

Hybrid Forming - A Method for Simultaneous Forming of High Strength Metal Sheet and Long Fiber Reinforced Plastic

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Abstract. Fiber reinforced plastics (FRPs) are increasingly being used to reinforce steel and aluminum automotive structural components. Currently, these multi-material applications are generally realized by multi-stage manufacturing, which imposes considerable cost increases. To address this issue, a new hybrid forming method has been proposed and developed. In this method, half-liquid FRP is employed as a pressure medium to hydro-form the sheet metal, form the reinforcement ribs of FRPs, and create a bond between the metal sheet and FRP simultaneously. In this work, the die sealing concepts for two test geometries could be successfully developed. The hybrid forming parameters (such as temperature, pressure, and speed) are within a reasonable range and are acceptable for industry. It could be proved that high-strength steels with up to 800 MPa tensile strength could be hybrid formed successfully together with an LFT PA6 GF40 for a real car component, achieving a 20% weight reduction.

1. Introduction

Lightweight design is one of the most important measures to reduce fuel consumption of vehicles using internal combustion engines or extending the driving range of pure battery driven vehicles (BEVs) [1–3]. To realize economically acceptable lightweight designs, vehicle body in white (BIW) structures are increasingly being built using multi-material designs, consisting of steel, aluminum (Al), magnesium, and fiber reinforced plastic (FRP) [4,5]. However, all the wheel-guiding components in the chassis of series-production vehicles are still manufactured from steel or Al.

The multi-material designs in [4, 5] were both realized using the so-called “post molding assembly” (PMA) and “in-mold assembly” (IMA) approaches. In the PMA process, metal and FRP components are initially manufactured separately and then joined together in a third process step. However, the matching of the two parts is a problem due to different tolerances, in addition to the increased manufacturing costs. In contrast, in the IMA process, a preformed sheet metal part is over-molded by FRPs, such as by using an injection molding process. Another example is the forming of FRP (either a thermoplastic or thermoset prepreg) in a preformed sheet metal part when FRP forming and the creation of an adhesive bonding could be performed simultaneously [6]. Here, the step of making a pure FRP part is eliminated.

To further reduce the processing cost of IMAs, the forming of FRPs and sheet metals or the so called organo-sheets were carried out in the same die but at a separate time step for the injection molding process, as shown in [7]. However, these types of processes were only realized for very simple geometries such as rotational symmetrical parts made from low-strength mild steels [8, 9]. For high strength steels or even advanced high strength steels and complex geometries, this process has been not applied. In addition, due to the extruder of the injection molding system and the very small section size of the injection nozzle, the long fibers of the thermoplastics are cut or broken into short fibers with fiber length much lower than 1 mm.

Compared to injection molding, compression molding of FRPs results in much longer fiber lengths in the final parts. In addition to plastics with short fibers prepared by the extruder, additional long fibers are placed at the very end of the extruding process (see Fig. 1). These thermoplastics with longer fibers (up to 25 mm) are then press-formed in a well-sealed die to form the desired part. Moreover, since the fibers are only subjected to shear stress when filling the cavity of the die, the

fiber length degradation is significantly reduced compared to injection molding, with fiber lengths reaching up to 10 mm [10] for a PP GF (glass fiber) material. This type of material is referred to as long fiber thermoplastic (LFT). In [11], the relationships between fiber length and stiffness, strength, and impact resistance were revealed. In general, these properties increased with increasing fiber length. However, while the stiffness of the materials stopped increasing beyond ca. 1-2 mm, the strength continued to increase considerably with fiber lengths of more than 10 mm. The same relationship was found for impact resistance. Importantly, GMT materials may even have much longer fiber lengths, and properties.

An additional aspect, which results into the development of the new hybrid forming technique, is the special requirement for the wheel guiding component of vehicle chassis. For these components, “fail-safe” behavior is required, in addition to stiffness and strength [12]. This means that if a vehicle wheel bumps a curbstone at a high velocity for example, one or more wheel guiding components (mostly control arms) must be able to deform without total failure. More importantly, they must be able to deform in a predefined way. The driver can recognize changes in the driving behavior of the vehicle and drive to the nearest workshop for repairs. Since FRPs may not be able to fulfil these requirements but metals, metals are the only materials used in serial production vehicles for these parts.

