INTRODUCTION OF AN IN-MOULD INFRARED HEATING DEVICE FOR PROCESSING THERMOPLASTIC FIBRE-REINFORCED PREFORMS AND MANUFACTURING HYBRID COMPONENTS

Jan P. Beuscher[1], Raphael Schnurr[1], Anke Müller[1], Markus Kühn[1] and Klaus Dröder[1]

[1] Technische Universität Braunschweig,
Institute of Machine Tools and Production Technology (IWF),
Langer Kamp 19b, 38106 Braunschweig, Germany,
j.beuscher@tu-braunschweig.de, https://www.tu-braunschweig.de/iwf

Keywords: hybrid components, temperature management in thermoplastic production, injection moulding, infrared radiator, in-mould heating

ABSTRACT

Automated production technologies of hybrid structures and components are one key requirement to force the way of lightweight constructions and design into automotive large-scale production. Furthermore, lightweight constructions need to provide additional functionality compared to conventional components to compensate for higher material and manufacturing costs. Therefore, the aim of today's research is to find economic strategies for automated, function and process integrated final-shape-manufacturing processes.

Conventional manufacturing processes for large-scale production are applied in sheet-metal working and plastics processing industries. For this reason, industry and science try to apply the process expertise of these industries on processing fibre-reinforced plastics (FRP). The combination of thermoforming of thermoplastic fibre-reinforced preforms (TP-FRP) with metal sheet inserts and efficient injection moulding processes shows a high industrial potential and at the same time the complexity of transferring the expertise of conventional to composite materials.

The complexity occurs because of the differing material properties during the course of the process. The main challenge is the dynamic heat management of the TP-FRP during different process steps. For one thing, the preform must be molten and heated above melting point to perform a shaping process, an adhesive bonding with the injected material and the final consolidation. Conversely, a solidified preform has advantages in material handling and is less sensitive towards outside influences. Existing strategies of heating preforms during the process have several disadvantages. Either the preform must be overheated harmfully to balance the temperature losses or the process becomes inefficient because of the high thermal mass of the mould.

Therefore, this paper introduces an integrative approach to apply an infrared (IR) heating device in a mould for processing TP-FRP with gentle and effective heating.

1 INTRODUCTION

The automotive industry sector pursues various lightweight strategies in dependence of its specified application or target markets. These strategies, such as metal- or FRP-lightweight design, reach their economic limits whentrying to exploit the full weight saving potential and the implementation in large-scale production at the same time. For example, composite parts can have low weight, but cannot be considered as an alternative for volume markets yet, because of high material and manufacturing costs.

Therefore, automotive lightweight design still stands out primarily by fuel savings and CO2 reductions for combustion engines and extended ranges for electric vehicles. This is obviously a necessary reason to drive the development of lightweight design forward, but the potential of lightweight design to solve this problem exclusively on its own is limited. In practise, the fuel reduction value (FRV) shows a maximum of 0.35 l (100 km x 100 kg)$^{-1}$ [1]. Thus, there must exist further reasons for using new materials with lightweight design. The main benefit of lightweight design and multi material usage is to generate approaches for innovative components by neglecting conventional construction methods, part boundaries and function attribution while increasing the parts weight.

A promising way to enhance such an economic lightweight design is the multi-material design approach for integrated hybrid components. These components combine the advantages of different materials as well as material classes in a most efficient way to strengthen essential properties, specifications and additional functionality [2]. Metals, plastics, ceramics and fibres of different types own different advantages that can be applied for a most suitable function integration in the target part. Besides cost advantages, hybrid design enables a material based function integration within lightweight construction and production.

Two main manufacturing routes exist for the production of hybrid components as described in [3]. Both routes differ at the point of merging the materials (Figure 1). Each part of a component is manufactured separately in a conventional manufacturing route and is then merged to the final component at a late processing stage. Combined routes aspire to merge different materials at an early stage of the process, so that the multi-material preform follows jointly each consecutive process stage to the final product.

