CERAMIC PRESSING TOOL FOR VARIOTHERMAL PROCESSING OF THERMOPLASTIC FIBER COMPOSITES

F. Kühn[1], L. Medina[2], D. Becker[1], M. Zwick[3], M. Knoch[4], B. Romahn[5] and P. Mitschang[1]

[1] IVW GmbH, Erwin-Schroedinger-Str., Building 58, 67633 Kaiserslautern, Germany
Email: florian.kuehn@ivw.uni-kl.de, Web Page: http://www.ivw.uni-kl.de/
[2] University of Applied Sciences Kaiserslautern, Department of Applied Logistics and Polymer Sciences, Campus Pirmasens, Germany
[3] Forschungsinstitut für anorganische Werkstoffe – Glas/Keramik – GmbH, Höhr-Grenzhausen, Germany
[4] FCT Ingenieurkeramik GmbH, Frankenblick, Germany
[5] Weberit Werke Dräbing GmbH, Oberlahr, Germany

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Abstract

Variothermal processing of fiber reinforced polymer composites (FRPC) bears huge potential for the reduction of cycle times. In this context, the tool material used for the variothermal pressing is highly relevant for the process efficiency. Metallic materials such as steel are established for the tool construction, but due to the thermal properties of steel large temperature changes require relatively large amounts of energy and the heating respectively cooling rates are strongly limited. Ceramics on the other side provide more favorable thermal properties. Within the project "CompoMold", a tool made of the ceramic material silicon carbide (SiC) was developed. SiC offers a high thermal conductivity, a minimal thermal expansion, and a minimal heat capacity. However, tooling concepts for metals cannot be directly adapted since the special mechanical properties of ceramics e.g. in terms of damage behavior require a ceramic-appropriate design. In the study various tool concepts have been developed and tested in laboratory scale. Heating experiments revealed that compared to tools made of steel the cycle time for heating up the SiC tools can be reduced by up to 50% with equal heating power. Further results show the potential of intrinsically heated purely ceramic heating elements. In combination, these results allow novel tool concepts and open up many possibilities for innovative variothermal processes.

1. Introduction

In automotive and aerospace industry the demand for cost-effective lightweight components has increased steadily in recent years and it is believed that this trend will continue in the future. Fiber reinforced plastic composites are ideal lightweight materials and therefore an annual growth of 17 % is expected for high-strength fiber composites until 2020. Especially, fiber reinforced thermoplastic composites (TP-FRPC) are in the focus of research work since they allow very short processing times as they must be only physically cooled to solidify. Hence, technologies for mass production of TP-FRPC, such as pressing processes like thermoforming, are in demand [1, 2]. However, due to the relatively high costs of the semi-finished materials (so-called organic sheets) required for these processes, high volume application of continuous fiber-reinforced thermoplastics is not yet established, despite the high lightweight potential.

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An alternative to the use of semi-finished materials can be given by the in-situ impregnation of the reinforcing fibers with the thermoplastic matrix in a variothermal process [3]. This approach is illustrated in Figure 1.