2. Principles of the New Method

Based on the deficits mentioned above and the state-of-the-art, the idea of hybrid forming was developed [10] to produce a metal-FRP multi-material component with material-based large-area joining between metal sheets and FRPs. The FRP may have different thicknesses and rib structures to reinforce the sheet metal panels effectively. In this way, the lightweight potential of FRP and the fail-safe behavior of metals can be combined. Furthermore, the well-known hydro-mechanical sheet metal forming and FRP compression molding techniques should be combined to make such kind of multi-material parts in one process step.

During the hydro-mechanical forming of steel or Al, the sheet metals are deformed by the hydrostatic pressure of the pressure media such as water or oil in a well-sealed die cavity. Since the thermoplastic composite materials for FRP compression molding, such as PP or PA GF, are in a half liquid state before compression molding, they can be used as pressure media as well. This combined method is called the hybrid forming of sheet metal and FRPs [10].

Fig.1 depicts the total process chain of hybrid forming. In the first step, the long fibers with ca. 50 mm length are mixed with the extruded short fiber materials at the end of the extrusion process. This material, which was in a half-liquid state, is then placed on to the steel or Al sheet metal blanks that have already been positioned in a forming die. The sheet metal blanks are pre-coated with a bonding agent, for example a VESTAMELT from company Evonik in this work [13]. The sheet metal blanks are preheated in an oven to ca. 200 °C to activate the bonding agent, while a PA GF 40 should have a temperature of 280 °C.

Instead of direct feeding from an extruder, also pre-extruded LFT or GMT materials can be reheated in an IR-heater and then placed onto the sheet metal blanks.

In the third step, a special sealed hybrid forming die forms the LFTs or GMTs simultaneously with the sheet metals. At first, the punch presses and forms the LFT/GMT material, and the LFT/GMT on the other side forms the sheet metal. Since the LFT/GMT materials are enclosed by the die sealing, high pressures are created, which finally forms the LFT/GMT over the entire surface of the sheet metal with a pre-defined thickness, and the sheet metal is formed to the final shape as well. In the same time, ribs for reinforcement and functional integration are formed. In the final step, after approximately 20 s die closing time (when the LFT/GMT is cooled to approx. 80 °C), the adhesive bonding of the materials is completed, and the part can be removed from the press.

Beside the advantage of unifying three different process steps into one, hybrid forming can be introduced in any sheet metal stamping facility that has a hydraulic press. The LFT/GMT materials can be purchased as raw materials and heated by an IR heater, which is inexpensive. Therefore, each classic metal stamping factory can produce metal-FRP hybrid parts with very low investment.

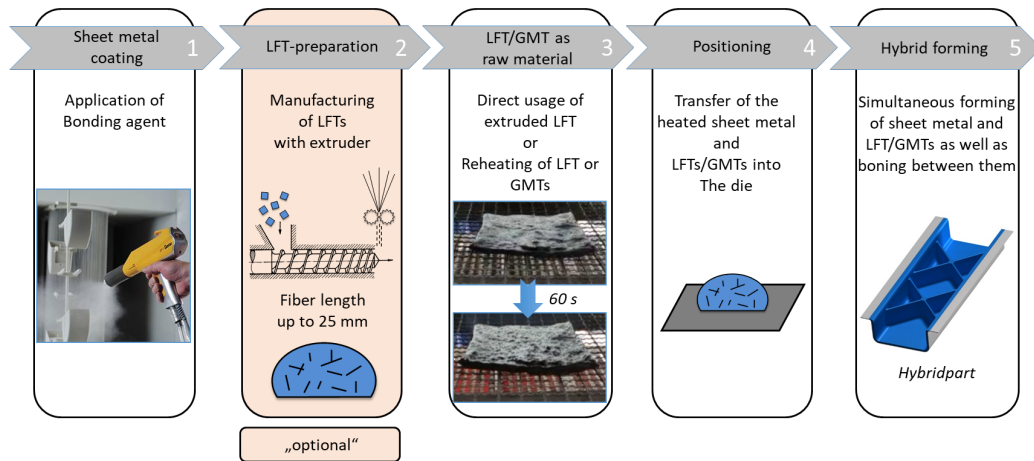


Fig. 1: Process chain of hybrid forming of sheet metals and FRPs

3. Tooling Concept

Real vehicle parts in BIW have very complex geometries. In order to develop generic forming and sealing concepts, which are the two most challenging aspects of a hybrid forming die, a tube geometry and a u-profile with two open ends were studied. The sealing should prevent LFT/GMT press-outs, and the material flow of sheet metals should not be affected. Moreover, a balance must be found between sealing and avoiding wrinkles and splits in the sheet metal.