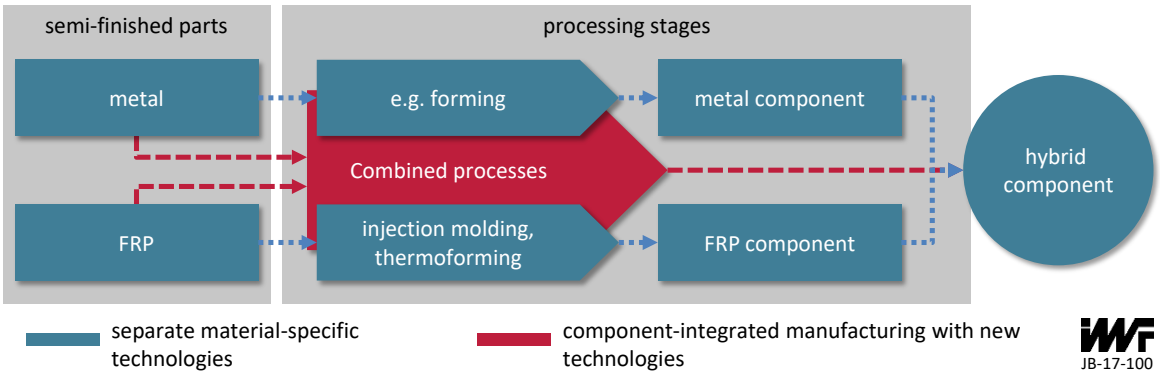

Figure 1: Manufacturing routes of combining metals and FRP in one component. [3]

Economic manufacturing processes for hybrid components are necessary to compensate for higher material costs. Conventional plants are material-specific orientated and are not suitable for volume production of multi-material components. Economic manufacturing of hybrid components therefore involves production technologies that can be adapted and integrated into existing plants and machinery. These production systems must be automated and contain final shaping manufacturing processes such as injection moulding. In conclusion, these production technologies must provide continuous process chains and therefore a high degree of automation. [4–7]

This research approach aims at developing an automated and integrated process chain (red track in Figure 1). In this setting, continuous fibre-reinforced thermoplastics (TP-FRP), metal inserts and injection moulding of short-fibred thermoplastics are used to create complex thin-walled hybrid components. Due to complicated processing conditions and properties of heated TP-FRP, a promising approach is to use a metal structure to improve handling properties and processability. Furthermore, the structure supports the achievement of mechanical properties and component functionality. The concept of an integrative approach in automated manufacturing of hybrid components using support structures to meet automation challenges has been introduced in [3, 8]. Furthermore, different approaches for in-mould or in-line heating metal [9, 10] or thermoplastic preforms have already been introduced [11].

2 INTEGRATED PROCESSING OF HYBRID COMPONENTS

Major manufacturing technologies for automotive lightweight applications are still uneconomic because of long process cycle times, process complexity, material behaviour and recyclability. Therefore, the use of thermoplastic FRP and its production technologies are promising research fields.

2.1 Process design for manufacturing hybrid components

In contrast to thermosets, thermoplastics offer advantages even in terms of higher ductility, impact resistance and state of the art large scale production technologies [12]. TP-FRP are provided tailored,

pre-impregnated and consolidated as organo sheets. Processing them opens the possibility of adapting series production technologies to subsequent combined thermoforming and shaping processes, such as injection moulding. This process combination enables the adaption of production of complex, function integrated and final shaped parts [13, 14]. Recent TP-FRP manufacturing technologies include automation solutions to connect the process stations material supply, placement in a mould, component manufacture and extraction [15]. However, these technologies are either limited to processing merely a single material or a single semi-finished part in each cycle.

Current research focuses on processing multiple semi-finished parts in a single cycle to create complex components. Furthermore, these processes handle parts of various material classes and properties. The aim is to develop a continuous process chain that integrates all manufacturing steps, beginning with material supply and cutting, containing handling processes, preforming, interface functions and ending with final shaping the part (Figure 2). [16]