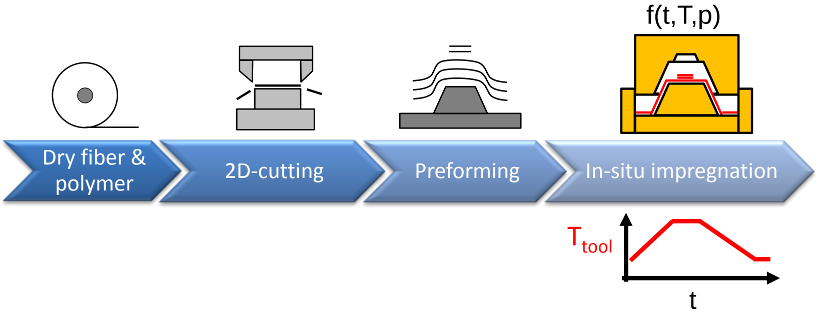

Figure 1. Process chain of a variothermal process for in-situ impregnation

In case of the in-situ impregnation the tool must be heated and cooled at very high rates so that the tool temperature can be varied at rates of several Kelvin per second within one cycle [4]. Therefore, the ideal material for highly efficient tools for variothermal processes should provide a high thermal conductivity for a fast heat transport, a minimal thermal expansion for best dimensional stability, and a minimal heat capacity for a high energy efficiency and fast temperature change. In this context ceramics are an ideal material since they show much more favorable thermal properties compared to steel. Compared to hot-working steel the ceramic material silicon carbide (SiC) has a three times higher thermal conductivity, one third of the thermal expansion and half of the density and lower heat capacity [5, 6]. However, tooling concepts for metals cannot be directly adapted since the special mechanical properties of ceramics e.g. in terms of damage behavior require a ceramic-appropriate design. In this study, for the first time, a ceramic pressing tool for variothermal processing of thermoplastic fiber composites has been developed within the project CompoMold. Compared to tools made of steel better energy efficiency as well as faster heating and cooling rates are intended. For that purpose innovative construction methods and ceramics-compatible tool concepts have been created and new ceramic systems with intrinsic electrical heating have been developed. The new tool concepts have been built, tested and evaluated in the form of experimental tools.
The Project „CompoMold“ was carried out together with the partners Weberit Werke Dräbing GmbH, FCT-I GmbH, FGK GmbH and IVW GmbH. The development of ceramic materials and components was realized by FGK GmbH and FCT-I GmbH, the creation, testing and evaluation of the tool concepts was perfomed by Weberit Werke Dräbing GmbH and IVW GmbH.

2. Materials (Properties of the ceramic SiC)

As a ceramic for the tool design silicon carbide (SiC) was used. Due to its thermal properties the SiC is more suitable for rapid temperature changes than the hot-work steel which is typically used for variothermal pressing tools. Unlike hot-work steel SiC has a nearly three times higher thermal conductivity. This feature reduces the time required for heating and cooling the tool significantly. The thermal conductivity of SiC and aluminum alloys is comparable, but because of its mechanical strength and high thermal expansion the latter will not come into consideration.
In Table 1, characteristics of various materials are partially illustrated.

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Table 1. Mechanical and thermal properties of various materials used for tools [5, 6, 7, 8, 9]

Material	Thermal cond. [W/(m*K)]	Coeff. of thermal expansion [10^{-6}/K]	Heat capacity [J/(cm³*K)]	Yield strength [MPa]
Steel 1.2312	39.6	13.3	3.59	800
Invar 1.3912	16.1	4.4 – 5.5	4.17	95
Aluminum (WELDURAL)	130	22.5	2.56	240
SiC	130	4.6	2.24	450 (Flexural strength)

Because of its lower density, lower heat capacity and higher thermal conductivity compared to steel the SiC achieves faster heating and cooling rates as well as more uniform temperature distribution in the tool.

The ceramic test tools used in this study were manufactured by the company FCT-I GmbH. In a first step the ceramic powder is compacted in a cold isostatic press with hydrostatic pressures of up to 3000 bar to homogeneous green bodies. In a second step these green bodies can be pre-structured by machining near to their final structure. Shrinkage of 20% during the subsequent sintering must be considered at this point. In a third step the machined green bodies are sintered at temperatures up to 2400 °C. After the sintering the ceramic parts can be brought to nominal dimensions by grinding [10].

3. Integrated Ceramic / Steel Tool Concept Design

To operate tools made of SiC, they must be integrated into a peripheral structure (hydraulic press, positioning systems, actuators etc.). Although favorable concerning the thermal properties, the mechanical performance of ceramics is quite challenging in terms of tool design. Due to the high hardness of the SiC and the resulting brittle behavior local loads and canting must be avoided. Accordingly, special tool designs are necessary to avoid damage to the ceramic tools since even very small deformations can lead to fractures and severe damage. The best way to ensure that male and female tool never get into contact, is to integrate the ceramic tool into a metallic peripheral tool. A main issue which has to be considered when combining two materials in a heated tool is the different thermal expansion. For SiC and steel the ratio of the thermal expansion coefficient is about 1:3. Therefore, a firm connection for the ceramic and steel parts is not possible. Furthermore, a tensile load of the ceramic must be avoided; all loads have to be introduced in the form of compression loads due to the high compression strength of SiC. Within the project, a floating attachment of the ceramic parts with central fixation was developed.

This concept of assembly centers the ceramic inserts, creates only compressive force and compensates the different thermal expansion of steel and SiC.

The concept was transferred into a design for laboratory-scale testing tool to be used for experimental tests by Weberit Werke Dräbing GmbH. Within this study, two tool designs suitable for ceramics have been developed (see Figure 2 and Figure 3) and transferred into laboratory-scale tools for experimental testing.

