# Using 3D Weaving for Additive Manufacturing of Ceramic Preforms

**Textile manufacturing essentially is an additive manufacturing process with near net-shape performance. Modern textile machines combined with computational tools allow for a well-aimed design of complicated 3D structures. Ceramic fibres can be manufactured at these machines if process parameters are carefully adapted. Thereby ceramic fibre preforms are produced in one step at high throughput. They are used for the manufacture of high-performance ceramic composites. The potential of this technique is illustrated with an airfoil for gas turbines.**

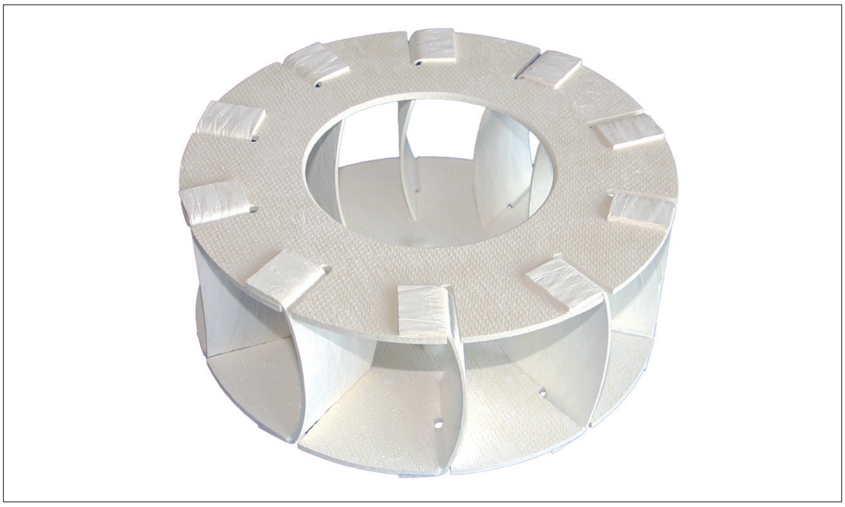

*Fig. 1*
*Hot gas fan made of a ceramic matrix composite with oxide ceramics*

## Potential of textile manufacturing for ceramic components

Additive manufacturing is considered as the basic production process for industry 4.0 due to its high flexibility and the capability to save assembly steps by integrating smaller components in a single-stage process. Moreover, it implies high material efficiency and allows lightweight constructions which applies also for ceramic components [1]. In this respect additive manufacturing is similar to traditional textile manufacturing techniques like weaving, knitting or braiding. Recently these techniques have been significantly improved to enable complicated 3D structures. At the Münchberg site of the Fraunhofer Center for High Temperature Materials and Design (HTL), the Working Group Textile Fibre Ceramics (TFK) transfers textile manufacturing techniques to ceramic fibres. Inorganic fibre rovings, e.g. made of silicon carbide, mullite, alumina, carbon, basalt or glasses are used as raw materials. After the textile manufacture of the preform, a ceramic slurry is impregnated into the weak and porous structure and the final shape is adjusted. Heating processes like sintering and melt infiltration provide the final strength of the ceramic matrix components (CMC). The interaction between the fibre rovings and the ceramic matrix ensures high fracture toughness. CMC are used as high-performance components in transportation, energy and heating technology. They are damage tolerant compared to brittle monolithic ceramics. Moreover, they have a low density and a good resistance to high temperatures, thermal shock and corrosion [2]. CMC for operation temperatures up to 1000 °C can be produced at low cost if cheap inorganic fibres are used as a starting material and the successive production steps are fully automatised [3]. As an example for a complex CMC part, Fig. 1 shows a fan wheel of a backward curved centrifugal fan. The blades were made from wound fabrics of slurry impregnated mullite fibre rovings and the bottom and top disk are based on woven mullite fibres. The individual components