3.1 Tooling concept for a tube geometry

In Fig. 2a, a tube geometry with different draw depths, radii, and closed ends was designed. The hybrid formability of sheet metal should be evaluated, especially with regard to whether the geometry transitions can be formed by LFT pressure and if the LFTs may be pressed out when wrinkles appear in the four corners of the part.

Similar to a deep drawing die, draw beads were introduced around the part, which may control both sheet metal forming and wrinkle formation. They should also prevent LFT pressout. However, during the trials, we discovered that draw beads were not needed for LFT sealing. However, they are needed for wrinkle and forming control, since the LFTs are kept in the die through the contact pressure between the blank holder (BH), sheet metal, and the die (upper die) (see Fig. 2b). Small wrinkles at the corners did not deteriorate the sealing. Accordingly, the functions of sheet metal flow control and LFT sealing can be separated, which is a significant advantage.

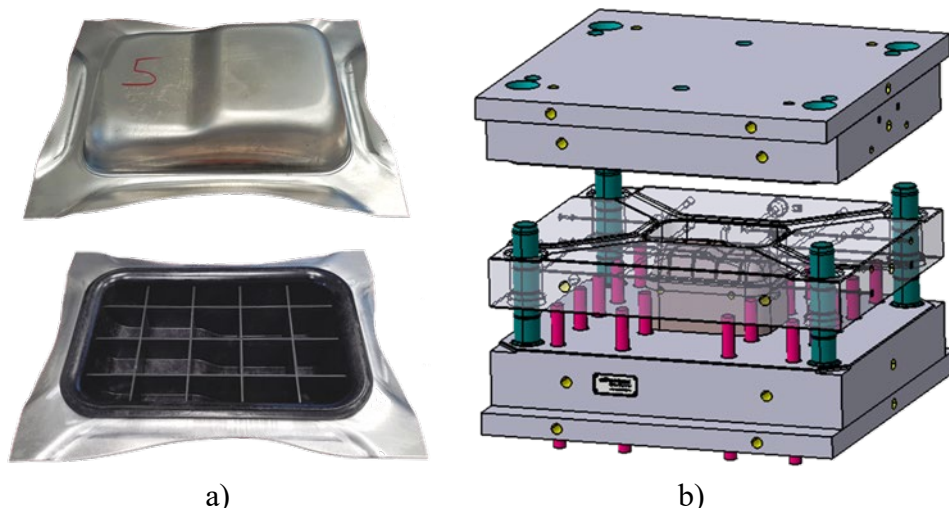


Fig. 2: Test part with tube geometry a) and the corresponding hybrid forming die b) [10]

The die is guided by four columns and can be tempered by water to different temperatures, e.g. 80°C. Furthermore, the different parts of the die (die, punch, and BH) can be tempered differently. The BH is supported by a die cushion so that the BH-force can be adjusted depending on the press stroke (see Fig. 2b).

At the beginning of the process, the BH-force must be kept low to enable a good material flow of the sheet metal, as in the case of sheet metal forming. Later, when the LFT/GMT materials, which are placed in the middle of the blank or the lower die, are pressed out- and upwards to the corner of the die, the BH-force must be increased. Towards the end of the process, a few mm before dead end, when LFT pressure is very high, since it must fill the entire hollow space between die and punch, the BH-force must be further increased. In this way, a good formability of even high strength steels and the sealing of LFT can be achieved. In addition, the velocity of the press must be chosen appropriately to enable process capability, LFT flow, and die sealing. Details can be found in [10].

3.2 Tooling concept for a U-profile with open ends

Looking at Fig. 3a, it is obvious that the sheet metal forming is very easy. However, the LFT/GMT materials can be very easily pressed out due to the open ends. In order to guarantee the sealing, two measures were introduced. One is the introduction of a small geometry characteristic in the profile and the other is the separation of the die into several segments.

