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# Combined deep drawing and fusion bonding of structural FRP-metal hybrid parts

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**Abstract**

This research describes the development of a combined process of forming and thermal joining without adhesives of high strength steels and organosheets. In order to achieve cycle times below 20 s the temperature of the forming tool remains constant at 110 °C throughout the process. Thus, the removal of the component can take place immediately after the forming process without cooling of the forming tool. The thermal energy required to assure the thermal joining process at 280 °C at the beginning of the intermediate forming step is applied by means of heating the steel in a furnace before the transfer to the forming tool. By choosing certain coating depended heat treatment parameters during the heating step, galvannealed rough surfaces of the steel blanks can be generated in order to increase the joint strength. The paper includes a surface analysis and lap-shear testing results to quantify the respective joint strength to be achieved with the proposed surface treatment. In addition tensile test results of the heated DP800 steel to characterize the thermal influence on the mechanical properties of the heated high-strength steels will be shown. Furthermore the paper presents a tool concept with a graded blank holder to perform stretching of the metal on the one hand and draping of the organosheet on the other hand as well as preliminary forming results.

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## 1. Introduction

More and more structural parts consist of combinations between fiber reinforced plastics (FRP) and metals [1]. This shift to multi-material structures requires the development of cost-efficient production processes to enable affordable lightweight construction. From the point of view of production technology, there are two basic approaches to manufacture metal-FRP hybrid components. On the one hand, the composite partners can be joined before or after a separate forming process. On the other hand, forming and joining can occur in one process step.

### *1.1. Combined forming and joining*

A combination of forming and joining processes with thermoplastics was investigated as part of two subprojects of the research cluster "Process chains suitable for large-scale production for highly integrated components made of hybrid fiber-plastic/metal composites". [2, 3] The tools were heated up to 270 - 280 °C surface temperature. Subsequently, a preheated sandwich composite of aluminum cover plates and glass-fiber reinforced thermoplastic was inserted into the core and formed. The greatest forming challenge is to suppress wrinkles in the flange area of the hybrid component. Due to the soft polymer matrix, there is only a one-sided unyielding contact between the thin cover plates and the blank holder or drawing ring, which does not succeed in completely suppressing the formation of folds. If the holding-down forces are too high, the matrix is squeezed out. After reaching the bottom dead center of the forming process the variothermal tool actively cools down close to the surface. The cooling time lasts 45 s. [3]

The thermal joining of metal and plastics with hot and cold tools is a well-known process in research in the field of joining technology. The heat conduction joining of metal-plastic hybrid joints is the most common process. The tool is heated with the help of heating cartridges. Due to the contact between the tool and the workpiece, the thermoplastic matrix is melted in the joining zone [4]. Flock showed that different Polyamides (PA6.6) can achieve sufficient joints when a surface pre-treatment is applied. Without a surface pre-treatment on the metal side only poor joint qualities were achieved [5]. For a combination of polyamide (PA6.6) and steel, an optimum joining temperature in the range 260 - 270 °C was determined. The complete joining process within the scope of these investigations took up to 600 s [5]. In order to reduce process times, projects developed test facilities in which the tool is heated inductively [6] or the metallic joining component is heated conductively [6]. In order to achieve higher bond strengths during fusion bonding, various pretreatment processes of the joining partners have been investigated. These pretreatment processes include for example sand blasting [7], embossing of structures [8], corundum blasting [9, 10] and laser pre-treatment [11].

### *1.2. Galvannealing*

Within the framework of this research project, a galvannealed layer is produced on the surface of the steel for surface structuring. Galvannealed coatings are produced by annealing galvanized steel sheets at temperatures around 500 °C [12]. During the heat treatment, iron atoms diffuse into the zinc layer and a zinc-iron layer is formed, which is characterized by improved corrosion protection, improved weldability and higher scratch resistance compared to hot-dip galvanized sheets. A further and decisive advantage for this research project is the significantly improved adhesion of substances to the coating, as a rough surface is formed [13].

