, an aesthetic impression of the surface, global availability, recyclability and the material-specific CO_2-footprint (life cycle engineering) must be also keep in mind during material selection and vehicle development [4, 5].

As one outcome of material development inside Outokumpu to support the efforts of the automotive industry and to realize the future expectations for transport systems, Figure 1 summarizes different material-related solutions to fulfil the alleged contra-diction between the four key-topics lightweight, strength, stiffness and crash-safety.

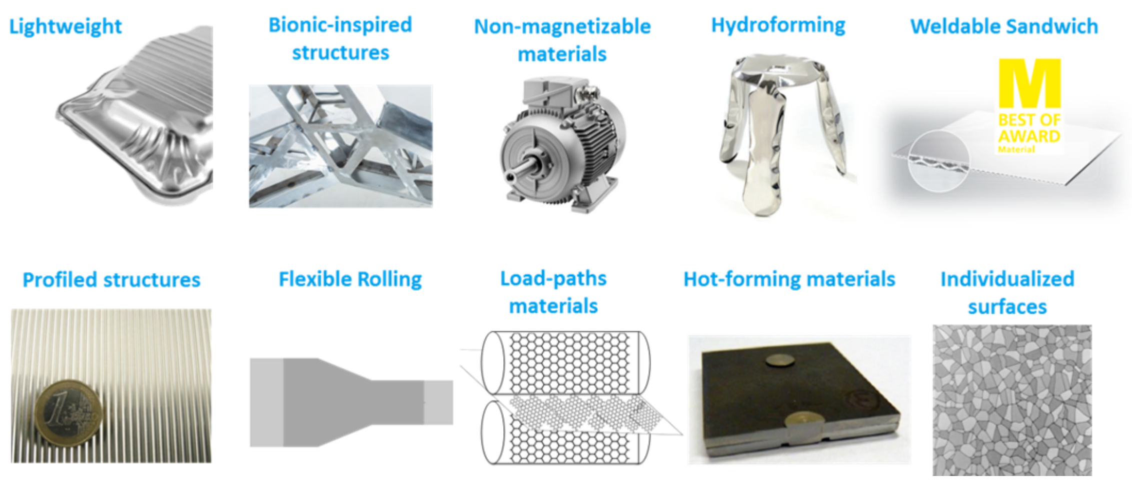

Figure 1: Overview of innovative material concepts by Outokumpu

2 AUSTENITIC COLD-HARDENING STAINLESS STEELS

Stainless steels with a stable one-phase, fully austenitic microstructure can be developed because of a special hardening mechanism called TWIP-effect (Twinning-Induced Plasticity) into the material category of ultra-high strength steels. Responsible for this characteristic profile are the coordinated alloying elements like chromium and manganese reaching in a specific stacking fault energy. As a result, the cold-formable material enables an intensive work-hardening during cold-rolling of the material but also during cold-forming of the component or during impact situation of the vehicle. At the same time an enormous energy absorption can be realized because of the outstanding relation of the mechanical-technological values. By taking advantage of the work-hardening effect, a complete material series could be created by cold-rolling with just one chemical analysis, view Figure 2. [6]

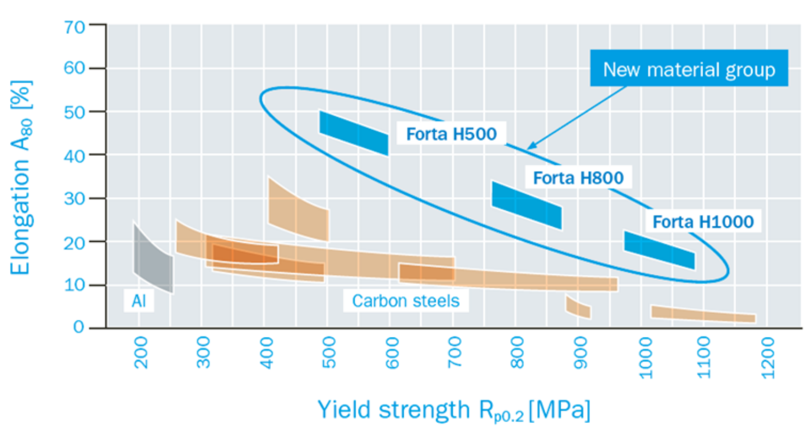

Figure 2: Mechanical-technological values of Forta H-series

The same effect supports the application during an impact or crash-situation. Furthermore, the component-manufacturer is able to adjust the local desired properties of the material in dependence of the cold-forming degree, view Figure 3. Design engineers can create higher strength or higher ductility areas inside one component where the usage conditions of the components require it.