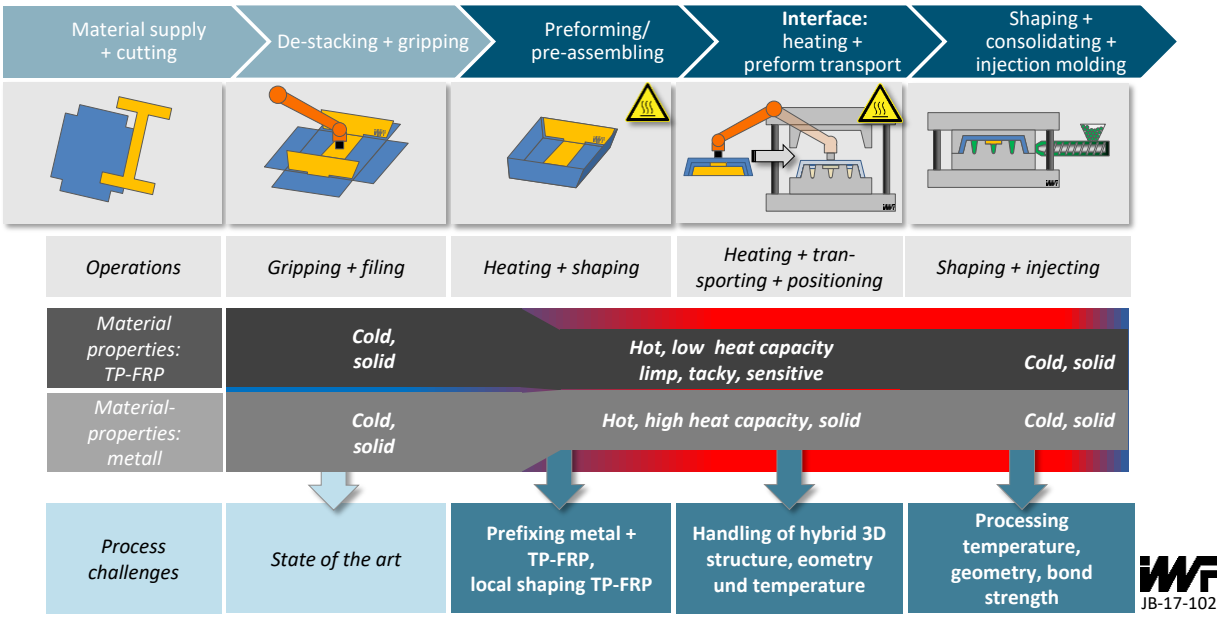

Figure 2: Process chain for manufacturing hybrid components containing combined thermoforming and injection moulding.

2.2 Challenges in processing hybrid preforms

Despite many advantages, the integrative approach of combined processing induces several challenges. These arise from differing material properties at different stages of the process. Figure 2 shows the material properties of TP-FRP and metal varying during the integrated process. The background colour indicates the processing temperature at special stages of the process. From the beginning of the preforming until the consolidation temperatures above or around the melting temperature are necessary. Three main challenges can be identified because of the pointed out material properties.

1. **Heat management**
   TP-FRP must be processed above the melting point for shaping and consolidation. Because of its material properties and process steps it is difficult to reach ideal temperature without damaging the material.
2. **Handling**
   In a cold state TP-FRP behaves in the same way as other solid materials and is easy to handle. As soon as the material becomes molten, it shows limp and textile behaviour. Because of this reason a precise handling, transportation and inserting into moulds of cut preforms becomes impossible.

3. **Material damage**
   Molten TP-FRP becomes very sensitive and tacky, which increases the chance of material damages during the process.

Additional challenges can occur, but in this paper mainly the first challenge is discussed.

2.2 Recent heating approaches

Recent production technologies trying to combine thermoforming and injection moulding make use of external heating technologies. Convection or IR-ovens are in common use. The main disadvantage of such a device is the distance to the mould. After reaching the targeted preform temperature the ovens must be opened, the preforms handled and inserted to the mould. Even fast and fully automated processes need several seconds of transferring time and involve temperatures losses.

Heating solutions combined with handling technologies or moving IR-radiators, as shown in Figure 3, try to reduce this disadvantage and the resulting problems. These solutions imply high technical efforts, they still have waiting times with temperatures losses. However, many applications for these technological approaches are suitable. In case of increasing geometric complexity and demands on the parts and surface quality, these approaches reach their limits.

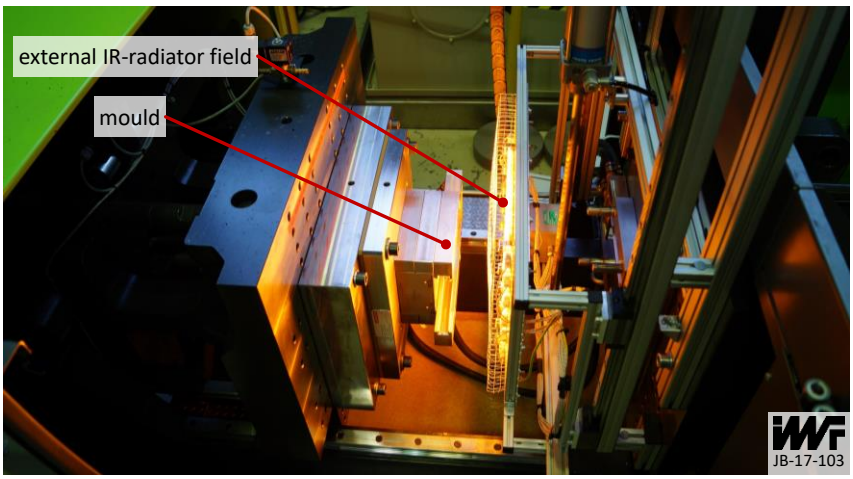

Figure 3: External IR-radiator heats in open mould.

