# A SIMPLE MODEL TO PREDICT THE TEMPERATURE PROFILE DURING ULTRASONIC WELDING OF BINDER PREFORMS

F. Weiland[1*], C. Weimer[1], P. Mitschang[2]

[1] *Eurocopter Deutschland GmbH, 81663 München*
[2] *Institut für Verbundwerkstoffe GmbH (IVW), 67663 Kaiserslautern*
**frank.weiland@eurocopter.com*

**Keywords:** Preforming, Automation, Binder, Ultrasonic Welding

## Abstract

*For the efficient and automated assembly of bindered fiber preforms the ultrasonic welding technology has been investigated. Through the conversion of acoustic into thermal energy a local temperature rise of more than 300 °C can be effected within few seconds.*
*In order to predict the temperature profile within the preform a simple heat flux model has been established based on the heat conduction model between semi-infinite bodies. It divides the heating process in two phases; the adiabatic heat up and the heat flux into ultrasonic horn and tool. The model has been validated with the measurement of four different heat profiles showing peak temperatures between 190 °C and 400 °C. A deviation of the model from the measurements of 14% in average has been observed. The use of the model as means to shorten the parameter finding process is intended.*

## 1 Introduction

*1.1 Preforming Processes*

The development of preforming process technology for components made of carbon fiber reinforced polymer composites (CFRPC) has always been focused on decreasing costs through automation and reduction of material costs and process time [1]. Within the last years also energy efficiency in production has become of increasing interest. Not only cost aspects are considered; production means also have to be put in context of efforts to lower the environmental impact of the air transportation industry [2]. Flexibility, as a further key aspect for future manufacturing technologies, is necessary to serve for a wide range of part geometries and new material systems.

Within the sequential preforming routine, rolls of fabric are processed. These are optionally inter-layered with preforming auxiliary materials like veil binders (e.g. thermoplastic polyamide). In at least one process step the binder is heated above its softening temperature under application of pressure in order to either create compaction and adhesive bond between layers (preform “activation” and compaction) or to join preforms (“preform assembly”). Convection ovens, infrared fields or heated tools are common to perform this step. These processes are time and energy intensive or expose lack of flexibility. The part usually needs a manual preparation with auxiliary material for vacuum compaction during binder activation [3].

*1.2 Ultrasonic Welding*

Ultrasonic (US) welding is well established in the fields of thermal bonding for thermoplastics and thermoplastic composites [4]. During the welding process the acoustic load is induced into the part by an ultrasonic horn with a frequency between 10 and 70 kHz and an amplitude of 10-200 µm under application of pressure [5]; in this context this operation is referred to as "insonification". The horn is either cylindrical and rotating to create continuous welds or it is of stamp-like shape for spot welding operations. The components to be bonded are heated up by surface friction until a significant decrease of viscosity in the polymer is reached. Beyond this point the dominating mechanism is intermolecular friction in the polymer which leads to further heat up and melting of the material [6]. With application of pressure, which is held until solidification of the material, a strong bond can be created. The ability to internally convert the mechanical vibrations into thermal energy determines the suitability of a polymer for ultrasonic welding. An ultrasonic spot weld cycle usually takes between 0.5 and 4 seconds.

*1.3 Ultrasonic Preform Welding*

The US Welding Technology has been identified as a process element with enormous potential to efficiently process established and novel preforming material systems with reduced process time and a high degree of automation. Both preform assembly processes for complex, integrated structures under use of polymers with raised melting temperatures and also preform stabilization through binder activation are targeted applications.

The mechanism of heat generation during US Welding has been identified as mechanical friction between the fibers; comparative studies did not indicate any influence of intermolecular friction within the binder polymer [7].

With a customized design of the ultrasonic horn both spot welds and continuous welds can be applied with one end effecter; in the following however, only spot welds (area of 10 x 20 mm) will be discussed. A welding frequency of 30 kHz has been identified as suitable for the welding of preforms. Preform thicknesses of more than 4 mm (equals a weight per unit area of around 4000 g/m² Carbon fiber) have been successfully welded following requirements regarding seam strength and allowable fiber distortions based on aerospace standards. During comprehensive parameter studies, welding amplitudes of 17 µm, welding pressure of 6.8 bar and weld time of 2 s have been identified as optimum for a polyamide bindered Non Crimp Fabric (NCF) laminate with an areal weight of 2540 g/m² [7].

The process' degree of efficiency has been determined with 30.5 %. This is the fraction of the electrical power consumed by the ultrasonic generator that actually is converted into heat within the preform. Most of the energy saving potential of the ultrasonic technology however lies in the fact that heat is only generated where needed: In the welding zone under the ultrasonic horn. Virtually no heating of tooling, air or surrounding preform takes place.