The challenge in producing the galvannealed layer is to generate a surface that enables mechanical interlocking which still ensures a defect-free formability. The main types of failure of galvannealed layers during forming are powdering and flaking. Powdering is the removal of layer particles, in which the size of the particles is significantly smaller than the layer thickness. The delamination of larger particles is referred to as flaking. Flaking and powdering are influenced by the Fe content in the layer which can be adjusted via the diffusion time and temperature. [14, 15]

## 2. Experimental setup

This research examines the potential and challenges of a combined forming and joining process to manufacture metal-FRP hybrid parts. The heating of the FRP and the metal component are performed in two separate ovens which are decoupled from the forming process. The forming tool remains constant at a temperature of 110 °C throughout the process. Thus, the removal of the component can take place immediately after the forming process without cooling of the forming tool. The thermal energy required to assure the fusion bonding process at 280 °C at the beginning of the intermediate forming step is applied by means of heating the steel in a furnace before the transfer to the forming tool. In addition to the heating of the metal sheets, the galvannealing takes place. The reference part for this research is a deep-drawn s-rail part consisting of a high strength steel and glass fiber reinforced thermoplastic depicted in Fig. 1.

Fig. 1. Hybrid s-rail (high strength steel/organosheet).

### 2.1. Experimental Devices, Methods and Materials

Within this research, DP800_GI (GI: hot-dip galvanized) and HX340_LAD+Z100 with a sheet thickness of $s_0$ = 1 mm were used as the steel components of the hybrid joint. The FRP was an organosheet which consist of a polyamide 6 (PA6) matrix and 0/90° woven (twill 50:50) continuous glass fiber sheets with a glass fiber content of 66 % and a material thickness of 1.5 mm. The melting temperature of the organosheet is about 220 °C.

To screen the effect of the heat treatment different investigations have been carried out. On the one hand the influence of the heat treatment on the surface roughness and the mechanical properties of the steel have been measured. On the other hand single lap-shear tests have been made in order to characterize the joint strength with different pretreatment settings. The heat treatment of the steel sheets is conducted in a convection oven at a temperature of 470 °C and 550 °C for 15 s and 30 s. The heat treatment temperatures and dwell times were selected accordingly to the parameters of an industrial galvannealing processes. Additional heat treatments at 420 - 460 °C and 15 s dwell time were performed for the tensile test specimen in order to identify the lower limits of a thermal effect on the mechanical properties of the steel adherend.

The surface characterization is done by using a stylus instrument and a scanning electron microscope (SEM). This combination was chosen to provide not only SEM images but also quantitative values from surface roughness measurements. The surface roughness measurements have been performed on the cleaned (with isopropyl) and pre-treated metal surfaces. The stylus instrument is a MarSurf M400 from Mahr GmbH (Goettingen, Germany). In order to measure the average surface roughness ($R_Z$) the line distance was set to 5.6 mm. The surface was measured alongside the later applied test force of the lap-shear test. In order to achieve a statistic relevance three samples have been measured three times at different locations.

The SEM recordings have been acquired with a FEM Quanta FEG 650 from Thermo Fisher Scientific Inc. (Waltham, USA) with an acceleration voltage of 10 kV. The samples were cleaned with isopropyl and blasted with Nitrogen to prevent loose residues on the metal surface which could otherwise interfere with the electron beam of the SEM.

The tensile test was conducted accordingly to DIN EN ISO 6892 on a Dynamess S100/ZD tensile testing machine with $A_{80}$ specimen with five iterations.

The size of the test specimen for the lap shear test were 100 * 25 mm with an overlap of 12.5 mm according to DIN EN 1465with also five iterations. The test speed was set to 10 mm/min. The lap shear specimens were joined in a hydraulic press (Hydrap HPDZb 63) with a heatable panel tool. Firstly, the specimens were cleaned with isopropanol und placed in the tool at a tool temperature of 60-80 °C. Secondly, the tool was closed and the tool temperature was increased to 280 °C. When the bonding temperature was reached, the bonding pressure of 8 MPa was applied. The target melting depth was 0.1 mm. After a dwell time of 10 s the tool was cooled down to 80 -100 °C removal temperature.