If TP-FRP is heated both with an external device outside of a mould or already inserted, it must be overheated to balance the temperature loss while transferring it into the mould or the device movement outwards of the mould. In this case, the overheating difference to the necessary temperature rises with the bridging time until overmoulding or thermoforming starts. This causes material damages and degradation of the thermoplastic matrix of the preform.

If the material is heated conductively inside of the mould, the process becomes inefficient because of the high thermal mass of the mould and the low ejecting temperature of the resulting part.

2.2 Remaining research demands

The aim of developing economic production strategies requires the knowledge of basic thermodynamic interrelationships in these processes. Furthermore, new mould concepts must be considered which allow functional integration of process stages into a single step. This may either be reached by integrating process technology into moulds or by integrating the mould into comprehensive handling and automation technologies.

The research scope of this paper is to investigate the thermodynamic behaviour of the system of mould, preform and external heating device and to transfer the findings into an in-mould heating concept. Therefore, the heating and cooling behaviour of TP-FRP in contact with mould surfaces are investigated. In this special case, external IR-radiators are used for basic investigations.

Furthermore, the already mentioned in-line approaches are extended by an introduction of an in-mould IR-radiator heating concept.

3 INVESTIGATION OF THE HEAT MANAGEMENT

This chapter deals with investigations of the thermodynamic behaviour of TP-FRP specimens inserted into a mould. It neglects the material's behaviour outside of the mould or during transportation processes because of the assumption that the most efficient and most gentle way of heating such specimens can be reached with in-mould technologies.

3.1 Specimen material

The experimental investigation is carried out with specimens out of organo sheets, because due to their thermodynamic behaviour they are significantly more difficult to process than metal parts. The geometric dimensions of the applied specimens can be found in Table 1.

Dimension	Unit	Value
Length l	[mm]	90
Width w	[mm]	25
Thickness t	[mm]	2

Table 1: Geometrical dimension of specimens.

The material is semi-finished laminate and consists of a polyamide 6 matrix and continuous woven glass fibre fabrics. The laminate has a glass fibre content of 66%. The melting temperature of polyamide 6 is above 220 °C and its thermal decomposition temperature above 300 °C. Despite its high specific heat capacity of around 2,700 J K^{-1} kg^{-1} in molten state the absolute heat capacity is still lower than the one of metal. However, the most disadvantageous property of polyamide compared to metals regarding the heat management is the thermal conductivity, which is many times smaller and complicates a homogenous heating of the thermoplastic matrix. [17] This explains the importance of a precise and gentle heating. The properties are shown in Table 2.

Properties of polyamide 6	Unit	Value
Melting temperature T_m	[°C]	220-260
Decomposition temperature T_d	[°C]	> 300
Specific heat capacity (melt) c_m	[J K^{-1} kg^{-1}]	2,680-2,730
Specific heat capacity (solid) c_s	[J K^{-1} kg^{-1}]	1,400
Thermal conductivity (melt) λ_m	[W m^{-1} K^{-1}]	0.23
Density at 20 °C ρ	[g cm^{-3}]	1.06-1.16

Table 2: Physical properties of polyamide 6. [17]

3.2 Experimental setup

The specimens are investigated in the cavity of a lap-shear mould, that has also been used for manufacturing hybrid components in an overmoulding process. This mould permits to manufacture specimens referring to norm DIN EN ISO 1465. The provided injection moulding machine is a machine of the type ENGEL victory 120 spex. Hence, the investigations take place in a realistic scenario with an isothermal tempered mould. During the experiments, the mould has a constant temperature of 140 °C and has just convectional temperature losses of a few degrees at its cavity's surface. The preforms are heated with an IR-radiator field that is moveable in and outside the mould's cavity with in total 6 kW radiator power.

The presented experimental process scenario has already been shown in Figure 3. The process cycle starts with inserting preforms into the open mould. Subsequently, an IR-radiator field moves into the mould, between both mould halves the IR-radiator heats up the inserted preforms to a target temperature

above the melting point. After reaching the target temperature, the radiators are shut down and moved outside of the mould. As soon as the machine space is safe, the mould is closed and the injection moulding process starts.

To investigate the thermodynamic behaviour the process scenario is interrupted after reaching the target temperature. The main interest is to regard the temperature curves during heating up with IR-radiation and cooling down after turning off the IR-radiator field. Temperatures are measured with thermocouples of type K at two specimens in the mould. Two thermocouples are installed at the centre of each specimen. Each specimen has a cavity faced thermocouple and an IR-faced one (Figure 4).