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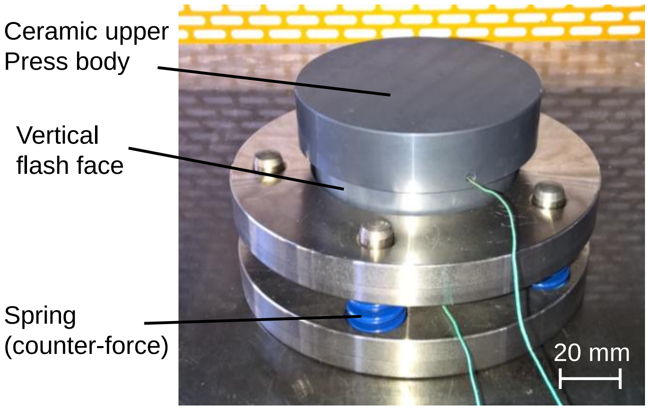

Figure 2. Developed tool design “floating flash face” suitable for ceramics to avoid damages

In the tool concept „floating flash face“ (Figure 2) the vertical flash face remains permanently on a press body and is pressed against a second press body by a counter-force (spring, actuator). The advantage of this concept is that the ceramic components never come into point or line contact, which reduces the risk of edge damages.

The second tool concept “double vertical flash face” (Figure 3) has the self-centering of the ceramic inserts in the peripheral steel tool. Thus, the different thermal expansion of both materials can be compensated without an offset of the center axis of the two tool halves. When the two tool halves are put together, the steel flash faces (peripheral tool) first slide into each other. Therefore, the ceramic flash face is mechanically protected and a contact of the ceramic mold halves is prevented.

Figure 3. Experimental tool concept **“**double flash face”

Within the project experimental tools were externally tempered by a laboratory hot press in which they were positioned. Yet, ceramics also offer possibilities for direct active heating, which has also been

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investigated. For this, intrinsically heatable ceramic heating elements have been developed by the project partners FCT-I GmbH and FGK GmbH. To allow active heating modified, electrically conductive SiC was pressed into non-conductive SiC and sintered together (see Figure 4).

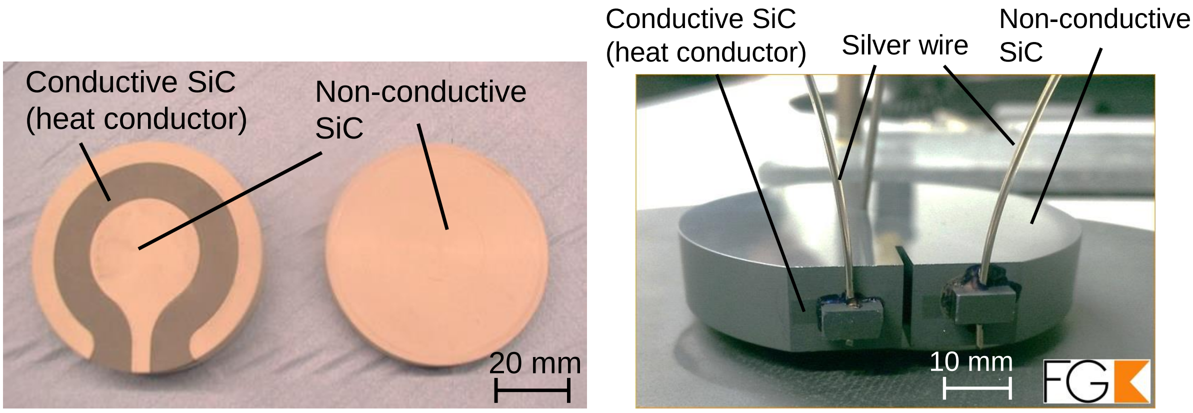

Figure 4. Intrinsically heatable ceramic heating elements; before sintering (left); sintered and electrically contacted by soldering (right)

Through material modifications a stable sintering was achieved and the conductive ceramic element was contacted by soldering. When an electric current flows through the ceramic heating conductor joule`s heat is generated by the ohmic resistance. This new developed ceramic heating element was also implemented in a test tool and tested.

4. Heating/Cooling tests

In order to evaluate the potential of the ceramic tool technology, two identical testing tools made of steel and SiC were constructed by Weberit Werke Dräbing GmbH. Due to this fact, the thermal behavior of both tools (steel and SiC) could be investigated. The testing tools were positioned in a laboratory hot press as shown in Figure 5.