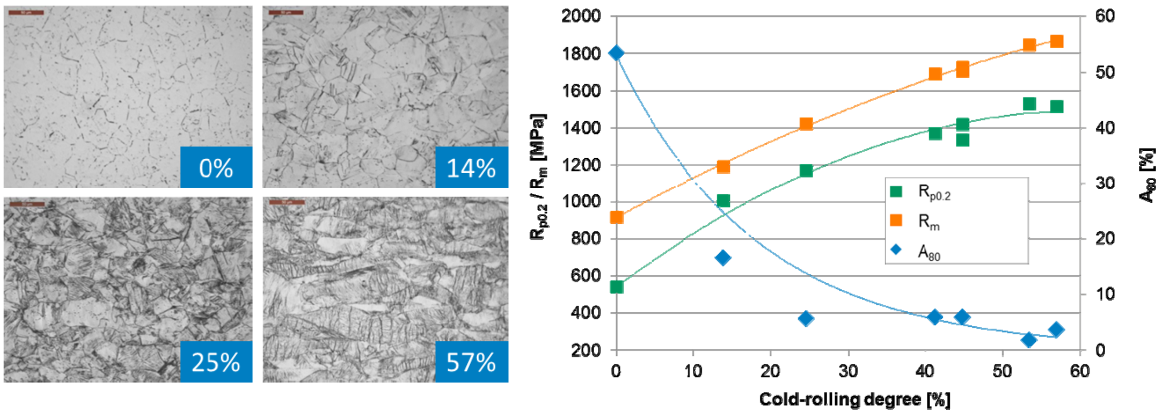

Figure 3: Resulting microstructure and mechanical values depending on the cold-forming degree.

In manufacturing of transport system, especially automotive car bodies, engineers use arrangements to have the right material at the right place and therefore to reach the relevant properties. Such approaches are called “multi-material design” or “using tailored products”. [7]

A further developed approach in combination with the described material characteristic is therefore to initiate areas with a higher strength in combination with areas having a higher ductility. In relation to state-of-the-art material usage, this circumstance leads to an additional design criteria for materials beside a varying thickness with homogeneous mechanical values.

2.1 Integrated load-paths

The material concept of a TWIP-hardening and fully austenitic steel was now complemented by a process innovation to create ductility areas inside a high strength matrix having the same chemical composition and microstructure inside one material. Figure 4 points out one possible cold-rolling with a structured roll inspired by a honeycomb structure to integrate load-paths into the steel.

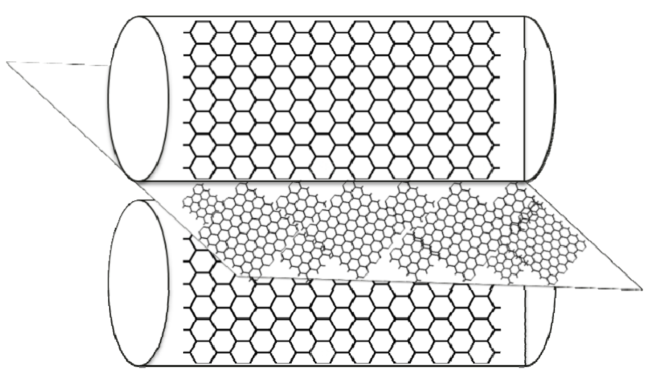

Figure 4: Cold-rolling with a structured roll to integrate load-paths into steels

Simple wave structure as 1st trials were carried out whereby the waves are displaced to each other to realize ductile areas called “combs” or “core” surrounded by higher strength indentations called “load paths” or “webs”. The local-shaping is directly related to the above described cold-forming degree of the base material and results with a global view of sample properties in an increased yield strength but with nearly original ductility, view Figure 5. The deformed product with cold-formed indentations seems to have a better fatigue behaviour by creating a supporting effect of the ductile areas to the higher strengthened webs. Furthermore, the thesis of a particularly lower springback during forming operations when compared with state-of-the-art homogeneous materials can be formulated. Summarizing the product combines areas of higher ductility embedded in a matrix with a higher strength. The resulting product can be used because of its properties in crash-relevant applications like pillars or crash-boxes but also in fatigue and strength optimized structures like cantilever cranes, outriggers or agricultural machines.

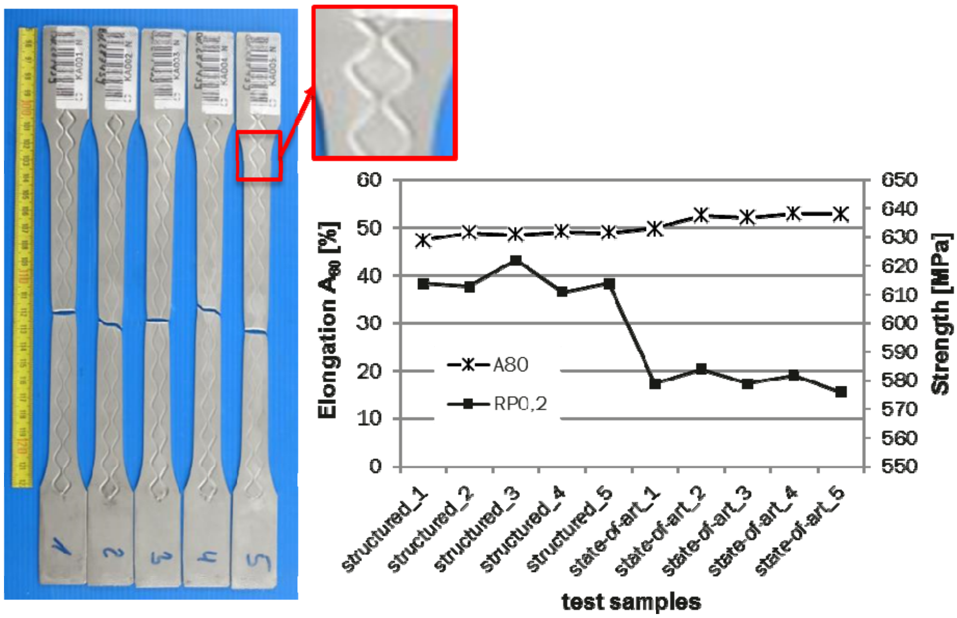

Figure 5: Effects on the mechanical properties because of inserting load paths

2.2 Flexible rolling

Another combination of a process and a material concept to create Tailored properties are flexible rolled blanks, which are metal products having different material thicknesses along its length. Usually, a subsequent recrystallization annealing process and a galvanizing step follow to the origin flexible cold rolling or eccentric rolling process. As a consequence, homogeneous mechanical-technological properties result.