## 3. Results and Discussion

### *3.1. Mechanical properties after heat treatment*

Fig. 2 shows stress strain diagrams of DP800 and HX340 in the initial state and after a particular heat treatment at 420 – 470 °C at 15 s. For both steels the heat treatment performed to increase the surface roughness, effects the mechanical properties.

For the DP800 the heat treatment causes a formation of Lüders bands, a considerable increase in the yield strength as well as a decrease in the tensile strength compared to the untreated specimen (initial state). Above 450 °C there is a considerable drop in elongation at break and yield strength is lower compared to the heat-treated specimen under 450 °C.

The heat-treated HX340 specimens have a major increase in upper and lower yield strength from 350 (initial state) to 430 MPa. Taking the variance of test results into account, there is no significant change in tensile strength and elongation break.

The change in mechanical properties can lead to certain unpredictability for forming or springback behavior. For both materials, a lower limit of a thermal effect on the mechanical properties could not be identified within the tested temperature range. For the actual combined forming and joining process, the heating temperature cannot be chosen significantly lower considering the transfer of steel sheet from the furnace to the forming press. Thus, the material choice has to be reconsidered or a modification on part of the steel manufacturer has to be made before an industrial application of the process.

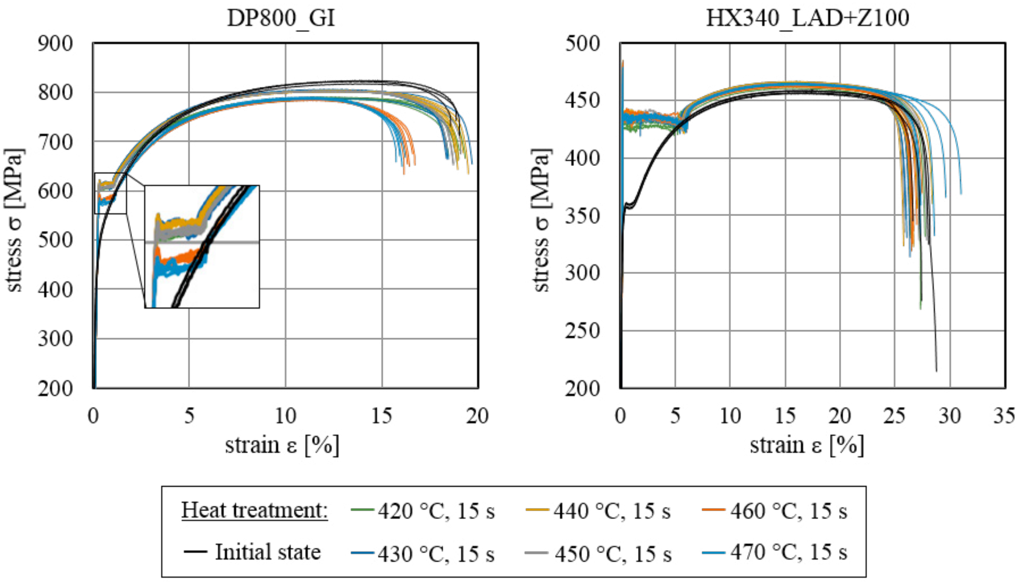


Fig. 2. Stress-strain diagram for (a) DP800_GI (b) HX340_LAD+Z100.