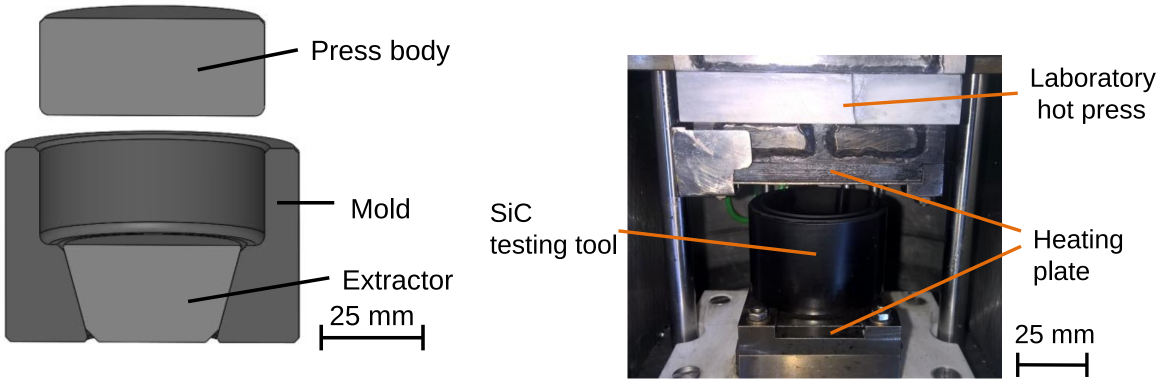

Figure 5. Testing tool (steel and SiC); draft (left), positioned in a laboratory hot press (right)

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The steel and the SiC tool were placed in the laboratory hot press successively and the heating and cooling rates as well as the temperature distribution on the surface of the tools could be measured and evaluated. In both cases (steel and ceramic tool) the laboratory hot press was operated with the same heating and cooling power. The determination of the mold temperatures was achieved by the analysis of the thermographic images (see Figure 7). The measurement results are shown in Figure 6.

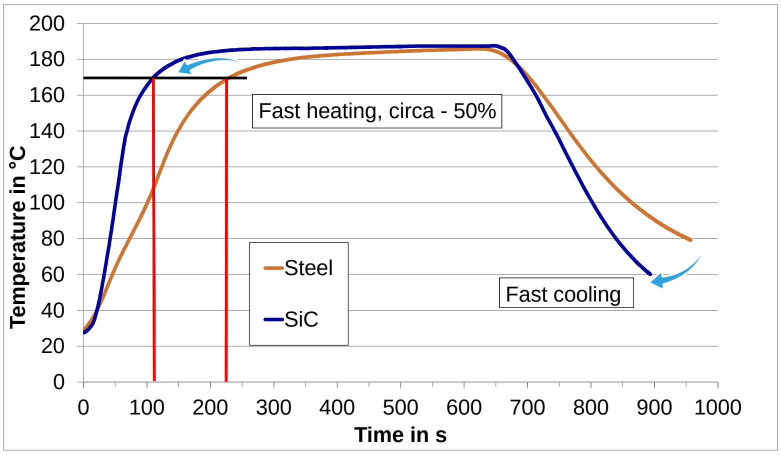

Figure 6. Temperature profiles of steel and SiC tools in comparison

The SiC tool follows a direct and defined temperature profile; the steel tool shows a delayed behavior regarding the fast temperature changes. Compared to the steel tool the target temperature (190 °C in this experiment) on the SiC tool is reached in a shorter period of time and can be consistently maintained until the cool down. A direct comparison of the temperature profiles of the tools illustrates the different thermal behavior. With the same heating power the SiC tool reaches the target temperature much faster and can hold it over the entire experimental period. In an explicit consideration of the heating rates the threshold temperature of 170 °C (90 % of the target temperature) is reached in an up to 50 % shorter period in the case of the SiC tool.

Besides the heating rates also the homogeneity is highly relevant for FRPC processing. Figure 7 shows thermal images of geometric identical steel and ceramic tools during an experiment in a laboratory hot press.