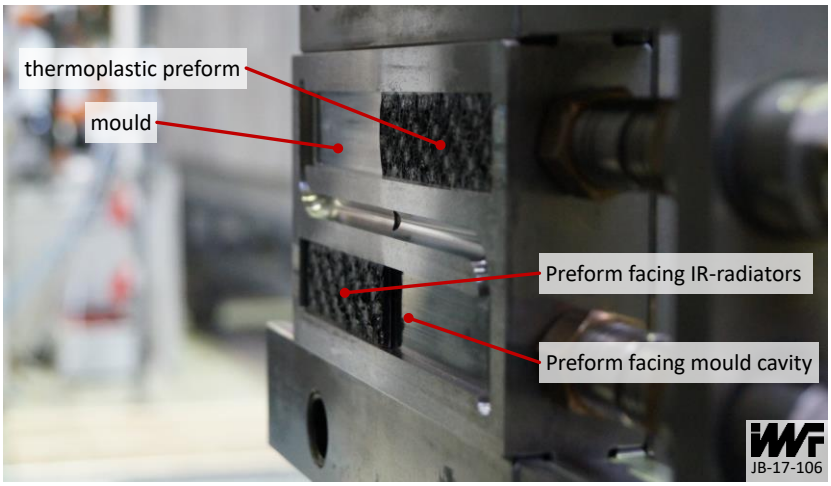

Figure 4: Measuring points of inserted specimen.

3.4 Heating behaviour of mould inserted TP-FRP

As described before, the measurement of the temperature curves at two faces of the preform is required due to the high thermal conductivity of the steel mould behind the preform. However, no perfect contact between both surfaces is expectable, the simultaneous occurrence of the high thermal mass of the mould and the high thermal conductivity works like a heat sink. Concurrently, the low thermal conductivity of the polyamide prevents a homogenous distribution of heat within the preform.

Hence, the temperature difference between the radiator and cavity faced surfaces are of major interest. Figure 5 shows the temperature curves of different measuring points of a single specimen in the experimental setup during the heating process. The heating process stops after recognizing asymptotic convergence to 350 °C. This temperature defines the maximum reachable temperature and mean either the individual decomposition temperature of the matrix or a balance of heat transfer of the external heating device and the cooling device of the mould.

The IR-radiators provide a heat input up to 100 W m^{-2} and a heat rate of 1.19 K s^{-1} when the radiators face the preform surface. Within 40 s the surface is heated up to its melting temperature and within 150 s it reaches its maximum temperature.

Conversely, the surface facing the mould cavity conversely did not reach the melting temperature of the matrix at any time. In despite higher starting temperatures, caused by the influence of the isothermal tempered mould, the temperature rates are much smaller because of the insufficient conductivity of the polyamide and the high conductivity of the steel mould. That shows that thermoforming processes are very difficult to proceed if the preform is in touch with a colder mould. Overmoulding processes may still work under these conditions.

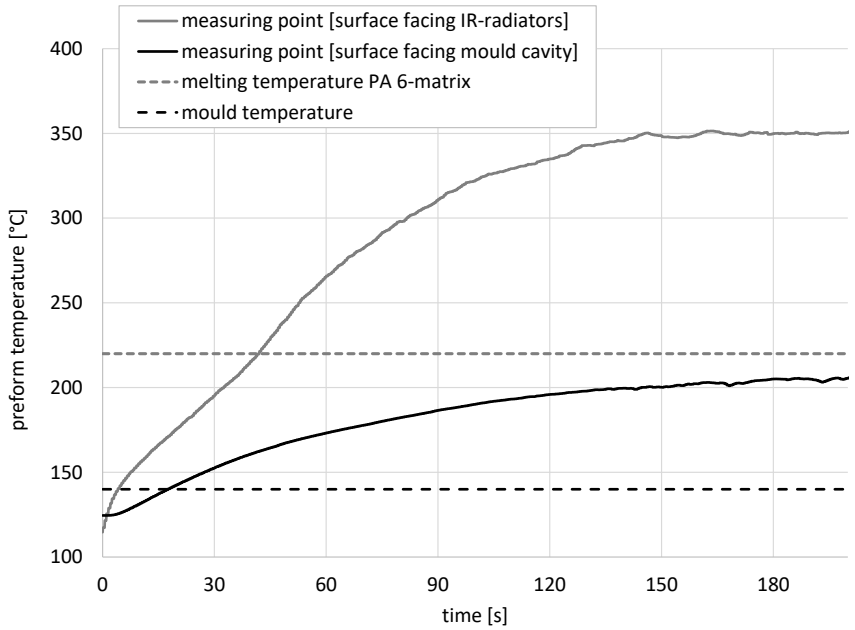

Figure 5: IR-radiation heating temperature curves of polyamide 6 TP-FRP.