For the first measure, a small (<5 mm) step was incorporated at the open end of the U-profile (see Fig. 3a). The punch was then divided into three segments: the main punch in the middle and two sealing elements at each end (Fig 3b). The sealing elements are supported by gas pressure springs and can deflect by an offset to the major punch, which is responsible for the the hybrid forming of metal sheet and LFT. During the forming process, the sealing elements move ahead. In combination with the counter holders of the lower die (Fig. 4a), these sealing elements clamp and deform the metal sheet on both lateral ends before the main forming by the major punch and LFT pressure increases. It was assumed that if both ends of the profile were pre-formed, these undercuts could work as mechanical sealing.

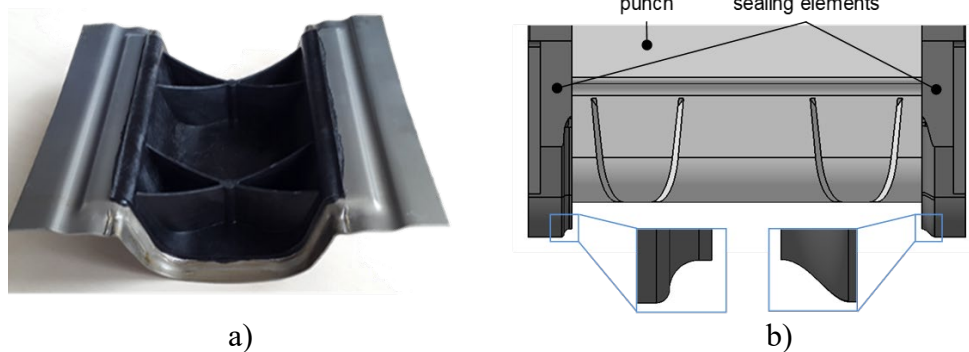


Fig. 3: Test part with open end a) and the corresponding hybrid forming die b) [10]

However, the LFTs can still be pressed out at the upper end of the profile since the gap in the triangle sealing element - die – BH can only be fully closed only at the dead end. To avoid this situation, the blank holder was extended inward of the die (Fig. 4b). In a top view of the tool, the sealing element has a step, as shown in Fig. 4a. In this way, the press out of the LFT can be fully avoided, as shown by the pressed part in Fig. 3a.

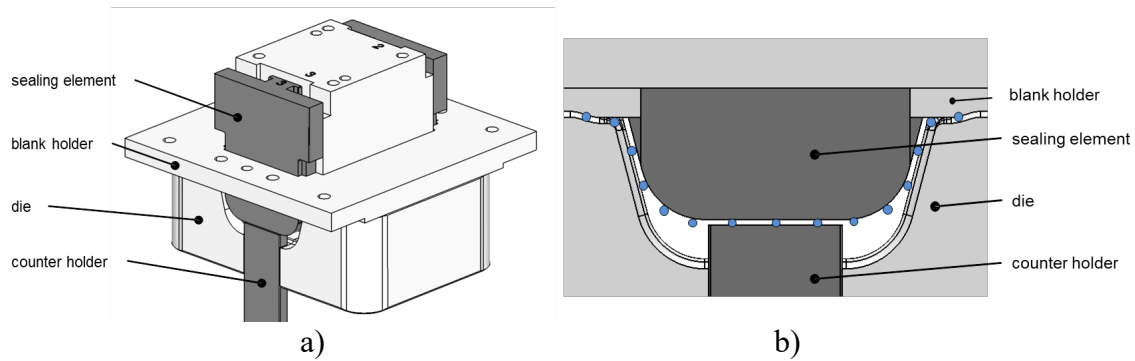


Fig. 4: Sealing for the open end of the U-profile: a) Overview, b) side view

4. Results and Analysis

Using the dies described above, hybrid forming tests were conducted on different steels (see table 1) in combination with a LFT which is PA6-LGF 40 with a fiber length of up to 25 mm when placed on the sheet metal.

Table 1: Properties of sheet steel used for hybrid forming trials

	$R_{p0.2}$ [MPa]	$R_{m,min}$ [MPa]	$A_{80,min}$ [%]
DC04	140-210	270-350	38
HC340LAD	340-420	410-510	21
HCT 590X / DP 600	330-430	590-700	20
HCT780X / DP 800	440-550	780	14
SZBS800 / CP-W800	660-820	760-960	10