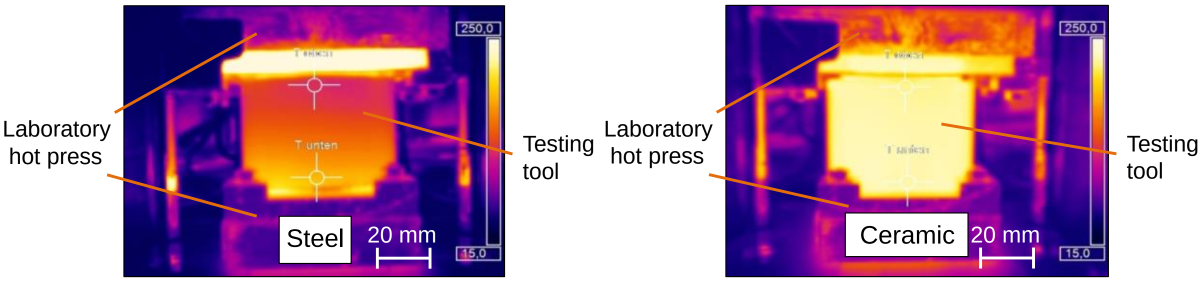

Figure 7. Heat distribution on the tool surface made of steel (left) and SiC (right), recorded with a thermal imaging camera

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The images in Figure 7 were recorded at the same time after the start of heating. This example shows that the SiC has a homogeneous temperature distribution during a rapid temperature change, whereby thermal stresses of the tool can be reduced.
From the thermal properties of ceramics also a high potential for direct cooling can be derived. To validate this assumption also a test heatsink (see Figure 8) was constructed and tested.

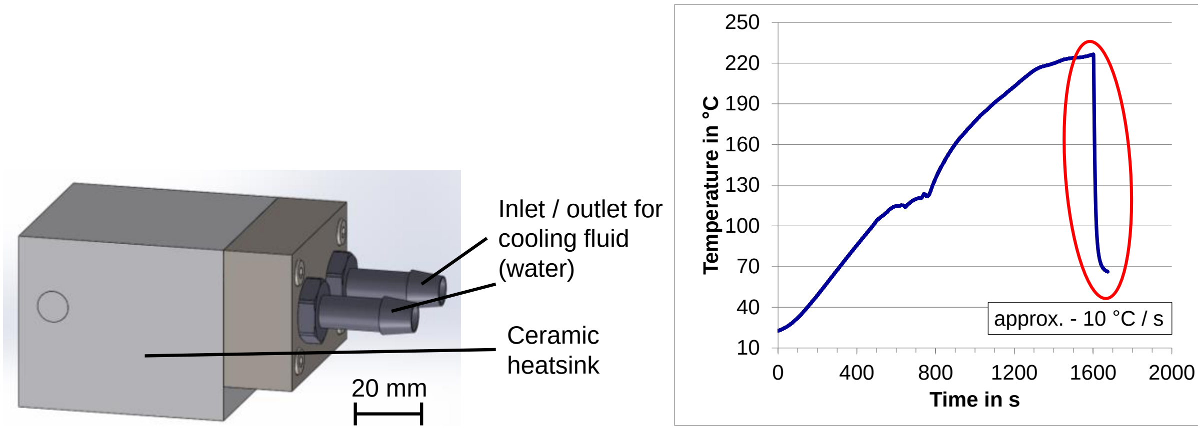

Figure 8. Draft of a ceramic heatsink (left); cooling rate during an experiment with water as coolant (right)

In the experiments the SiC heatsink was mounted on a hotplate which was heated to about 220 °C. Subsequently, the heatsink was flushed with cooling water (approx. 20 °C) and a cooling rate of up to -10 °C/s was determined.
Finally the results proof, that ceramic tools bear high potential for variothermal technologies.

5. Conclusions and Outlook

Within the project "CompoMold" a ceramic pressing tool for variothermal processing of thermoplastic fiber composites has been developed. In order to characterize the new tool technology various experimental tools have been designed and built. By laboratory tests fundamental knowledge of the thermal behavior could be generated and various tool designs suitable for SiC could be defined. Due to the brittle material behavior the special tool concepts are necessary to prevent damage to the tools. The results demonstrated that the tools made of SiC are appropriate for rapid temperature changes because of their special thermal behavior. For example, the cycle time for heating up the SiC tools could be reduced by up to 50% with the same heating power compared to tools made of steel. Along with the newly developed, intrinsically heated ceramic heating elements as well as cooling elements an energy efficient variothermal tool concept for rapid temperature changes was created. Applications in new manufacturing techniques as hybridized processes are conceivable and will be further explored. In a further step, the intrinsic heating and direct cooling of SiC tools with coolant (such as water, oil, steam and air) can be combined in a single tool concept.

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