Following the design rule of having the "right material at the right place", it means for flexible rolled blanks in state-of-the-art status just to have the right thickness at the right place. The mechanical properties, such as the tensile strength, will maintain at the same value as well as the ratio of the ultimate loads F as the product of the thickness, the tensile strength Rm and the width of the material between the flexible rolled area and the unrolled area. Thus, it is not possible to create areas with different strength and ductility, e.g. for a subsequent forming process or for fatigue depended component properties.

Using a stable one-phase, fully austenitic microstructure with the cold-hardening effect of TWIP in combination with the flexible rolling process, a combination of mechanical properties with thickness variation can be realized. As a result, the thickness reduction in the further cold deformed areas of the initial material is now combined with a specific and balanced local change in the mechanical properties of the material, such as yield strength, tensile strength and elongation, view Figure 6.

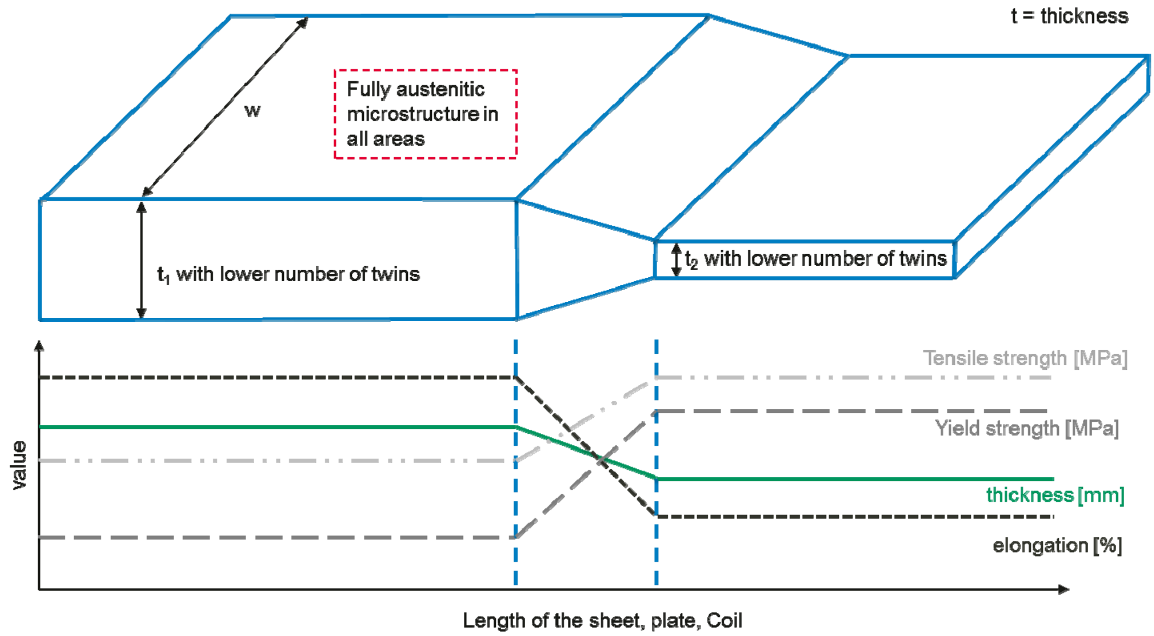

Figure 6: Relationship of thickness and technological values for enhanced flexible rolling

To point out the resulting benefits in mechanical properties, Figure 7 shows a simple way of calculation for a state-of-the-art flexible rolling process with annealing and galvanizing in relation to the enhanced process using a fully austenitic material with TWIP hardening and without a further annealing step.

