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# Forming and Joining of Carbon-Fiber-Reinforced Thermoplastics and Sheet Metal in One Step

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**Abstract**

The processing and component properties of metals have led to their worldwide success in mechanical engineering. Their advantages are high ductility, efficient production methods, good joining ability and nearly isotropic mechanical properties. Fiber-reinforced plastics (FRP) are known for an excellent lightweight design potential, due to low density as well as high and anisotropic tensile stiffness. By using thermoplastics instead of thermoset matrices, processing times and therefore component costs have already been reduced significantly and thus have become affordable in large-scale application. If the advantages of both, metal and FRP, are intelligently combined, a part with tailored properties is created. However, suitable forming processes, which take the different forming effects of both materials into account, have to be developed yet.

The scope of this research was to enable the combined forming, joining and impregnation of pre-impregnated FRP-sheets and sheet metal to steel-CFRP-steel-sandwich-parts in one process step. As forming and joining must be executed at temperatures above the melting point of the thermoplastic while the part removal must take place beneath this temperature, a heating concept for drawing tools was developed to enable short production cycles. In order to ensure an economic industrial production a fast heating and cooling of the tool is essential. Afterwards optimal impregnation and joining process parameters for short cycle times were determined with planar samplings. The influence of the process parameters on part quality was investigated microscopically. Based on this research, a forming tool was constructed and hat profiles of steel-FRP-steel sandwiches were drawn successfully. Subsequently, the impregnation quality was investigated based on the process parameter tool temperature. Furthermore, the geometrical deviation of formed hat profiles was investigated.


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*Keywords:* Variotherm Forming, Fiber-Reinforced Thermoplastics, Metal

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## 1. Introduction

Metals are used widely in engineering due to their outstanding processing and component properties. In particular, the processes for the production of sheet metal parts are characterized by a high productivity and therefore they are presently predominant in large-scale production. In contrast, fibre-reinforced thermoplastics are characterized by great potential for lightweight design but inefficient manufacturing processes. Although the forming effects and forming characteristics of both materials differ considerably, the forming processes of sheet metal and fibre-reinforced thermoplastic sheets themselves do resemble. In sheet metal forming tools consisting of punch, die and, if necessary, blank holder are used to manufacture efficiently. Based on this efficient forming technology, a new technology was to be developed to form steel-FRP-steel sandwich parts using common forming facilities.

## 2. Process Development

### *2.1. Design of the steel-FRP-bond*

In [1] and [2] a hybrid demonstrator component, which is similar to a roof cross rail, has been developed and evaluated in terms of lightweight potential towards conventional steel components. One solution with a great lightweight potential is a sandwich structure consisting of cover sheet metals from steel and unidirectional carbon fibre reinforced plastic in between. The scope of this investigation is the development of a manufacturing technology, which allows producing such a component. Since there are no semi-finished products meeting this layer setup, an already impregnated and consolidated semi-finished product has been used in previous investigations for the FRP centre. This organic sheet has been heated with the cover sheet metals above the melting point of the thermoplastic and then been joined and formed simultaneously in a tool. The resulting process chain consists therefore only of the process steps heating and forming, which is very short and cost-saving [3].

An evaluation of the whole process chain regarding the manufacturing of the organic sheets too shows, that this chain is not designed optimally. Since the partially impregnated tapes (prepregs) of the thermoplastic and the fibres are stacked, heated, pressurized to impregnate and consolidate and cooled to get the mentioned organic sheet. Subsequently, the cover sheet metals and the organic sheet are stacked again, heated, pressurized to allow forming and the final consolidation and cooled again. So the FRP passes very similar process steps several times. For further investigations, the process chain has been shortened to an impregnation, consolidation and forming in one tool step only. The resulting process chain is stacking the prepregs and sheet metals, heating, pressurizing (forming, impregnating and consolidating) and cooling. Figure 1 shows the setup of the applied semi-finished products and their stacking order.

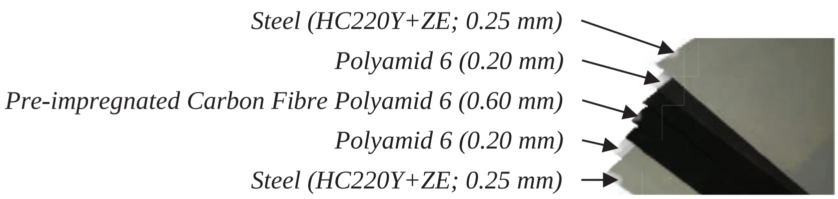


Fig. 1. Stacked semi-finished materials

The additional PA6 layers between the cover sheet metals and the actual FRP have been used to increase the adhesive joint between the cover sheet metals and the FRP. The adhesive bond between thermoplastic and sheet metals is enabled by the adhesive properties of the polyamide and it may be a potential weakness of the bond. This issue is increased during forming, if fibres push towards the sheet metal surface and thus reduce the adhesive area. A buffer layer of PA6 hinders the fibres getting to the surface. Furthermore, there is a risk of contact corrosion if fibres and sheet metal contact. The PA6 buffer layer prevents such a contact, too.