3.5 Cooling behaviour of mould inserted TP-FRP

After stopping the heating process, the preforms start to cool down rapidly inside the mould (Figure 6). Compared to the temperature increase during heating, the cool down happens even in an accelerated manner. Therefore, regarding the process design, the cooling behaviour is very important towards an efficient and gentle temperature course. The progress of the temperature decrease shows a very high cooling performance of the mould, which is firstly necessary after injection moulding, but secondly causes a conflict with ideal TP-FRP processing.

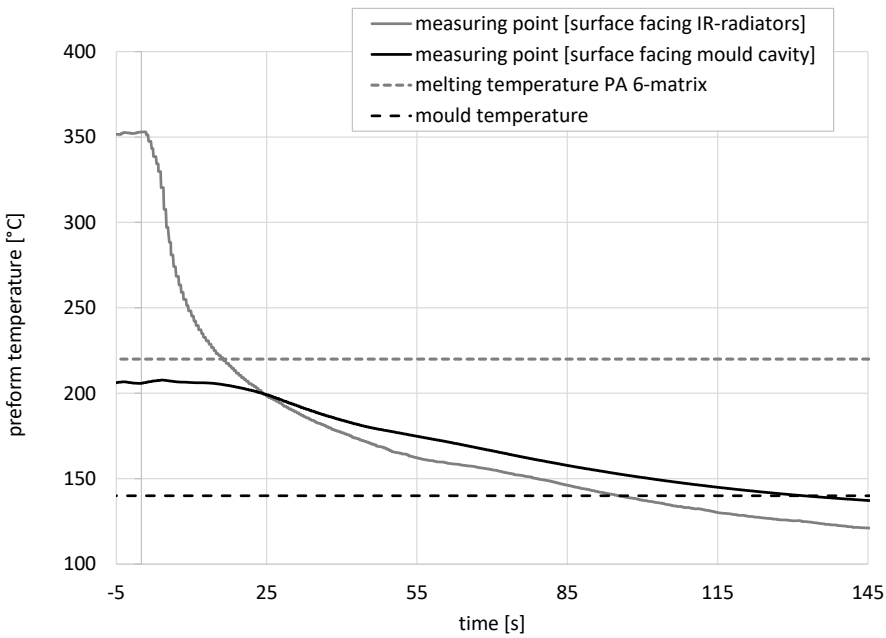

Figure 6: Cooling temperature curves of polyamide 6 TP-FRP inserted in a mould.

The resulting average cooling rate between the maximum temperature and the melting point of the matrix amounts to 7.31 K s^{-1} and is six times higher than the heating rate. The critical cooling time between these both temperature points is 15.88 s and defines the maximum operating and processing range. Due to the attempt to prevent material damages, the target temperature after heating should be as low as possible. But, since the material can be heated inside of the mould, major parts of handling and transportation do not appear, whereby the process of this experimental investigation presents itself as fast.

4 CONCEPT DEVELOPMENT

The investigation of the heating and cooling behaviour shows that the heat management is one key to develop efficient production technologies for multi-material components. This concept approach tries to find a reasonable solution, using conventional and proven heating technologies for TP-FRP in a more process efficient way.

4.1 Heating technologies

The main requirement of the new heating approach is to apply conventional, effective, proven and secured heating technologies. It is not the aim of the concept development to invent new heating mechanisms or technologies. The idea is to use a preferred technology and transfer it into new heating device applications. That is why some important technologies such as laser scanning heating are not pursued further. Because of intensive experiences with that technology and many advantages, e.g. efficiency and industrial safety, IR-radiator technology are meant to be used. Its disadvantage of direct visual contact to the target needs to be solved though.

4.2 In-mould heating concept

This disadvantage disappears by making the mould transparent. Because of material properties of glasses and typical ceramics a complete substitution of tool steel is not possible. Thus, the mould gets partial substitution areas that act like windows in the closed mould. In the first step of the development of the in-mould heating concept, a simple cavity is chosen. This cavity enables to manufacture the same kind of specimens as already done before with the benefit of comparable studies and reusable mould halves.