Furthermore it has been observed, that during pressurized insonification, additional compaction in the preform laminate takes place. The degree of compaction increases with a decreased number of filaments carrying the acoustic load. After the end of the welding process a fiber volume content (FVC) of around 55 % has been measured in the welding seam of bindered NCF. With the welded preform samples, infiltration and cure has been conducted using the Resin Transfer Moulding technology (RTM) as well as the Vacuum Assisted Resin Infusion process (VARI). The VARI laminates with a FVC of around 52 % showed residual imprints of the weld process. These could not be observed in the RTM laminate with its FVC of 55 % [8].

The interlaminar shear strength ("ILSS") has been measured for samples with different welding configurations. Each configuration has been attributed a possible defect induced by the welding operation. These defects were fiber squeeze out, damage of fiber sizing and fiber undulation. No reduction of the ILSS has been detected; neither for NCF nor for the woven fabric [8].

*1.4 Motivation*

For each binder system to be used during preform operations a process window has to be defined. A minimum temperature has to be overrun in order to ensure a complete softening of the binder and sufficient interlaminar adherence within the preform. Maximum temperatures are defined to control the cure process of an epoxy binder or any degradation of binder, sewing threads or fiber sizing.

Measurement of the temperature development over the thickness of a preform laminate revealed a temperature profile which is strongly influenced by thermal flux into the ultrasonic horn and the tool ("skin effect"). If parameters are not chosen carefully, areas of the bindered preform might exhibit a peak temperature outside the targeted process window with the consequences mentioned above. In the other use cases it might be acceptable to reach the required temperature only in a certain layer.

In both cases the knowledge of the temperature profile which forms itself during the welding process is essential for ensuring process stability and qualification for serial applications. Iterative methods to determine the optimum parameter set are time consuming and theoretically have to be conducted for each weld set up (material, lay-up, tooling).

A thermal model to predict the temperature profile within the laminate can therefore significantly shorten the process of parameter finding.

## 2 Experimental

The temperature profile of four welding configurations has been measured. Different fiber materials, weight per unit area and welding parameters have been applied. Table 1 lists the investigated configurations.

The temperatures have been measured using thin thermo couples (type K, NiCr-Ni, diameter 0.8 mm). Each layer has been measured 8 times to achieve statistical relevance.

| **Material and graphical representation in figure 3** | **Lay up** | **Material values** | **Welding parameters** |
|---|---|---|---|
| Carbon NCF w/ PA binder veil | 10 layers (each 254 g/m²), symmetric | $m_{LVU}$=0.4256 g; ρ=1.33 g*cm$^{-1}$ $c_p$=0,78; $\lambda_L$=0.1 W*m$^{-1}$*K$^{-1}$ | $t_W$ =1.5 s A=17 µm F=113 N |
| Carbon NCF w/ PA binder veil | 16 layers (each 254 g/m²), symmetric | $m_{LVU}$ =0.681 g; ρ=1.33 g*cm$^{-1}$ $c_p$=0.78; $\lambda_L$=0.1 W*m$^{-1}$*K$^{-1}$ | $t_W$=2.5 s A=22 µm F=163 N |
| Glass NCF w/ PA binder veil | 11 layers (each 316 g/m²) | $m_{LVU}$=0.524 g; ρ=1.47 g*cm$^{-1}$ $c_p$=0.66; $\lambda_L$=0.06 W * m$^{-1}$*K$^{-1}$ | $t_W$=2.5 s A=17 µm F=120 N |
| Carbon fabric w/ binder veil | 10 layers (each 220 g/m²), symmetric | $m_{LVU}$=0.369 g; $\rho_C$=1.25 g*cm$^{-1}$ $c_p$ =0.78; $\lambda_L$=0.1 W*m$^{-1}$*K$^{-1}$ | $t_W$=2.5 s A=17 µm F=107 N |

**Table 1.** List of material and welding configurations applied during temperature profile measurements

A 30 kHz ultrasonic welding system has been used during these studies. The maximum amplitude is ~29 µm. The horn is shaped in a way to slide over the fabric without causing major distortions (see figure 1 on the following page). The horn has been integrated into a computer controlled test bench that allows maximum reproducibility and measurement and logging of all relevant process data.

## 3 Modell

The space under the ultrasonic horn with the length $l_{LVU}$, the width $b_{LVU}$ and the height $h_{LVU}$ is defined as the "Laminate Volume Unit" LVU. $l_{LVE}$ equates the length of the weld zone, $b_{LVU}$ equates its width and $h_{LVU}$ equates the thickness of the preform laminate.