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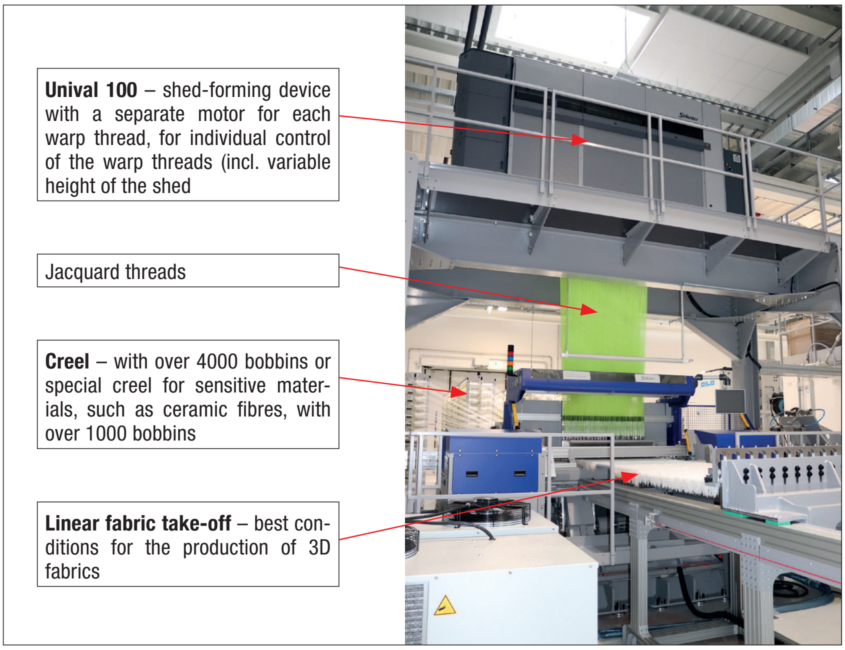
*Silke Grosch*
*Fraunhofer-Institute for Silicate Research, Center for High Temperature Materials and Design – HTL*
*95448 Bayreuth, Germany*

*Frank Ficker*
*University of Applied Science*
*95032 Hof, Germany*
*E-mail: frank.ficker@isc.fraunhofer.de*

*Corresponding author:*
*Email: silke.grosch@isc.fraunhofer.de*

were joined with a crystallizing glass. This oxidic CMC enables operating temperatures above 1000 °C in air or fuel gas atmospheres. However, there are many process steps during production of the fan and many of them have to be performed manually.

Sophisticated textile processing enables the single-stage production of such complicated parts. Fig. 2 shows a novel 3D weaving machine which was produced by company Stäubli and installed recently at the new textile technology center at Hof University of Applied Sciences in Münchberg/DE [4]. The double rapier machine is equipped with a Texmer creel suitable for the sensitive ceramic fibres, a warp beam harness for the draw warp and an Unival jacquard device for individual control of the more than 4000 warp threads. It also has special rapiers for processing ceramic materials and a linear take-off for highly and especially pressure-sensitive multilayer structures.



**Unival 100** – shed-forming device with a separate motor for each warp thread, for individual control of the warp threads (incl. variable height of the shed

Jacquard threads

**Creel** – with over 4000 bobbins or special creel for sensitive materials, such as ceramic fibres, with over 1000 bobbins

**Linear fabric take-off** – best conditions for the production of 3D fabrics

*Fig. 2*
*New double rapier weaving machine in Münchberg*

This weaving machine complements the modern textile equipment which was installed at Münchberg site during the last years. For the production of 3D textile preforms with ceramic fibres different technologies can be used and researched on, too.

Here to be mentioned are variation braiders for the production of complex braid structures and branch braids to be used as reinforcement for e.g. tooth structures (Fig. 3). Another milestone in textile reinforcing is done with the continuous production of tube structures with Z-reinforcements with help of a circular needling technique for stabilisation in z-direction given torsional stability to CMC preforms (Fig. 4).

In the following, the single-stage textile manufacturing of a complex preform is illustrated using an airfoil for a gas turbine.

## Development of a 3D preform for CMC airfoils

In a project, started in 2021 at HTL, an airfoil is developed, which consists of an oxidic CMC. A particular challenge is the production of the near-net-shape textile preform in a single-stage process as a multilayer fabric. Based on a standard geometry for aircraft gas turbines with a reinforcing bar (Fig. 5), the fabric was designed for a wall thickness of 2–3 mm to achieve sufficient stiffness. Particularly critical points for the binding of the airfoil are the trailing edge (1), which should be as pointed as possible, the web (2), which is to be integrated, and the rounding after the mould has been set up (3).