### *3.2. Surface analysis*

The surface roughness measurements of the two materials show a different behavior for the applied heat treatments (Fig. 3). The DP800_GI achieves a surface roughness of 5.0 ± 1.2 µm on cleaned surfaces. By applying a heat treatment of 470 °C for a dwelling time of 15 s the surface roughness decreases to 3.1 ± 0.3 µm and achieves comparable results to a cleaned surface, when the dwelling time is increased to 30 seconds. By increasing the temperature of the heat treatment to 550 °C the measured average surface roughness can be increased. A dwelling time of 15 s achieves an increase of $R_Z$ to 16.5 ± 1.2 µm which could not be increased by prolonging the dwelling time. The HX340 material in comparison shows a different behavior throughout the heat treatment. The cleaned surface shows a $R_Z$ of 7.1 ± 0.6 µm which was increased to 11.0 ± 0.8 µm with a treatment at 470 °C for 15 s. A further increase of the dwelling time did not provide an increased surface roughness. A higher dwelling temperature shows also no promising increase of the surface roughness.

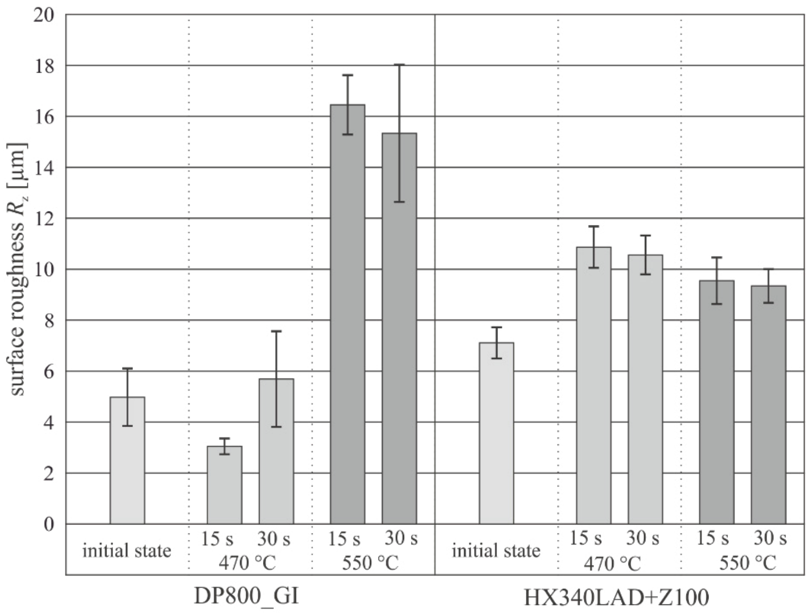


Fig. 3. Surface roughness of DP800 and HX340 specimen before and after heat treatment.

## *3.3. SEM recordings of galvanealled surfaces*

The results of the qualitative surface analysis with the SEM are discussed in the following section. The investigation starts with the DP800_GI surfaces before the images of the HX340. The DP800_GI and HX340 surfaces with the investigated dwelling temperature (470 and 550 °C) and dwelling times (15 and 30 s) are shown Fig. 4.

The SEM images of the DP800_GI show no significant surface characteristics for the surface pre-treated at 470 °C for 15 s. An increase of the dwelling time leads to a change of the surface topography and the zinc coating seems to ripple in some discrete areas from the applied heat. Both surfaces show no signs of undercuts which should have a negative influence on the fusion bonding process. The surface topography changes when the dwelling temperature is increased to 550 °C as the images show (see Fig. 3).The increased dwelling temperature leads to a significant change in the surface topography of the DP800_GI. The surface is now covered with small cubic shaped structures. These structures seem to lie on top of each other and should provide a good mechanical interlocking for a later fusion bonding process due to the formation of undercuts. By increasing the dwelling time no changes of the surface topography can be observed.