Therefore, merely the injection side of the existing mould is to be adapted. Conventional double pipe IR-radiators will be integrated into the mould hiding behind thick transparent tool inserts. Figure 7 shows the exploded view of the resulting mould concept.

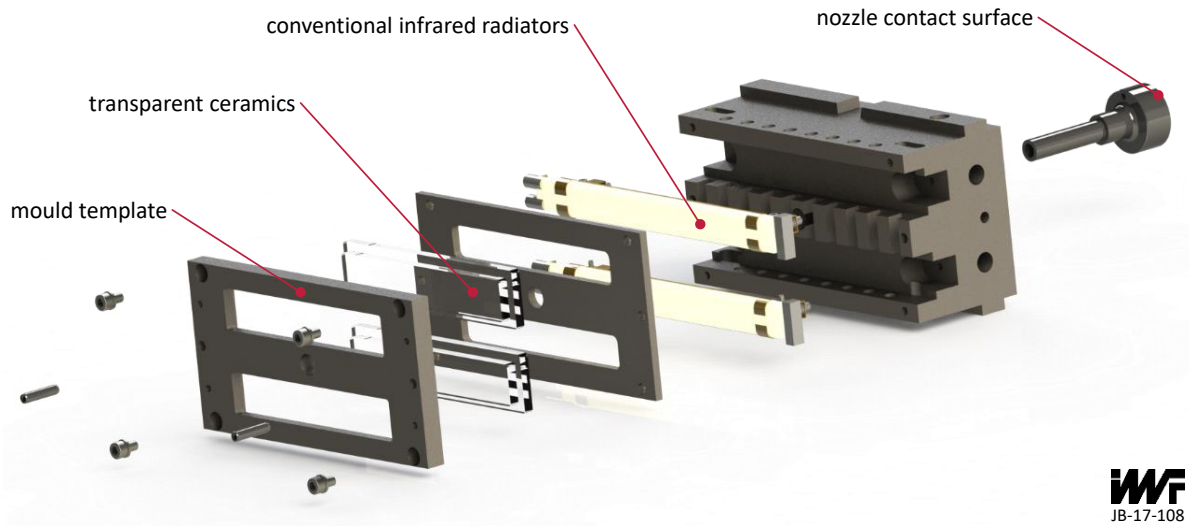

Figure 7: Exploded view of the in-mould IR-radiator heating device.

4.2 Ceramic mould insert

For a successful implementation of this mould concept, an appropriate insert material must be selected. Literature research led to the result that glasses do not meet the requirements towards pressure loads and impact behaviour. In an injection moulding process such an insert must stand pressure loads of more than 1000 bar and contact temperatures above 300 °C. In addition, a high transparency in the infrared area is necessary to enable the transmission of the heating radiators.

Hence, the first mould prototype is being built up using a $MgAl_2O_4$ ceramic with a transmission coefficient of over 0.8 in the range between 1 and 3 µm wave length and compression strengths of over 2000 MPa. Figure 8 shows the ceramic insert using for the in-mould heating device.

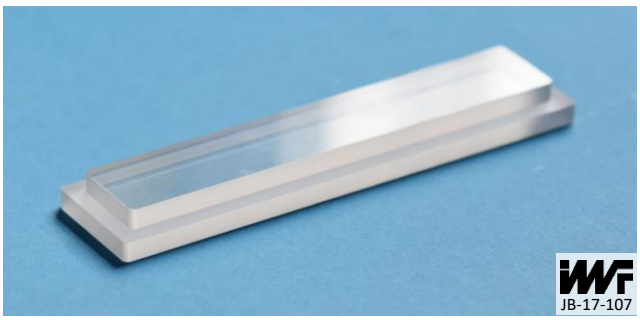

Figure 8: $MgAl_2O_4$ ceramic mould insert.

5 CONCLUSIONS AND OUTLOOK

Today's demands for reasonable lightweight design in automotive or other volume markets require new production technologies and integrative approaches. This paper explained integrative manufacturing routes for hybrid components and process challenges. These challenges contain primarily linkage of process steps and a consistent heat management. Investigations to the heating and cooling behaviour of TP-FRP that are already inserted to a mould have been carried out. The results showed the high importance of the heat transfer to the processability of the preforms and the impact of tempered moulds on the cooling. As a consequence the unheated times in a mould should have been removed as well as overheating and damaging the material. Finally, a mould concept has been developed using transparent ceramics to substitute single areas of the mould to allow IR-heating of TP-FRP inside the mould.