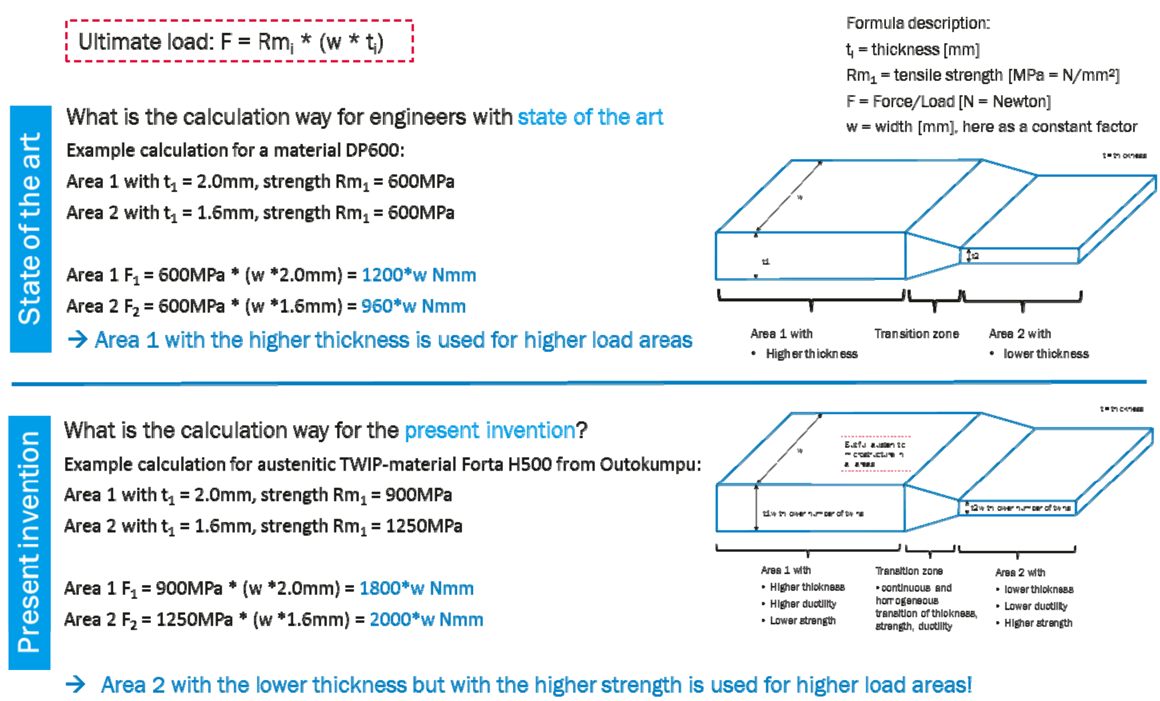

Figure 7: Relationship of thickness and technological values for enhanced flexible rolling

As a consequence, the method of construction changes: State of the art, the higher thick areas are used for higher load areas. With this kind of innovation, it is now possible that thinner areas can bear higher loads than other areas, depending on the applied material. One further benefit could be that the strength can be adapted to the following forming steps of the component manufacturer: Areas like flanges which will not be formed during component manufacturing can have a higher strength in a thin state. Other areas with a thicker initial thickness can be formed because of the higher ductility and therefore thin-out during forming operation.

3 PROFILED SHEETS

Beside the direct material related lightweight, there exist further lightweight designs like concept lightweight design, conditional lightweight design or form and structure lightweight design [8]. The last one was applied in a targeted manner to realize lightweight of thin steel sheets just because of a local change of the surface structure. One solution was a profiled sheet, in more detail an anisotropic corrugated sheet with the geometry represented in Figure 8. The profiled structure was manufactured with cold-rolling using double-sided sinusoidal structured rollers.

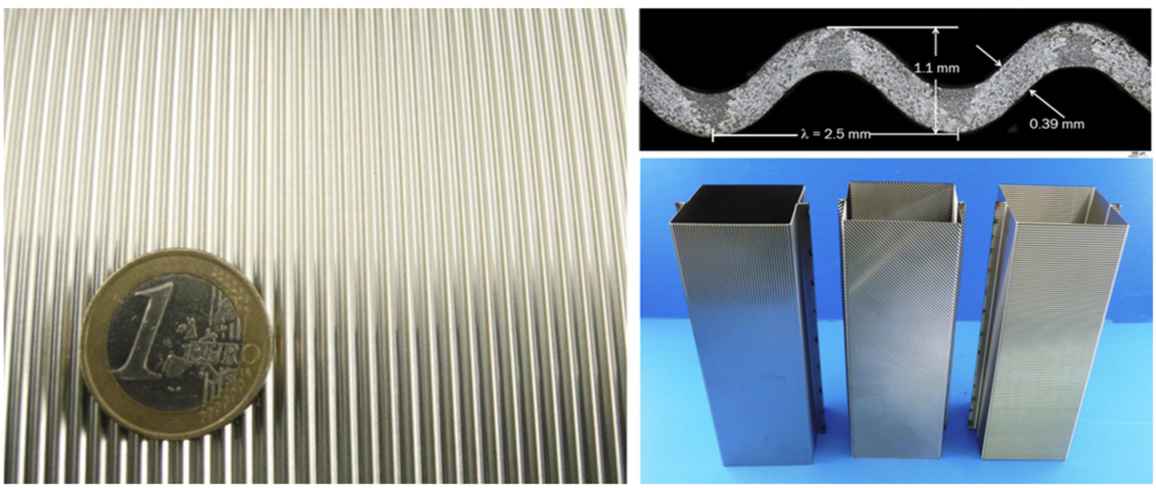

Figure 8: Profiled structured stainless steel sheet

As a result, a significant higher bending strength of +150 %, depending on the material direction, was able to create. At the same time, a lightweight of 27–29 % depending on the microstructure and material rigidity can be worked out. Further, an attractive appearance and a modified acoustic-behaviour can be added with the present structure. With a view to electric mobility and more specific to battery compartments, additional functionalities like sensor and measuring technologies as well as a defined thermal management can be integrated into the wave troughs. Setting-up the corrugated sheets as a package, functions of a heat exchanger or channels for cooling fluids can be realized. The profiled structure can be produced within a standard cold-rolling process for stainless steels. The solution can be adapted for all grades of stainless steels as coils or sheets with a width of 1250mm. Thereby annealed but also cold-hardened materials like pointed out in chapter 2 can be used. With the last aspect, it is further possible to combine different technologies and material concepts to reach at the end an increase of strength, stiffness and lightweight at the same time. Further profiles also with an isotropic rigidity are under development.