### 2.2. Designing a variotherm forming and joining process

To form, impregnate and consolidate the bond in only one tool step, a variotherm tool system is necessary, since the thermoplastic has to be molten for the impregnation and simultaneously pressurized for a specific time. In this time period, the matrix penetrates the still dry fibres and surrounds them completely. Heating in an upstream oven with subsequent forming in a relative cold tool is not possible, as the bond solidifies almost immediately when connecting with the tool and thus impregnation proceeds insufficiently. On the other hand, because the bond adopts the tool temperature that quickly, no further heating step is necessary before forming when a heated tool is used. Consequently, the semi-finished material passes the temperature curve shown in figure 2 during forming in a variotherm forming tool. At first, the insertion takes place. A few seconds after tool contact under pressure, the thermoplastic reaches the tool temperature $T_T$ above its melting temperature $T_M$. Forming starts by closing the tool. At the bottom dead centre, the tool is closed and the FRP pressurized for a few seconds to allow the impregnation, before cooling the tool along with the component to the removal temperature $T_R$ followed by the extraction of the component.

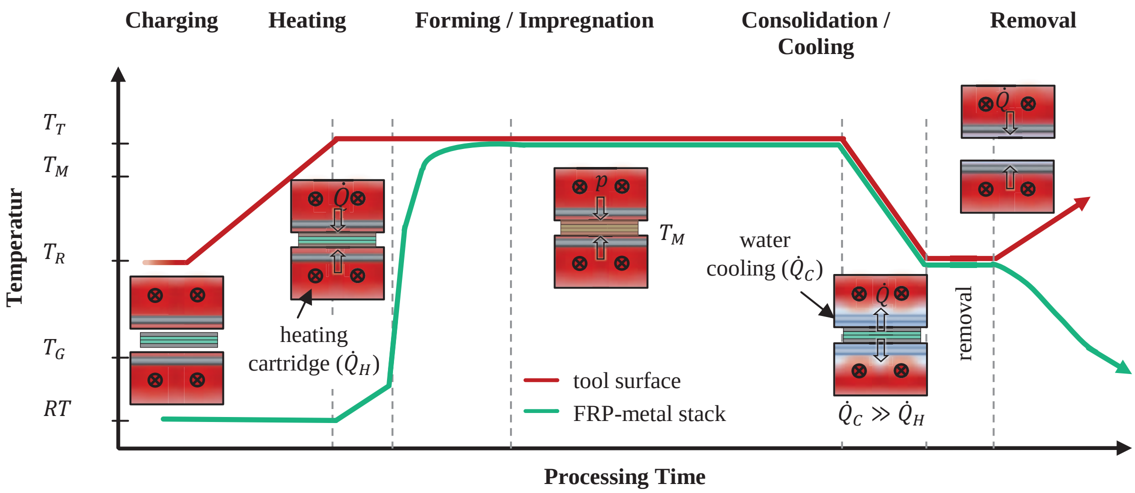


Fig. 2. Temperature-time profile of the tool surface and the part in one forming cycle

Because heating and cooling of the whole tool is very time- and energy-consuming, a tool system according to [4] has been developed. The main idea is that it is sufficient to control the temperature of the tool surface only and thereby tempering the component. Thus, it is not necessary to heat and cool the whole tool periodically. After several preliminary tests, a concept has been chosen, in which the tool is permanent at the targeted forming temperature and is only cooled at the surface in the area of the component for the removal. This results in a high temperature gradient, which enables a quick reheating of the active surfaces after shutting down the cooling. The quicker and closer to the contour the tool is cooled, the higher is the temperature gradient in the tool and the quicker the reheating takes place.

Figure 3 shows a forming tool, which has been designed with this heating concept. The tool consists of a punch, blank holder and a die. With this tool, hat profiles with a maximum length of 200 mm can be produced. The blank holder and punch are distanced adjustably to the die in order not displace the plastic excessively during the impregnation, but nevertheless to build up enough impregnation pressure. Even though a blank holder is not required necessarily when manufacturing hat profiles without tangential compressive stress, one has been realized to gain knowledge for further investigation with more complex component geometries. Specifically in Fig. 3 a the close-to-contour bores of the punch are well visible, which allow fast heating cycles.