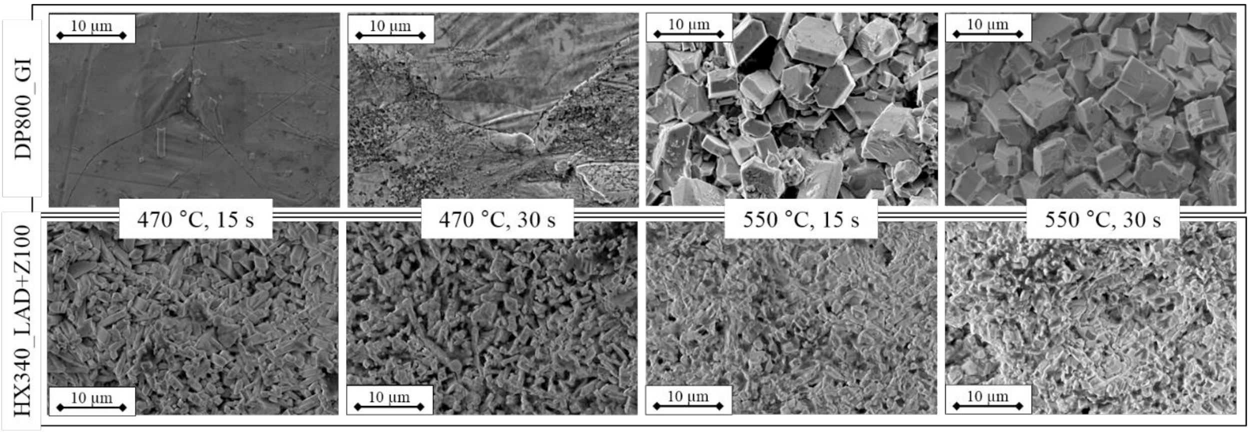


Fig. 4. SEM images of DP800_GI and HX340 surfaces after the heat treatment (acceleration voltage: 10 kV).

The SEM images of the HX340 at a dwelling temperature of 470 °C show a surface which is covered with stick like structures which seem to grow out of the zinc coated surface. The structures are better distinguishable from the surface when the dwelling time is increased to 30 s. An increase of the dwelling temperature leads to the formation of shorter structures which seem to be vague. This does not change for higher dwelling times.

The analysis of the surfaces after the introduced heat treatment shows the potential of a suchlike pre-treatment. The surface roughness can be significantly increased from the initial state depending on the base material. The DP800_GI surface roughness could only be increased when a high pre-treatment temperature (550 °C) was applied. In this case the surface roughness increased by 230 % (550 °C for 15 s) compared to the initial state. The increase in surface roughness was also visible in the SEM recordings of the surface, which showed a surface that was characterized by undercuts formed from overlaying cubes. The lower dwelling temperature (470 °C) shows a decrease of surface roughness which also correlated well with the appearance of the surfaces as the SEM images shown in Fig. 3. The effect of the heat pre-treatment on the HX340 surfaces was not as severe as it has been for the DP800_GI. The surface roughness could also be increased by up to 52 % compared to the initial state but the increase was not correlated to the dwelling temperatures. The results of the stylus instrument measurements and the SEM images show nearly no difference throughout the investigated heat pre-treatment settings for the HX340. In case of the HX340 a lower heat pre-treatment is sufficient to achieve a rougher surface whereas the DP800_GI needs higher dwelling temperatures in order to form a rougher surface topography.

### 3.4. Lap shear strength

The results of the lap shear test for D800_GI/PA6-organosheet and HX340/PA6-organosheet are depicted in Fig. 5. With the exception of one test series (DP800_GI, 470 °C for 30 s), the heat treatment of the steel component enables high bond strengths. However, the influence varying heat treatment parameters differs.

The tensile shear strength of the DP800_GI/PA6GF66 samples increases with higher heat treatment temperatures. The highest shear strength is achieved with heat treatment at 550 °C for 30 s. The tensile shear strength of the HX340/PA6GF66 specimen increases with lower heat treatment temperatures with a maximum mean of 18 MPa after a heat treatment at 470 °C for 15 s. Against the background of the high variance of the results, an influence of the heat treatment time cannot be clearly proven. Since there is no clear correlation between the surface measurement results and the lap shear test results the assumption can be drawn, that there is a strong superposition between structural and chemical adhesion mechanism.