Bonding agent:	VESTAMELT Hylink from Evonik
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Prior to hybrid forming, the sheet metal blanks were etched with grids so that after the forming the deformation of the sheet metal can be determined by using GOM ARGUS system. In Fig. 5a the equivalent strain on the tube geometry is shown directly on the part itself with different colors. The corresponding minor and major strains are plotted against the FLC with 10% and 20% margins of the steel used (HCT590X) at room temperature (RT) (Fig. 5b). The color of the measurement points in the FLC was chosen to be the same as those indicated in the part (as shown in Fig. 5a). Since some of the measurement points are far above the FLC and no splits were observed in the parts, FLCs for hybrid forming must be modified in the future. They could be shifted due to two effects: a) the FLCs of the steel at 200 °C should be higher than at RT; and b) during the hybrid forming, LFT works as a pressure media with low viscosity, and the friction between the punch/die and sheet metals may be reduced; c) however, the flow direction of LFT is the opposite to that of sheet metal (at least at the beginning of the hybrid forming process), and an adhesive bonding forms between the sheet metal and LFT during the process. Both effects (b and c) may increase the “friction” and reduce the FLC. Further investigations must be undertaken to understand these inter-actions.

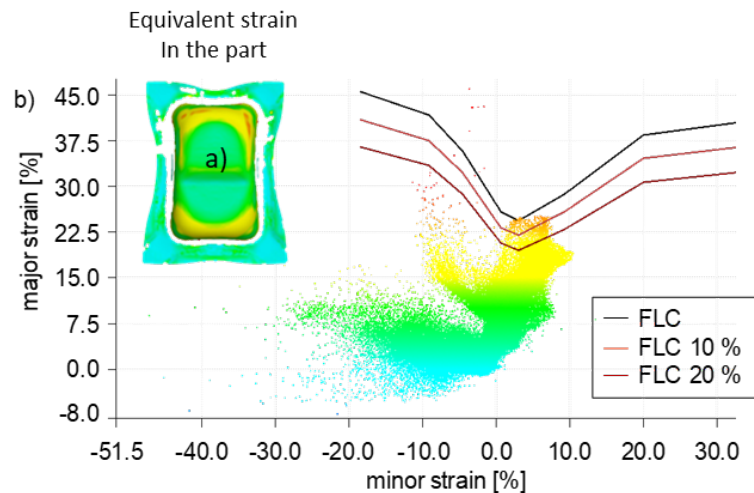


Fig. 5: (a) Equivalent strain on the part, and (b) strain measurements against FLC of HCT590X. The color of the strain in the part (a) corresponds to the color in FLD (b).

Since the pre-etched grids on the steel sheets were destroyed on the radii of the parts, the strains could not be determined there as can be seen by the white areas of the tube geometry in Fig. 5a. Therefore, the parts were cut in different sections to enable direct measurement of sheet thicknesses. In addition, LFT-thickness could also be determined, and the quality of bonding between LFT and steel could be visually inspected. These results are shown in Fig. 6. Due to the high strength of HCT 590 X steel (DP 600), LFT thickness at the radii are significantly reduced and often less than 1 mm whereas it was much thicker in the flat bottom area (Fig. 6b). For steels with lower strength, i.g. a mild steel DC04, the thickness distribution is much more homogeneous. In addition, the radii of the part made by DC04 formed more sharply in comparison to HCT550X when using the same die and press force. This fact must be considered at the CAD design stage of the part and/or when designing the die.