### *3.1 Material values*

The mass of the LVU, $m_{LVU,}$ consists of the mass of fibers $m_{F,LVU}$, the binder mass $m_{B,LVU}$ and the air mass within the LVU, $m_{A,LVU}$.

The specific heat capacity of LVU at constant pressure, $c_{p,LVU}$, consists of the fractions of the individual heat capacities according to their mass fractions.

$$c_{p,LVU} = \frac{m_{F,LVU} \cdot c_{p,F} + m_{B,LVU} \cdot c_{p,B} + m_{A,LVU} \cdot c_{p,A}}{m_{LVU}} \tag{1}$$

The thermal conductivity of the laminate in z-direction, $\lambda_Z$, has been extracted from the studies of Yamashita et al. [9]. In the frame of these studies the conductivity of carbon, glass and aramide fabrics have been modeled and measured. The conductivity of carbon was determined with $\lambda_{Z,C} \sim 0.08$ W/m*K, the one of glass with $\lambda_{Z,G} \sim 0.06$ W/m*K.

### *3.2 Calculation steps*

The heating process has been divided in two phases: "heat up" and "skin cooling". During "heat up" the LVU heats up homogeneously and adiabatic; the temperature profile shows a temperature step between horn and laminate (respectively laminate and tool), figure 1, center. The temperature profile itself forms during the second phase, when thermal energy flows from the laminate into horn and tool ("skin cooling", figure 1, right).

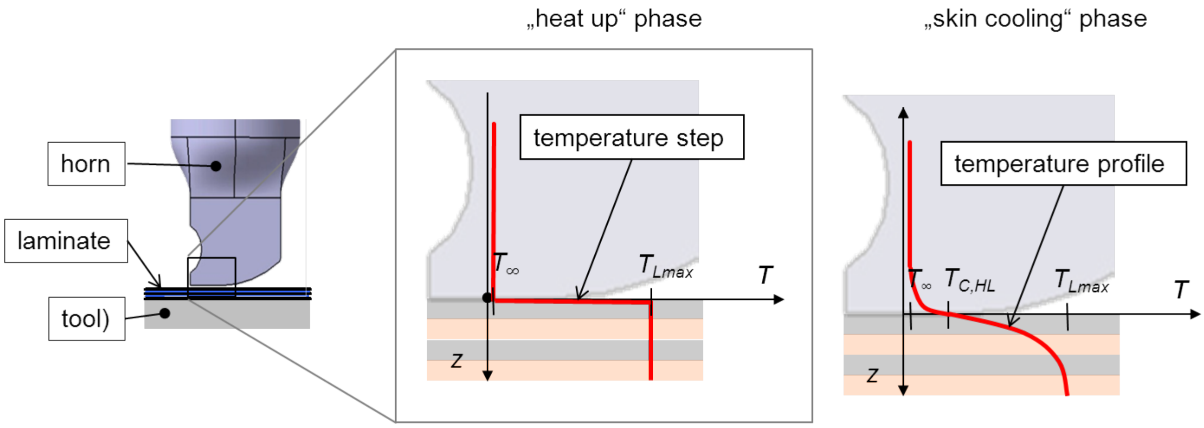


**Figure 1.** Depiction of calculation phases of heat flux model

First Phase: "Heat up":

During Heat up, the LVU is considered adiabatic with internal heat source. At the end of the phase, the whole LVU reaches the laminate maximum temperature.

The energy to heat up a mass *m* with the specific heat capacity $c_p$ from room temperature $T_\infty$ to $T_{L,max}$ is defined as

$$E_{th} = m \cdot c_p \cdot (T_{L,\max} - T_\infty) \tag{2}$$

The fraction of ultrasonic generator power which is actually converted into heat in the preform, $P_{eff}$, is

$$P_{eff} = \eta_{US} \cdot P_{USG} \tag{3}$$

$\eta_{US}$ being the degree of efficiency and $P_{USG}$ the generator power including losses. $\eta_{US}$ had been determined with 0.305 in previous studies [8].
With equation 2 it is

$$E_{th} = P_{eff} \cdot t_W = m \cdot c_p \cdot (T_{L,\max} - T_\infty) \tag{4}$$

The LVU temperature after the end of the heat up with the effective ultrasonic generator power $P_{eff}$ and a weld time of $t_W$ is calculated as follows:

$$T_{Lmax} = T_\infty + \frac{t_W \cdot P_{eff}}{m_{LVU} \cdot c_{p,LVE}} \tag{5}$$

Second Phase: Thermal flux into horn and tool
The thermal flux from the hot laminate into the US horn (made from titanium) and the aluminium tool (mould) is calculated by theoretically dividing the laminate in thickness center and treating two separate systems; one system being "horn - half laminate", the other system being "half laminate – tool", see figure 2.