4 WELDABLE SANDWICH WITH 3D-PROFILED CORE

By using this profiled sheet as a 3D-profiled core material, a subsequent innovation for steel-polymeric composite structures, often called “sandwich structures”, was possible to develop. The key of the material innovation is to combine the profiled metal with a polymeric material filled in from two sides. A dual-material core with an unidirectional supporting effect results, added by two thin stainless steel sheets as outer-layers, view Figure 9 and 10.

Former sandwich solutions had not been successful in spite of their enormous lightweight potential because of their insufficient weldability and a lower stiffness compared to monolithic metals.

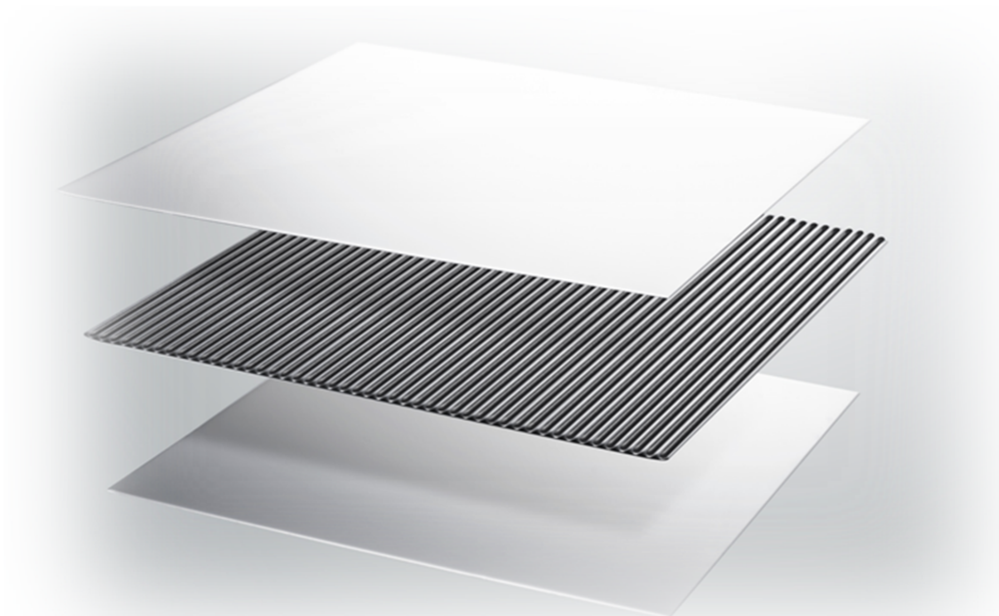

Figure 9: Up-set of the different layers of Outokumpu’s Weldable Sandwich

The resulting stainless sandwich structure called “Weldable Sandwich” is the first direct weldable steel-polymeric composite structure for automotive car body, transport and construction engineering. The developed sandwich structure is now able to combine the automotive challenges consisting of a reduced weight (–30 %) with an increased stiffness of +80 % compared to a monolithic material with the same thickness at the same time. Further, a better behaviour in point of acoustic, energy absorption and crash safety is enabled. Thereby no changes during manufacturing are necessary: the Weldable Sandwich can be handled like a conventional steel sheet during component manufacturing in point of joining, cutting or punching and limited in point of forming. The profiled core, pointed out in detail in Figure 10, enables at every time a metallic contact between booth thin stainless outer-layers with the result of having a constant electrical current flow during resistance welding. Thereby, no special clamping devices, welding machines or specific welding parameters like more-impulse welding or a previous displacing of the polymeric core material are necessary.

Figure 10: Final structure of the Weldable Sandwich with metallic contacts

Dissimilar welding combinations in a lap-joint configuration with monolithic metals are possible. Moreover, also similar sandwich-with-sandwich combinations are possible, view Figure 11. In such a case, the current flow can be enabled by the profile over in sum six metal layers. Using typical contact diameters for electrode caps of d_{EL} = 5.5 mm, the used profiled sheet core material enables at every location a minimum number of two waves as a contact for current flow because of the wave length λ = 2.5 mm.