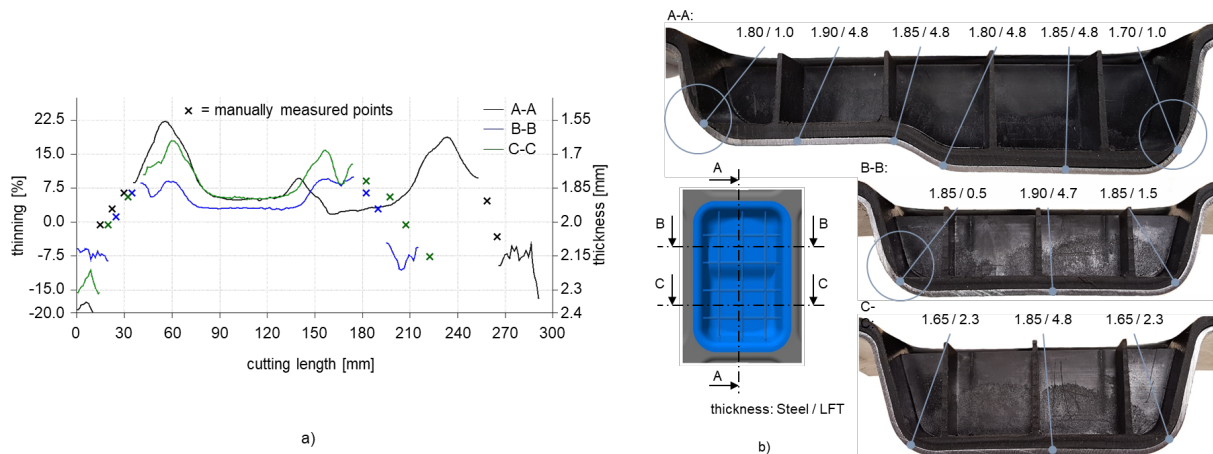


Fig. 6: Thickness distribution of steel sheets HCT590X and LFT PA8 LGF 40 in the hybrid-formed tube geometry. In a), the solid lines are thicknesses calculated from the major and minor strains in Fig. 5. In b), the first number is the thickness of the steel, and second is that of the LFT

As demonstrated in Fig. 6b, the overall bonding quality is very good. There are only a few small gaps between steel and LFT in the upper area of the part, which is a result of the spring back of high strength steel and the internal stresses between the steel and LFT.

With the help of coupon tests (Fig. 7), the shear strength could be measured (11 MPa), and the peel strength was 14 MPa. Both are quite high and comparable to the usual structural adhesives used in the automotive industry.

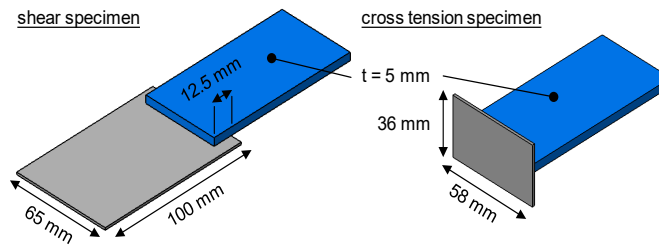


Fig. 7: Shear and peel test on hybrid formed steel sheet and LFT

5. Application Example

The hybrid forming technology was applied on two wheel-guiding components of a compact class vehicle (VW MQB Golf 7) [14]. Both light weight design and fail safe behavior were determined when the longitudinal control arm of the rear multi-link axle and the front lower control arm of the McPherson front axle were redesigned from steel to a steel-LFT-hybrid design. Since both control arms are originally manufactured using advanced high strength steels SZBS 800 (see table 1), which is a CP-W800 type of steel, it was a great challenge to achieve further weight reductions by using a hybrid design.

The development results are shown on the example of the longitudinal control arm of the rear axle as follows. At first, all the load cases of VW for this control arm (Fig 8a) were calculated using FEM. The resulting stress values and their distribution then served as target values for the new hybrid design. In the second step, the original sheet metal thickness of 3.5 mm was reduced to different values beyond a restricted minimum steel thickness. However, due to corrosion issues, the thickness of chassis parts should not be less than about 2 mm, which is a common practice of European OEMs. Together with the base steel part and using a defined space above the sheet steel part (Fig.8b), free size and topology optimizations were carried out to deliver the material distribution shown in Fig. 8c. Using the general guidelines for designing ribbed compression molding structures of LFT, the final design of the hybrid-formed part was completed. This consisted of a 2.0 mm sheet steel, a 2 mm LFT layer over the entire steel part, and local rip structures for reinforcement (Fig. 8d). This hybrid formed part weighed 20% less than the pure steel reference.