This concept is being built and a proof of concept is still to be made. Future work will must develop more complex moulding concepts to transfer the gained knowledge to realistic manufacturing processes. In addition, other heating concepts, such as inductive, resistance and other radiant heating technologies, need to be investigated towards their in-mould suitability.

ACKNOWLEDGEMENTS

This research and development project is funded by the German Federal Ministry of Education and Research (BMBF) within the Forschungscampus "Open Hybrid LabFactory" and managed by the Project Management Agency Karlsruhe (PTKA) under research funding scheme 02PQ5100. The authors are responsible for the contents of this publication. Many thanks to Marco Münchow and CeramTec for providing ceramics for this project as well as many thanks to Tobias Wiechers for supporting the construction process.

References

[1] C. Koffler and K. Rohde-Brandenburger, "On the calculation of fuel savings through lightweight design in automotive life cycle assessments", in *Int J Life Cycle Assess (The International Journal of Life Cycle Assessment)*, pp. 128–135.

[2] F. Henning and E. Moeller, *Handbuch Leichtbau: Methoden, Werkstoffe, Fertigung*. München: Hanser, 2011.
[3] K. Dröder *et al.*, "An integrative approach towards improved processability and product properties in automated manufacturing of hybrid components", in *Euro Hybrid Materials and Structures 2016*, Kaiserslautern, Deutschland, 2016.
[4] K. Dröder *et al.*, "Symbiosis of plastics and metals: integrated manufacturing of functional lightweight structures in high-volume production", in *Kunststoffe im Automobilbau*, Düsseldorf, Germany: VDI-Verlag, 2014.
[5] C. Cherif, *Textile Materials for Lightweight Constructions: Technologies - Methods - Materials – Properties*. Heidelberg/Berlin, Deutschland: Springer, 2015.
[6] L. Ickert, D. Thomas, L. Eckstein, and T. Tröster, *Beitrag zum Fortschritt im Automobilleichtbau durch belastungsgerechte Gestaltung und innovative Lösungen für lokale Verstärkungen von Fahrzeugstrukturen in Mischbauweise, Berlin, Germany 2012*. Berlin: VDA/FAT, 2012.
[7] E. Staiger *et al.*, "CFK-sheet metal hybrid composites", in *7th International Textile Conference*, Dresden/Aachen, Deutschland, 2013.
[8] J. Beuscher *et al.*, "Improving the processing properties of hybrid components using interlocking effects on supporting structures", in *ECCM17: 17th European Conference on Composite Materials, Munich, Germany, 26-30th June 2016*
[9] M. Zülch, *Temperierung von Spritzgusswerkzeugen durch vollständig integrierte induktive Beheizung*. Stuttgart: IKFF, 2011.
[10] F. Thurner and C. Lammel, *ProVor - Produktionstechnologie zur Vorkonfektionierung von FVK-Metall-Hybriden: Teilprojekt: Induktive Erwärmung ; Forschungscampus: Open Hybrid LabFactory e.V. ; Schlussbericht ; Berichtszeitraum: 15.03.2013 bis 14.03.2014*. Ismaning, Hannover: IFF GmbH; Technische Informationsbibliothek u. Universitätsbibliothek, 2014.
[11] J. Beuscher *et al.*, "Introduction of approaches for in-line heating thermoplastic preforms for manufacturing hybrid components", in *7th International Symposium on Composites Manufacturing for High Performance Applications*, Braunschweig, Deutschland, 2016.
[12] P. K. Mallick, "Thermoplastics and thermoplastic–matrix composites for lightweight automotive structures", in *Woodhead Publishing in materials, Materials, design and manufacturing for lightweight vehicles*, P. K. Mallick, Ed., Boca Raton, Fla., Oxford: CRC Press; Woodhead, 2010, pp. 174–207.
[13] H.-P. Heim, Ed., *Specialized injection molding techniques*. Oxford, United Kingdom: William Andrew is an imprint of Elsevier, 2016.
[14] N. Reynolds and A. Balan Ramamohan, "High-Volume Thermoplastic Composite Technology for Automotive Structures", in *Advanced composite materials for automotive*, pp. 29–50.
[15] S. Seidel, *Anforderungsrechte, thermoplastische Preforms für den Hochleistungsleichtbau*. Zugl.: Bayreuth, Univ., Diss., 2014. Hamburg: TuTech Verl., 2015.
[16] K. Lippky *et al.*, "Integrierte Produktionstechnologien zur Herstellung hybrider Leichtbaustrukturen",, *Lightweight Des*, vol. 9, no. 2, pp. 59–63, 2016.
[17] G. Wypych, *Handbook of polymers*. Toronto: ChemTec Publ, 2012.