The design is based on multi-scale simulations of the micro- and mesostructures with different weave types, from which macroscopic properties of the material resulted. These were used as input variables for further simulation of the component geometry under different load cases. The simulation was performed with the Finite Element software ANSYS Material Designer, which was used in this case for an orthogonal bond. The objective was to qualitatively investigate which loads act on the finished airfoil in use and to determine critical points in the structure.

The distribution of the calculated maximum stresses in the airfoil for the CMC material is shown in Fig. 6. This shows

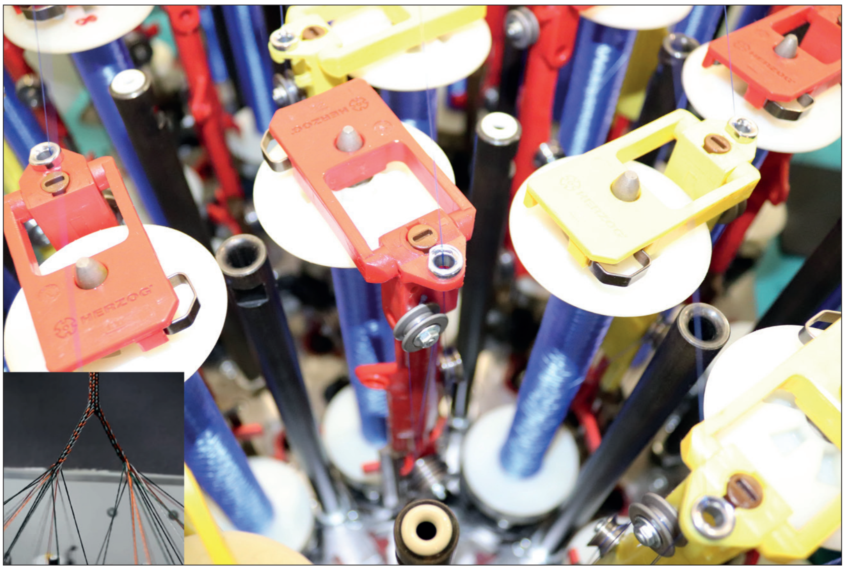


*Fig. 3*
*Variation braider for complex braid reinforcing structures (branch braid)*

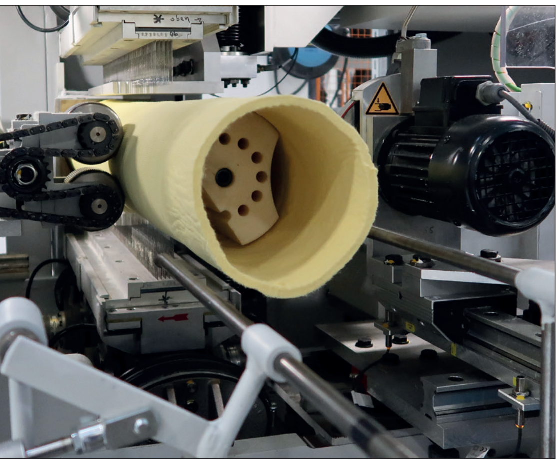


*Fig. 4*
*Circular needling machine*

where the greatest stresses act on the component and where critical points occur, at which the CMC material may have to be reinforced.

For the shaping of the preform, the pleating fabric technique was selected, and the first weave variants were developed on this basis. The incorporation of a tension warp, which is to perform a pull-back of the warp threads by means of special control in the industrial machine, enables the preform to be formed. The cover plies have different lengths and thus create the final contour of the airfoil. The weave development was carried out using the 3D Weave Composite software from EAT GmbH, which was specially developed for the implementation of complicated multilayer fabric structures and conveniently supports the generation of very complex component geometries. It is possible to design in the weft section and thus define the course for each warp thread (Fig. 7). With the help of the 3D view, the transitions between different sections can be corrected and optimized, before the preform is woven.

The first trials to produce the component shape were carried out on a laboratory loom since this requires only small amount of the ceramic fibres. Using a simple plain weave the target shape could already be nicely met (Fig. 8).