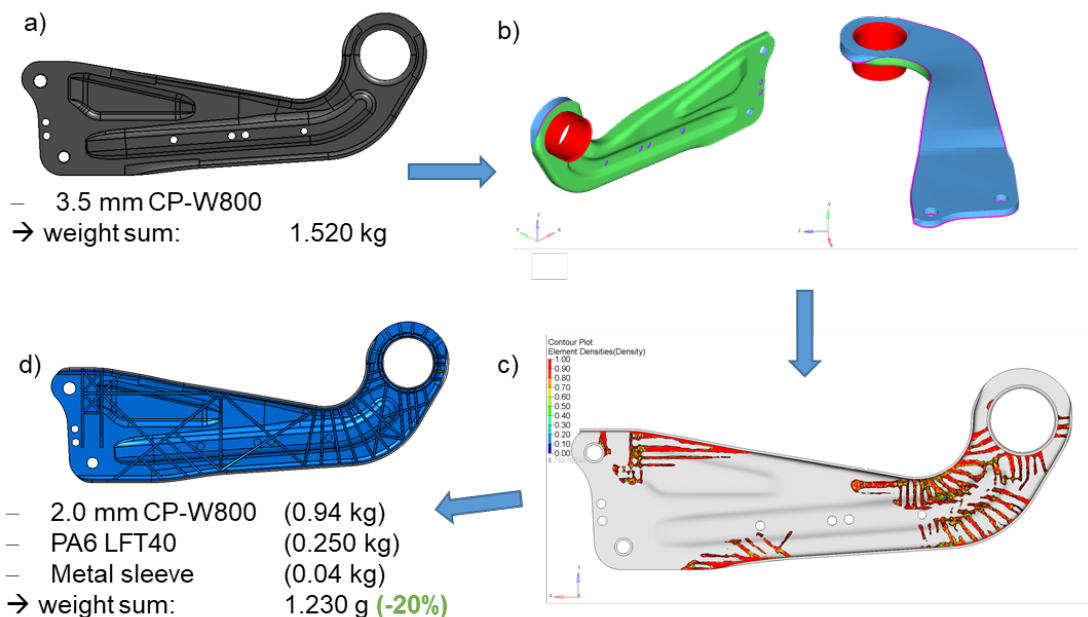


Fig. 8: Principle of designing a part for hybrid forming [14]: a) sheet metal part, b) basic FE-model for both free size and topology optimization with the design space, c) results of topology optimization, e) interpreted CAD design of the hybrid forming part

For this part, a hybrid forming die with the same sealing concept as for the tube geometry was designed and manufactured. After many trials with detailed changes to the die (radii and transition areas) and an adaptation of the process, hybrid parts could be stamped out of CP-W800 steel and PA6 GF40, as shown in Fig 9a. Furthermore, the draw parts could be trimmed by a water jet (Fig 9b). Cross section cuts (Fig 9c) indicate the good forming results of steel and LFT. Similar to the description related to the tube geometry, some small gaps were detected, especially in the upper area of the flange. These could have been caused by spring back of the high strength steel and the internal stresses caused by the different shrinking of LFT and steel.

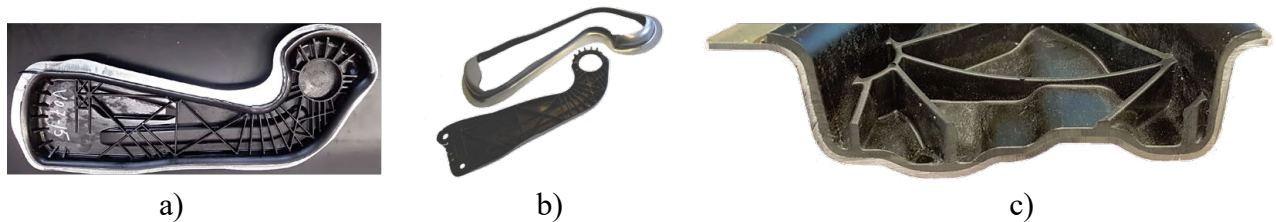


Fig. 9: (a) Hybrid formed longitudinal control arm, (b) after water jet trimming, and (c) cross section

Further investigations of the precision of the part geometry comparing to the CAD data were conducted using a 3D scanning technique. The results can be seen in Fig. 10. With increasing strength of the steel, the forming of geometric details, especially the sharp radii on the part, become increasingly imperfect. Spring backs also increase, as can be seen in by the blue color of the picture in the upper part of Fig. 10. Since the strength of Al alloy is lower, it was used as a reference, as the forming of all geometric details was almost perfect there.

As already known in sheet metal stamping, the spring back of high strength steels must thus also be considered during part design for hybrid forming. The radii and part depth must be changed accordingly to ensure that the desired geometry is obtained.