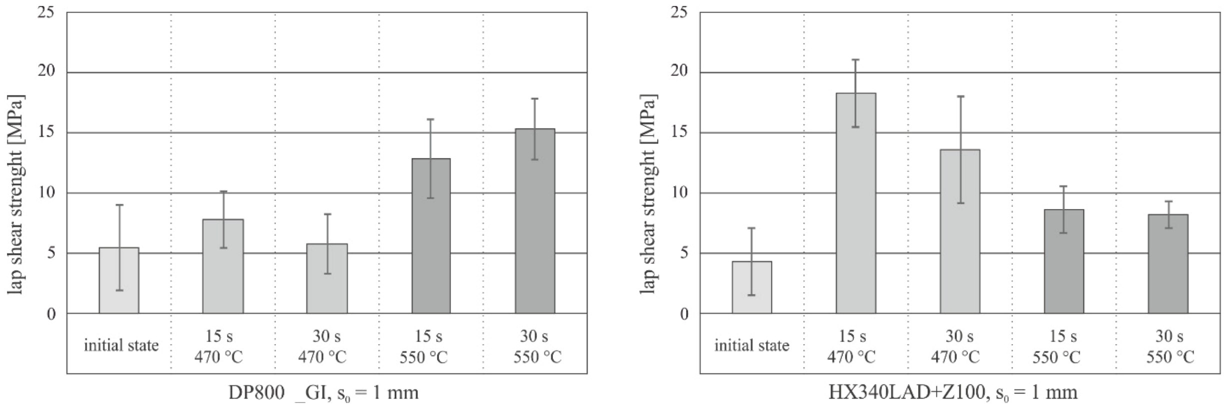


Fig. 5. Lap shear test results for DP800/HX340 and organosheet.

For the lower temperature at 470 °C, the HX340 samples show a cohesive failure of the zinc coating to the substrate as well as a matrix failure (Fig. 6). The appearance of the fracture patterns does not change significantly for the different dwelling times, which correlates with the results of the lap-shear test. The fracture patterns of the DP800_GI show an adhesive failure of the thermoplastic matrix with some minor matrix residues on the metal adherent. This fracture pattern could be expected when the low surface roughness measurements and the low lap-shear test results are taken into account.

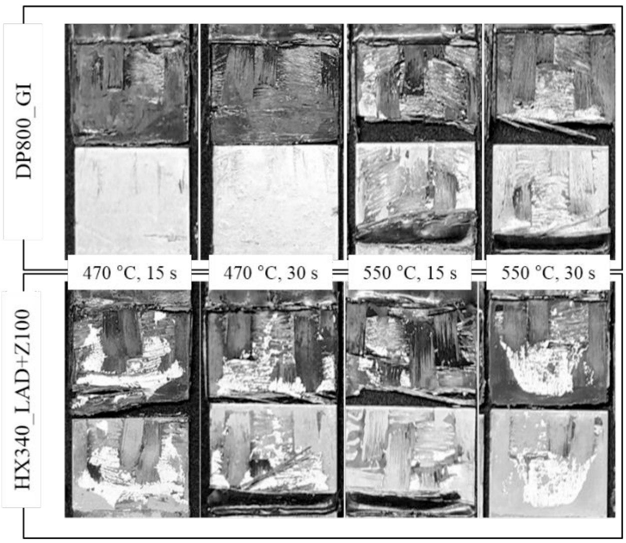


Fig. 6. Fracture patterns after the lap shear test for DP800/HX340 and organosheet.

The fracture patterns of the samples pre-treated with a higher dwelling temperature show for the HX340 material a cohesive failure of the thermoplastic matrix and only minor failures of the zinc coating. For longer dwelling times the fracture pattern changes into a combination of cohesive failure between the thermoplastic material and the zinc coating and a failure of the zinc coating with the substrate. In comparison to the fracture patterns at 470 °C the higher dwelling temperatures result in less thermoplastic residues on the surface which could explain the lower lap-shear strength. This result on the other hand is interesting because the surface roughness measurements did not show significant differences for the surface pre-treatments which should lead to the same result for all HX340 samples if the surface roughness or mechanical interlocking is the sole adhesion mechanism.