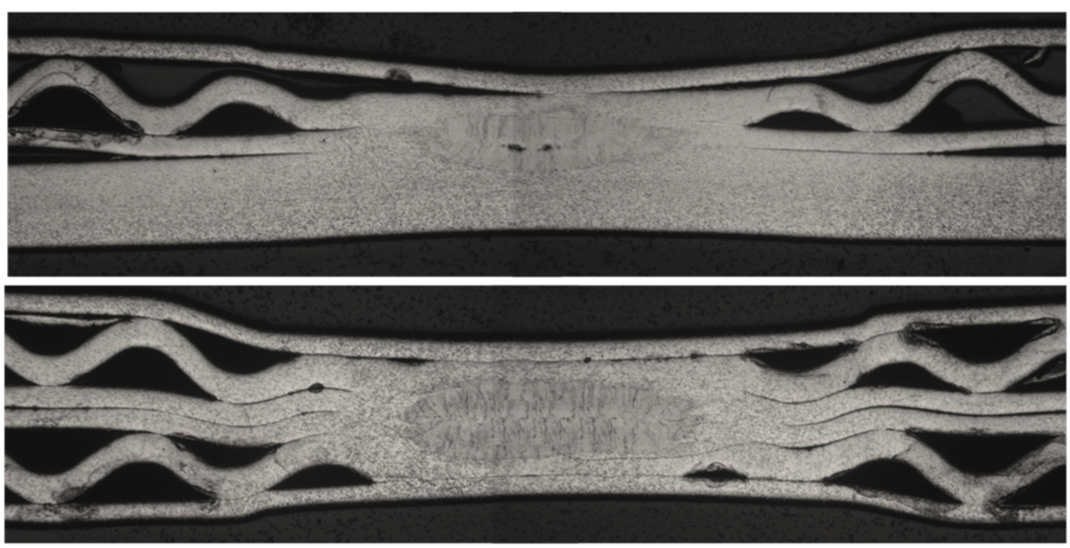

Figure 11: Dissimilar (above) and similar (below) resistance spot welding of the sandwich.

Furthermore, the sandwich solution offers also for mechanical joining processes like riveting advantages like a significant higher power transmission and compressive rigidity in comparison to other tested sandwich structures. The profiled core enables for these cases the possibility of a mechanical clamping and additional reinforcement between the core and the joining elements, view Figure 12.

Figure 12: Structure of Weldable Sandwich after mechanical joining with a half-hollow rivet

Summarizing, the innovation of a profiled core solves the question how to fulfill the requirements with a geometry depending answer: Because of the continuous contact between the metallic outer-layers at every time stiffness and acoustic advantages combined with a direct resistance weldability can be enabled. The Weldable Sandwich with its described benefits was awarded with the Best-of-Award for the category "material" during the 15th Materialica Design- and Technology Award-Show for the most innovative material development in 2017 (Munich, 10/2017).

5 CONCEPT IDEAS FOR ELECTRIC MOBILITY

One effective method to create new products or solutions is to apply cross-industry innovations whereby the method deals with drawing analogies and transferring approaches between contexts. Target is to enlarge the border of the own business to other sectors and areas where the new innovation for the own application field is used since many years with a high level of experience and reliability. Therefore Vullings and Heleven [9] concluded that "the best way to develop ideas is to look at other places". This method is applied in the following subchapters to introduce new ideas into the market of electric mobility.

5.1 Individualized surfaces

The electric mobility in combination with other major trends like autonomous driving or car sharing changes the requirements of the interior of the future. Because of this, some sources are speaking about the "interior as number one factor for future's purchase decision" [10]. At the same time, the outer-skin remains a character-shaping identifying feature of a car.

Inside this environment, stainless steel with its versatile possibilities of a patterned surface will act one important role in human-to-material-contact. Thereby, the well-known advantages of stainless steel surfaces for design-applications remain valid and open the possibility for cross-industry innovations. In architectural applications like the Empire-State Building, New York, from the 1930ies or the Burj Khalifa as the highest building of the world, stainless steel surfaces are used because of their aesthetical and tasteful impression. Furthermore, stainless steel is used in medical and food technology because of its antibacterial properties and additionally in the application field of railway vehicles because of its easy cleanability and resistance against aggressive cleaning media. With a harmonious adjustment of optical properties like gloss level or reflection factor in combination with a specific patterned surface, the visual appearance of a scratch-resistant surface can be emphasized. Furthermore, the optical properties can be combined with safety benefits, e.g. used in series applications like the underride guard of the Mercedes Benz Actros where design and crash properties are successfully used since many years. Summarizing, further developed stainless steel surfaces offer unique features for future design concepts and beside that are highly customizable for passengers as well as for brands.

5.2 Spring steels as safety protection

Another cross-industry innovation for electric mobility can be divided with a view to the application of springs where ultra-high strength austenitic stainless steels are produced by cold-forming since many years. According to DIN EN 10151 [11], tensile strength levels with the EN-code C1900 reaches 1,900 up to 2,200MPa.

The properties of cold-hardened spring steels were used to design a crash management system for a battery compartment to protect the battery modules and cells inside. The system refers to the physical operating principle of a mechanical compression spring combined with a double floor system, view Figure 13.

The last aspect is an additional cross-industry innovation, inspired from maritime navigation, where a double-floor between the outer-skin and the inner bottom is statutory since the 19th century and serves the ship for an increased safety in the event of grounding or collision. Further, the whole ship stiffness increases because the double floor for ships is rigidly connected with inner beams. As a result of adapting this well-known concept of shipbuilding in combination with an inside compression spring effect now for Battery electric vehicles (BEV), the double-floor system will be yielded because of the spring effect and therefore absorb the crash energy without destroying of the inner bottom. Beside the fact that the vehicle battery will be directly protected, the forces and accelerations affected to the occupants will decrease significantly, too.