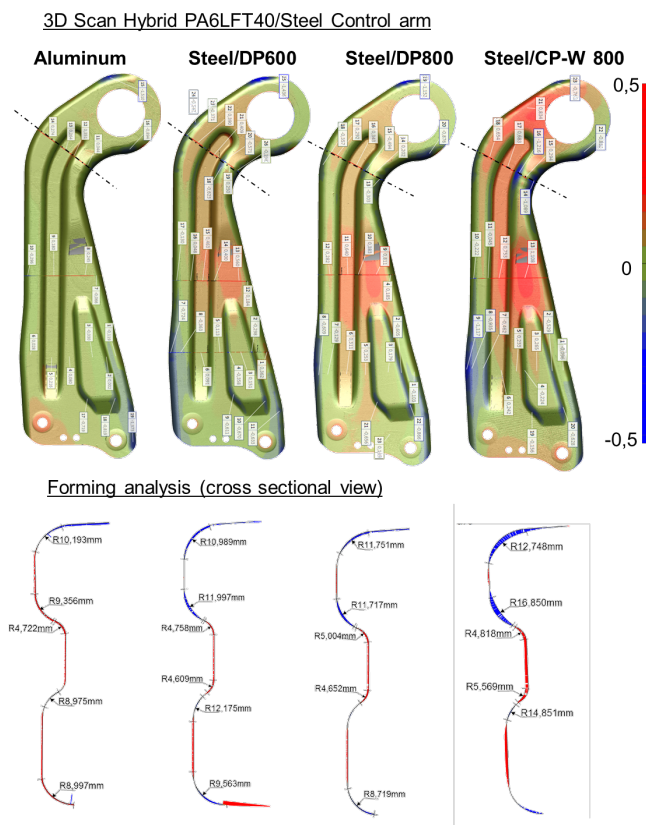


Fig. 10: 3D scans of control arms made from steels with different strengths (decreasing from CP-W 800 to DP 800 and DP 600) in comparison to a soft Al alloy

Further investigations (too extensive to be presented here) indicated that apart from the PA material, PP can also be used to hybrid form both steel and Al. The results of forming depend on the selected thermoplastic materials (for example, PA or PP), the pre-heating temperature of the sheet metal blanks, and the strength and formability of the sheet metal. The dependence on thermoplastic materials is caused a) by the different melting temperatures of PA (280 °C) and PP (220 °C), and b) the different viscosity, which have to be further investigated in detail. In addition to the FRP melting temperature, the pre-heating of the metal blanks also has an important influence. Due to the requirements for activation of the adhesion promotor VESTAMELT, the metal blanks must be pre-heated to 180 – 220 °C [13]. At this temperature, the formability of some of the metals may be increased while others may be reduced [15]. The sheet metal formability and strength, which are dependent to each other, have the most significant influence. As shown in Fig. 10, geometrical details of the part were clearly formed with higher precision as material strength decreased, with Steel CP-W 800 having the highest strength and Al the lowest. However, by considering this fact during the die design phase, geometric corrections in the die face can be conducted to ensure that the final part has the required geometry.

6. Summary

Automotive light weight design has been increasingly driven by multi-material approaches. Besides the development of different material combinations, and their design and development methods, new economical manufacturing methods are also required. The here presented new hybrid forming method is the result of such developments.

In contrast to most of the current multi-stage manufacturing processes for metal-FRP-multi-material components (PMA and IMA), the new hybrid forming method is a one-step method. It combines the hydro-mechanical sheet metal forming, the compression molding of FRPs and the joining between the two different materials in a simultaneous process. Hence, it is much more time and cost efficient compared to the well-known PMA and IMAs. In this method, half molten FRPs are used as the pressure media in a hydro-mechanical sheet metal forming process. If the die is sealed properly and hollow spaces for the rip structures are designed in the die, sheet metal parts with FRP reinforcement (rip structures) in the required positions and a large area of adhesive bonding between metal and FRPs can be formed.

In this work, in addition to the principle of the process, the die sealing concepts for two geometries, the closed end tube and the open end U-profile geometry were presented. Together with an appropriate process set up (press velocity, blank holder forces etc.), even high strength steel sheets could be hybrid formed with satisfactory geometrical details.

These die sealing and process concepts were applied to a real chassis component, a longitudinal control arm of the VW Golf rear axle. Using a new design method developed by the authors, the weight of the part could be reduced by 20% compared to the original steel design, while meeting all OEM performance requirements. The designed LFT and CP-W800 steel parts could be hybrid formed without cracks and good filling of the LFTs in the surface and rip-structures. However, sharp radii could not be fully formed, and spring backs were observed, which could generate separations between the LFT and steel. Thus, further development is required to avoid these problems.

Acknowledgments

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