In order to achieve the necessary fabric thickness, the weave is based on a multilayer structure, to realise the reinforcement in z-direction by ondulating warp yarns and high strength values by ondulation-free warp yarns. Multilayer fabrics were developed with four weft layers. The final shape is supported by an inside pleat connection of the bottom and top fabric layer (5). For better infiltration of the ceramic slurry, the incorporation of sacrificial materials is considered.

Based on the results of the preliminary tests, in particular the infiltration results, an angle interlock weave with four layers with 10 warp threads/cm and single weft insertion was elaborated and worked on the laboratory loom with alumina fibre material (Nextel TM 610) (Fig. 9).

The first preforms with PES as an alternative material were successfully produced on the double rapier machine shown in Fig. 1. Parallel to the preform development, HTL establishes a pilot line for the production of oxidic ceramic fibres at its site in Bayreuth, which will be able to provide enough fibres for the subsequent processing in 3D weaving. For the subsequent infiltration of the preform a pressure slurry process is used. For this innovative process, the slurry matrix was adapted in test series, and the mould for pressure slurry casting was developed together with Sama Maschinenbau GmbH.

## Conclusions

The textile processing of ceramic fibres to 3D preforms is a new field with high development potential. It allows near net-shape forming of complex parts and special arrangement of fibre rovings, e.g. in load conforming orientations. The binding between the fibres, the reinforcement between textile layers and the geometry of the parts are designed by computational tools. This reduces the development time for new products. Unlike additive manufacturing, textile methods are intended for

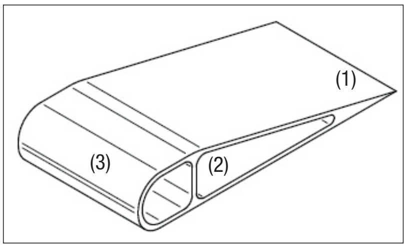


*Fig. 5*
*Target geometry of airfoil*

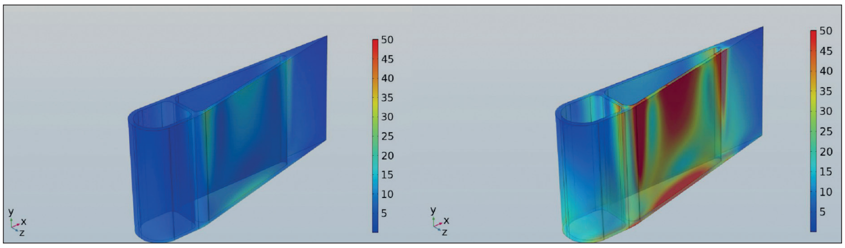


*Fig. 6*
*Distribution of tensile stresses [MPa] in the airfoil made of the CMC material at different rotational speeds: left: = 5000 1/min, right: 10 000 1/min*