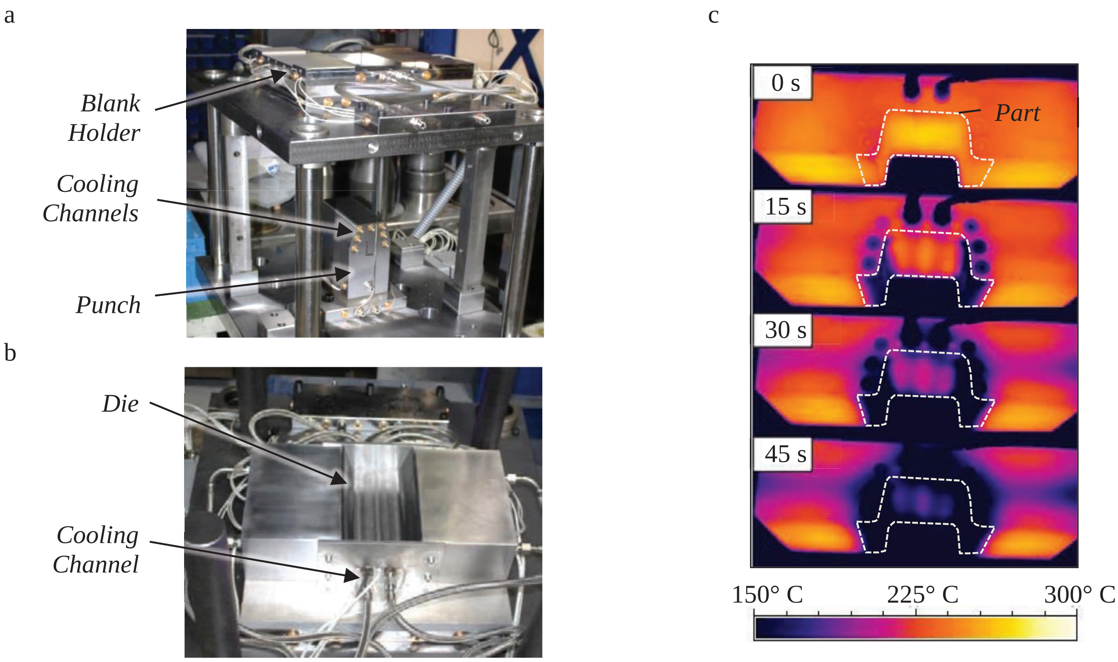


Fig. 3. Photograph of the (a) blank holder, punch and (b) die. (c) Thermal images of the forming time when cooling. Start of cooling at 0 s

Fig. 3 c shows a sequence of thermographic images of the die during cooling. The position of the component after forming is marked with an outline. First the die has the tool temperature of $T_T$ = 250° C. After activating the cooling, the die cools down in the component area to the removal temperature $T_R$ = 160° C in a few seconds. If the component is removed and the tool subsequently heated again, the tool can reach its target temperature again within 4 minutes. Considering loading, cooling and the actual forming and consolidation, cycle times of 6 minutes can be realized. With optimized cooling channels, for instance by shell design with cooling channels just underneath the actual tool surface, the locally restricted cooling time and with that the temperature gradient and finally the cycle time can be reduced even further.

## 3. Experimental Investigation

### *3.1. Impregnation parameters*

With the same heating concept and process parameters, flat samples have been produced in a separate sheet mold tool with variating tool temperature $T_T$ and been investigated microscopically to evaluate the impregnation and consolidation quality. Therefore samples have been stacked and pressed for 30 s in the heated tool, before activating the cooling. The tool temperature has been varied from 10° C above the melting temperature $T_L$ of the PA6 to the beginning of the decomposition temperature of 280° C.

Figure 4 shows the results of the microscopic investigation. The view direction is axially to the fibre direction. Of the samples produced with a tool temperature of 230° C, no microscopic analysis could be carried out, because the material bonding has not been sufficient. After cutting the microscopic samples from the produced plane components a delamination without load took place, so further investigations were irrelevant. Although a material joint has been produced with a tool temperature of 280° C, the microscopic analysis shows decomposition phenomena in the form of outgassing and therefore gas cavities in the matrix. The samples produced with 250° C showed however a good impregnation and consolidation quality. The buffer layer of PA6 is complete and separates the fibres and the sheet metal within the whole area, leading to an optimum connection. The single prepreg layers are also recognizable clearly in the microscopic investigation. Although small gas inclusions remain, the impregnation has been preceded well. It is known, that longer impregnation times of above 7 minutes leads to further interfuse of the layers and also a reduction of residual gas cavities [5], but also leads to a reduction of productivity.