For the DP800_GI an increase of the dwelling temperature leads to higher lap-shear strength which is also resembled by the resulting fracture patterns due to a cohesive failure of the thermoplastic matrix nearly without any failure of the zinc coating. In comparison to the fracture patterns of 470 °C, which showed a complete adhesion failure, the fracture pattern was improved by increasing the heat treatment temperature.

## 4. Forming process and forming tool

In contrast to combined processes for the production of hybrid components that are realized on injection molding lines, one of the hybrid components dominates the combined forming on forming machines. In this research it is the forming of the high strength steel. To prevent wrinkling caused by tangential compression stresses the hybrid stack has to be formed with blank holder. The required blank holder force is 250 kN to stretch the blank and avoid wrinkling.

However the glass fiber within the organosheet cannot be stretched. By heating beyond the melt temperature, the composite expands in the thickness direction, because the impregnated fabric layers, which were pressed and consolidated during the manufacturing process of the organosheet, relax and move in the starting position prior to the pressing. This effect is referred to as lofting.

The forming of the organosheet is enabled by the following forming effects: fiber elongation and yarn straightening (tensile stress along the fiber), inter ply slip and intra ply shear [16]. Thus, the die includes a pocket for the organosheet. Within the blank holder area, the pocket is 1.8 mm deep, which is the thickness of the lofted organosheet after the heating over melting temperature. Starting at the draw radius, the pocket narrows to the initial sheets thickness of the organosheet of 1.5 mm to re-consolidate the plies of the organosheet (Fig. 6).

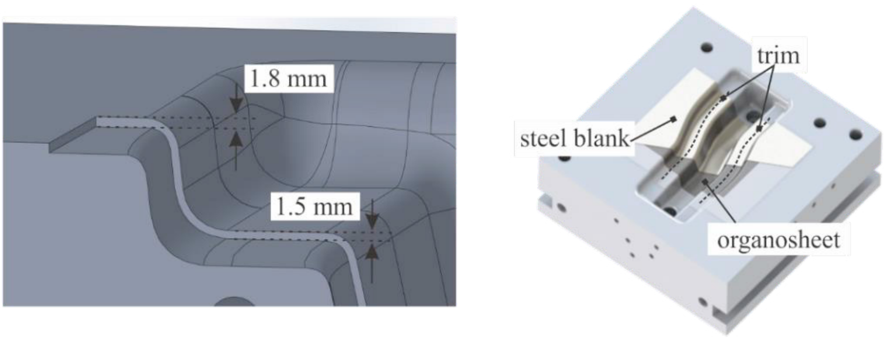


Fig. 7. Tool geometry with a graded blank holder.

## 4. Conclusion and outlook

This research shows the development of a combined deep drawing and fusion bonding process to manufacture hybrid structural parts. Both components are heated separately, transferred into an isothermal forming tool, formed with the help of a graded blank holder and joined at dead bottom center. The graded blank holder prevents wrinkling in the steel and at the same time ensures the feeding of the organosheet. In addition to the heating of the metal sheets, a heat treatment takes place to generate a rough iron-zinc surface. Depending on which high-strength steel alloy with the corresponding coating was used, different surface structures are formed.

The proposed heat-treated surface offers a significant potential for achieving high lap shear strengths up to 18 MPa with predominantly cohesive failure patterns. However, for both steels the heat treatment effects the mechanical properties. A lower limit where there is no influence on the mechanical properties could not be found within the tested temperature range. Thus in case of industrial application of the process, a reconsideration of the material choice or a modification on part of the steel manufacturer is required.

Further research on this topic will include the impact of the graded blank holder on forming of the steel sheet, fusion bonding at the end of the forming step under a wall angle of 5 - 15 ° in the reference part (s-rail). Moreover, the comparison of the surface roughness measurements and the lap shear tests results show that a chemical adhesion mechanism must be present for the investigated fusion bonds in order to explain the different results of the lap shear test, which has to be investigated.

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