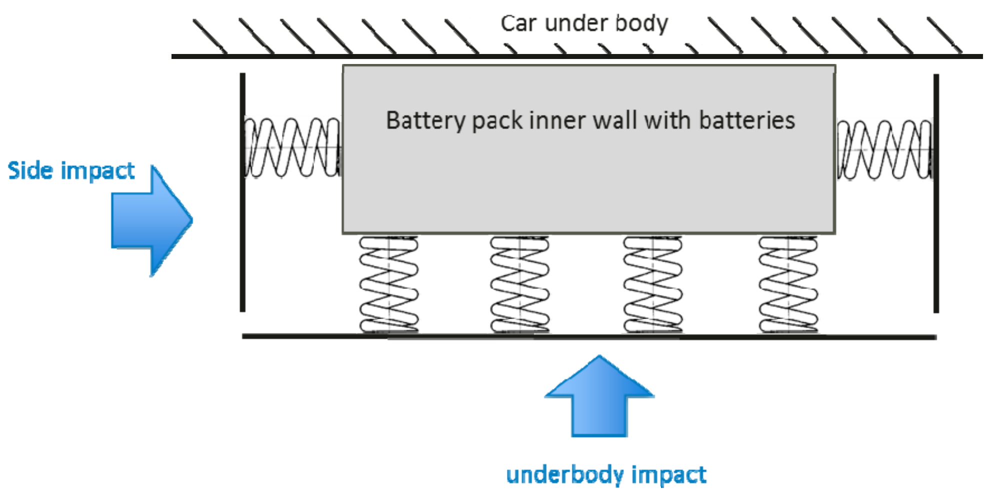

Figure 13: Schematically view of the spring system inside a double-floor arrangement

In the case of an underbody slitting, the sharp-pointed object will slip-off if the impact takes place with a slanted angle. The contact angle will decrease because of the spring effect. If the underbody impact of a sharp-pointed object takes place under a contact angle of 90° without the possibility of slipping, the outer-skin absorb the energy even if the sharp-pointed object will introduce into the space of the double-floor system but without damaging the battery system itself.

For every embodiment typical spring values can used to characterize the properties of the crash system. One parameter is the spring rate which defines the ratio of a force which contacts the spring and the therefore induced displacement of the spring. Depending on the desired crash behaviour, the ratio can be shown a linear or a non-linear characteristic. A non-linear progressive characteristic could be used if the OEM wants to absorb firstly the energy and at the end creating a high resistance against the impact. Conversely, a degressive characteristic can be used if initially a high resistance is desired and then the energy will be absorbed. Another spring characteristic is the block length which can be defined in general for a compression spring as the situation where all windings rest on top of each other. Adapted to the case of a vehicle crash, it is the situation where the energy absorption and the thereto related impact of a compression spring system is exhausted. Now the system is compressed and further energy must be dissipated over inner beams or cross members.

As one calculation example, the final way of the spring system inside the double-floor system reaching the block length can be calculated with 0.1 m in the case that a vehicle with 1.5 tonnes weight collides under side impact conditions with a speed before impacting of v_1 = 60 km/h.

The battery compartment using such a double-floor system can be executed as a repeatable non-destructed system which can be continued used after the crash without further effort by getting itself into its origin starting configuration.

One advantage of stainless spring steel systems is the benefit of corrosion resistance in the wet underbody area of an electric vehicle. Further, stainless steels have a higher acid-resistance in the case of a leakage with battery liquid and a higher heat and thermal resistance. The last point is important that the battery compartment can maintain the structure during a case of fire. Also this can be interpreted as a cross-industry innovation, in this case from exhaust systems.

5.3 Integrated safety cell

As an outlook, a further developed safety concept for a battery electric vehicle should be given. Having a view to passenger cars until the 1950ies, the disadvantage of having nearly the same material strength in longitudinal centre line of the vehicle affected the occupant safety significantly. Béla Barényi from Daimler AG defines in his DE patent application 854157C a passenger compartment whereby the strength decreases constant or in gradual phases in direction of the front and back end of the vehicle. The highest strength level of a material was reached inside the passenger compartment. Thereby, the security safety cell for passenger cars was invented to protect passengers during an accident or crash situation. Since then the front compartment and rear end of the car are known as deformable zones. Béla Barényi spoke about a centre cell for the higher strength passenger cell and outer cells for the softer front compartment and rear end. [2]

Today, the crash requirements change again by introducing a battery compartment into the vehicle floor which is critical against an impact and resulting deformation. In particular, 27 % of all accidents happened as side impacts whereby 2 % of all accidents showing a speed of $v \geq 64$ km/h. The number of side-impacts increases excessive for higher speed levels whereby 26 % of those side-impacts show a fatally effect and further 57 % with a severally injury of the occupants. [12]

The invention of Béla Barényi was adapted by using again the physical operation principle of a compression spring and extended also for side impact (y-orientation) and underbody impacts (z-orientation), view Figure 14. The battery compartment was integrated into the former passenger safety cell whereby the security cell works like a spring on the block. Further, the integrated security cell is surrounded by a lower strength energy absorbing area in cross direction as well as in height direction of the vehicle.

It is important to ensure that the physical protection according the UN R94 and R95 standards is given to protect against persons touching of the high-voltage components (IPXXB protection). Those components must be completely covered. For this, the integrated security safety cell can be designed into several inner rooms to separate the passengers from the engine. In this case the before described bulkheads known from ships but here in a horizontal orientation can separate the different spaces from each other.

During a rollover situation, the complete weight of the battery components works on the roof structure which must be stable without buckling to safe the passengers. This fact can be also integrated into the present concept. Also for the roof structure, the security cell can be defined as a non-deformable cell surrounded by an energy-absorbing area.