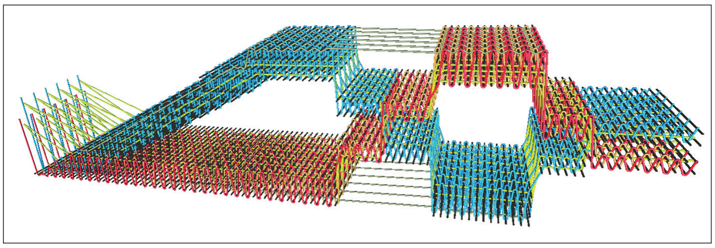


*Fig. 7*
*First attempt at binding development with simplified basic bindings*

*Fig. 8*
*First preform produced on a laboratory loom*

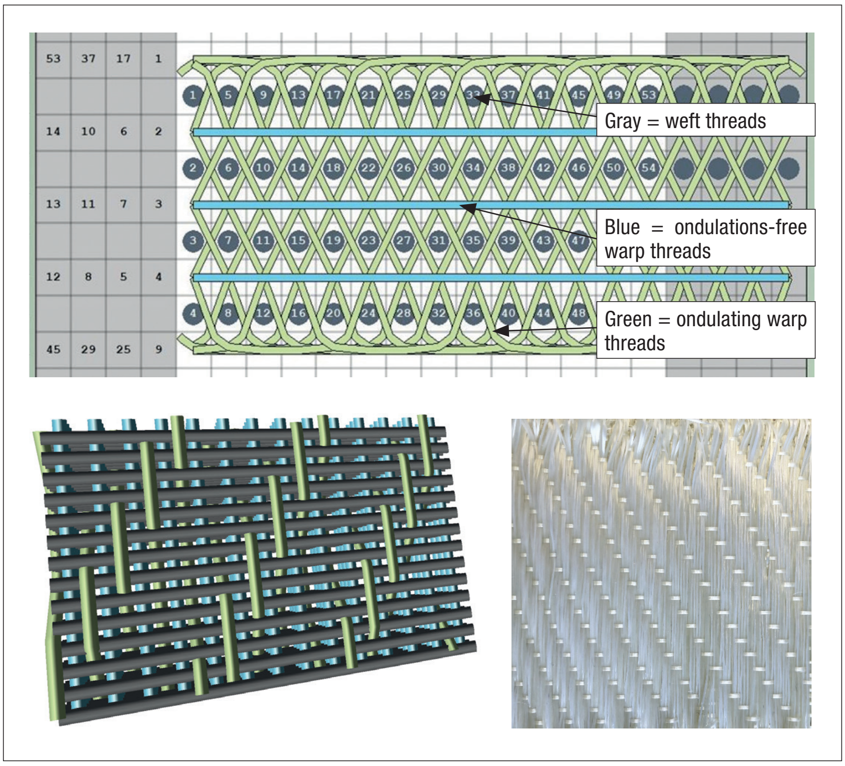


*Fig. 9*
*Weft pattern, simulation and top view of the selected multilayer fabric*

serial production and become even more efficient with increasing lot sizes.

Custom-fit solutions are available for a wide range of applications. The team of HTL has a modern machine park at its disposal. Extensive experience in the development of even complex textile structures has been gained in a wide variety of projects. The team gladly takes on such development tasks and is looking for industrial partners who are interested in implementation.

Finally we come back to the hot gas fan shown at the beginning (compare Fig. 1). In a feasibility study, we showed that the fibre preform of this complex part can be manufactured in a single-stage as a polar fabric (Fig. 10). Assembly and joining of the wheel can be completely eliminated [6]. The TFK is involved in the development and implementation of textile processes for the single-stage production of such preforms, near-net-shape and in series.

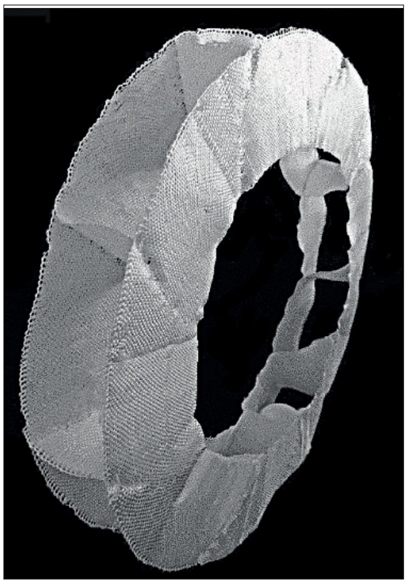


*Fig. 10*
*Feasibility study on a single-stage preform for a fan wheel*

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## References

[1] Vogt, J.; Seifert, G.; Raether, F.: Towards ceramic production via digitalization and additive manufacturing. Ceramic Applications **9** (2021) 36–44

[2] Raether, F.: Ceramic matrix composites – an alternative for challenging construction tasks. Ceramic Applications **1** (2013) [1] 45–49

[3] Vierhaus, P.; et al.: Low-cost ceramic matrix composites for applications at intermediate temperatures. Refractories Worldforum **13** (2021) [2] 20–24

[4] Die textile Zukunft erforschen – TF20-Websystem, https://www.staubli.com/de/de/textile/success-story/verbundstoffe-hochschule-fuer-angewandte-wissenschaften-hof.html

[5] Cherif, Ch.: Textile materials for lightweight constructions. Berlin, Heidelberg 2015

[6] Albert, D.; Ficker, F.: Reinforcement structure for component, component comprising the reinforcement structure as well as method for manufacturing the reinforcement structure and method for manufacturing the component. Patent application 10 2021 209 982.3