Tool Temperature 230° C Tool Temperature 250° C Tool Temperature 280° C

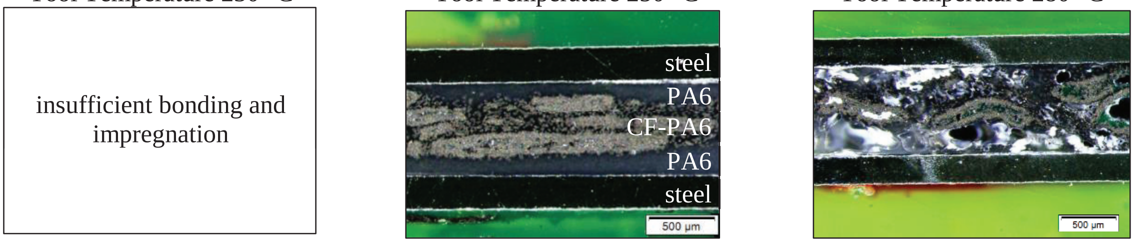


Fig. 4.: Microscopic investigation of the impregnation quality at different tool temperatures.

### 3.2. Geometrical deviation

With the mentioned material stack-up and the direction of the unidirectional fibers following the profile direction, hat profiles have been produced with a tool temperature of 250 °C. Such a component is shown in Figure 5a. The bonding has been produced successfully. Even in the steep component wall areas, the adhesive bonding as well as the impregnation succeeded. Peculiarly, each component had a material accumulation in the area of the drawing edge. With regard to the simulation results produced with the model developed at the IFUM [6], the reason for this material accumulation becomes apparent. Since the blank holder has to be distanced and no adhesive bond has yet been produced during forming, the sheet metals were not tightened and thus bulged over the punch during drawing because of their inherent stiffness. In figure 5 b, this material excess can be seen clearly as a wave formation. When the tool closes, the excess sheet metal will be displaced and moves along the tool profile. Then the plastic melt pressure forms the sheet metal similar to sheet-metal forming processes by means of plastic melt pressure [7], herein caused constructively between punch and blank holder.

a b c

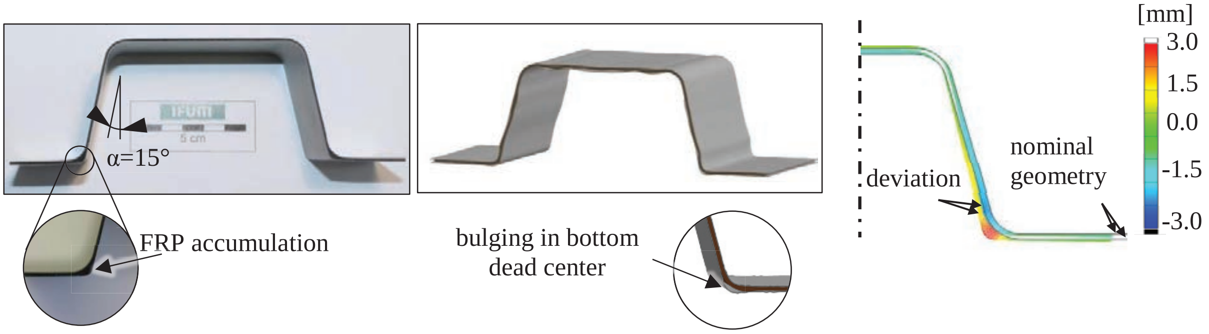


Fig. 5: (a) Photograph of a steel-FRP-steel-FRP hat profile; (b) numerical forming simulation of the hybrid part just before bottom dead center; (c) graphical representation of the nominal geometry and the deviation.

Figure 5 shows the geometric accuracy of a hat profile towards the target geometry. The material accumulation is clearly visible herein, too. In sheet metal forming elastic spring-back is a known phenomenon [8, 9]. While in forming fibre reinforced plastics the spring-in-effect [10] may occur, which can arise from thermic deformation. In these components, spring-back and spring-in effect will overlay, because cover sheet metals as well as FRP are formed. Figure 6 c shows a spring-in of the component of about 2.5°. Only a small downward deviation occurs in the flange area. Because of the opposite component curvature, it can be assumed that at this point a spring-in-effect occurred too, but according to the component curvature in the opposite direction. So both deviations cancel each other out. Since the spring-in-effect is highly depending on the removal temperature, the cooling rate, the material stack-up and the wall angle, further investigation considering these set-ups will follow.

## 4. Conclusion

Fibre-plastic-metal hybrids offer a great lightweight potential. But yet, no processes, which allows manufacturing of these components in a large scale exists. In this article, a process has been presented, allowing the manufacturing of sheet components consisting of sheet metals and carbon fibre reinforced thermoplastic prepregs. Because the application of variotherm tool systems cannot be avoided, a forming tool with close-to-contour cooling has been realized. The tool cooling close to the contour led to comparatively short reheating cycles, since not the whole tool has to be cooled and heated cyclically, which results also in economic benefits. With this tool, hat profiles could be produced successfully with a tool temperature of 250° C. Further optimization of the close-to-contour cooling for a further reduction of the cycle time, a transfer of the gained knowledge to more complex components and further investigation of the geometric accuracy of these components are necessary.

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