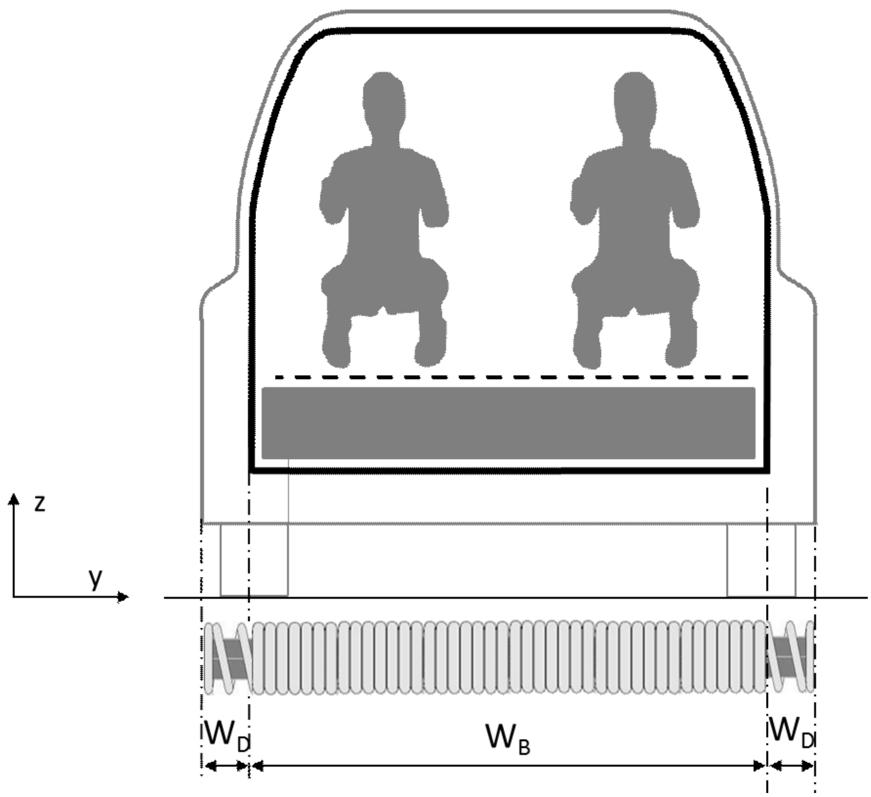

Figure 14: Schematically view of integrated safety cell for battery electric vehicles

Summarizing, this vehicle concept leads to a complete new design of vehicles, having a higher seating position for the passengers. In time of electric mobility in urban spaces, the traditional vehicle dimensions which are aerodynamically optimized and characterized by a longer length and lower height could be changed into dimensions which are more compact in length but enlarged in height. The necessity of consumption reduction by optimizing the aerodynamic seems to be not relevant for future battery electric vehicles in urban areas.

6 CONCLUSIONS

The present paper places further-developed material concepts within the context of changing customer demands and more challenging requirements in the automotive world. Innovative material concepts divided by cross-industry innovations could be one substantial enabler to solve these contrary goals by dealing with local adjustable properties. This characteristic unites different material concepts independent from their micro- or global structure, hardening mechanism or alloying concept. Further, all described material concepts combine general development objectives like lightweight, strength, stiffness and energy absorption. Summarizing, current developed material concepts must provide evidence about their ability for a worldwide and large scale production in the area of automotive over many years. But already nowadays, the outlook can be formulated that these material concepts result in new design possibilities, sometimes changing design rules and as demonstrated within the chapter about “concept ideas for electric mobility” in new ways of thinking automotive and transportation.

REFERENCES

[1] K. Stamm, H. Witte, Sandwich-Konstruktionen, Ingenieur-Bauten 3- Theorie und Praxis, Springer-Verlag, 1974.

[2] H. Niemann, Béla Barényi und seine Erben – Sicherheitstechnik made by Mercedes-Benz, Motorbuch-Verlag, 2016.

[3] A. Karle, Elektromobilität – Grundlagen und Praxis, Carl-Hanser-Verlag, 2015.

[4] Q. Zhou, Electric Mobility in China – Developments, Opportunities & Challenges, 30th International electric vehicle Symposium, Stuttgart, 10.09.2017.

[5] B. Müller, C. Zachäus, G. Meyer, European strategic processes towards competitive, sustainable and user-friendly electrified road transport, 30th International electric vehicle Symposium, Stuttgart, 10.09.2017.

[6] S. Lindner, Leichtbaupotenziale mit ultrahochfesten Mangan-Chrom-Stählen im Fahrzeugbau, Faszination Hybrider Leichtbau 2016, Wolfsburg, IST automotive nord e.V., 2016, pp. 356–375.

[7] J. Hillmann, The new Golf VII – Lightweight Design in Large Scale Production, Aachen Body Engineering Days, 2012.

[8] H. Friedrich, Leichtbau in der Fahrzeugtechnik, ATZ/MTZ-Fachbuch, Springer Vieweg, 2013.

[9] R. Vullings, M. Heleven, Not-invented here – cross-industry innovations, BIS Publishers, 1st edition, 2015.

[10] H. Hendriks, Automobil Produktion, volume 04/2017, p. 27.

[11] DIN EN 10151, Stainless steel strip for springs – Technical delivery conditions; German version EN 10151:2002.

[12] M. Büchsner, Integration of occupant safety systems into seating environment in the light of autonomous driving, presentation at 2nd Annual Seating Innovation Summit, Berlin, 6th April 2017.