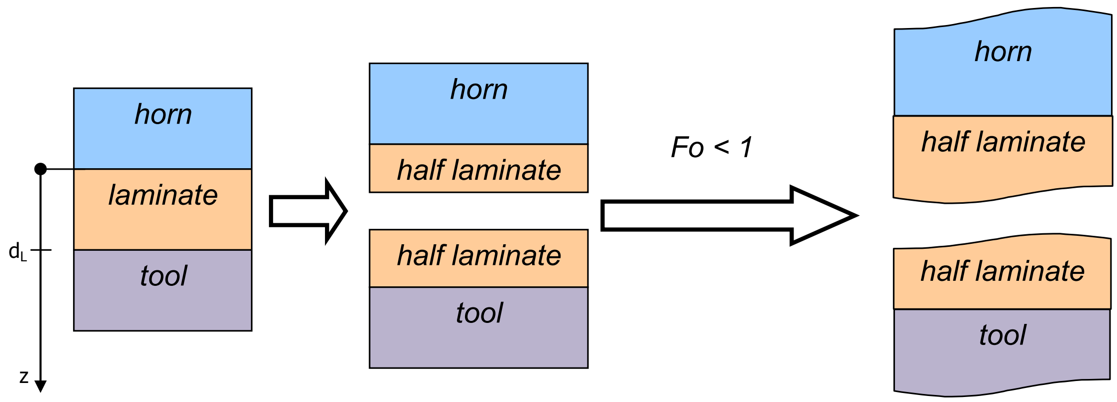


**Figure 2.** Division of 3-body-system into two systems of each two infinite bodies

Each system consists of two bodies, each body considered as half-infinite. This simplification of half infinite bodies is allowed, if the temperature profile is able to form itself in z-direction unaffected from the edge of the bodies. The formal condition is a Fourier number $Fo < 1$ [10]. It is

$$Fo = \frac{\lambda_z \cdot t_K}{\rho \cdot c_p \cdot l^2} \tag{6}$$

$\lambda z$ is the thermal conductivity of the preform , $\rho$ and $c_p$ are its density and specific heat capacity, $t_k$ is the contact time between hot laminate and cold "partner" and $l$ is half of the laminate thickness. The Fourier number of the considered laminates has been calculated as $0.1 < Fo < 0.2$, which fulfills above mentioned prerequisite.
In the following the calculation of the "half profile" between horn and laminate is described (the other half profile is calculated accordingly).
The hot laminate (temperature $T_{L,max}$) is brought in contact with the horn ($T_\infty$), the contact time $t_C$ being a fifth of the weld time.

$$t_C = 0.2 \cdot t_W \tag{7}$$

The calculation of the contact temperature between horn and laminate, $T_{C,HL}$, is in accordance with [10] (note: $T_{C,HL}$ is independent from the contact time).

$$T_{C,HL} = T_H \frac{b_H}{b_H + b_L} + T_{L\max} \frac{b_L}{b_H + b_L} \tag{8}$$

$b$ is the thermal effusivity of the horn (index „H") and the laminate (index „L"). It is defined as follows [11]:

$$b = \sqrt{\lambda_z \rho c} \tag{9}$$

with the thermal conductivity $\lambda z$, densitiy $\rho$ and speed of sound $c$.
The temperature profile within laminate and horn is represented in the Biot number $\Theta$. Its calculation requires the use of the Gauss error function („erf", [11]). It is

$$\theta(\eta_A) = erf(\eta_A) \tag{10}$$

With the thermical similarity indicator $\eta_A$ defined as

$$\eta_A = \frac{z}{2\sqrt{\lambda_z \cdot t_C}} \tag{11}$$

$z$ is the laminate depth ($z = 0$ in the contact plane between horn and laminate).
The Biot number $\Theta$ is the quotient between the temperature differences [11].

$$\theta(z) = \frac{T(z) - T_{C,HL}}{T_\infty - T_{C,HL}} \tag{12}$$

*T(z)* is the temperature in laminate depth *z*. Solving for *T(z)* equates:

$$T(z) = erf(\frac{z}{2\sqrt{\lambda_z t_C}}) \cdot (T_{L\max} - T_{C,HL}) + T_{C,HL} \tag{13}$$

By creating points using this equation the temperature curve within the laminate can be displayed with a validity for $0 < z < d_L/2$.
For $z < 0$ (i.e. temperature within horn) the according horn material constants have to be used.
The calculation of the half profile within the system "laminate-tool" is analogue.

### *3.3 Validation*

The configurations as described in table 1 have been measured and modelled. The following graph puts the model against the measured profiles, with dashed lines interpolating the measured values.

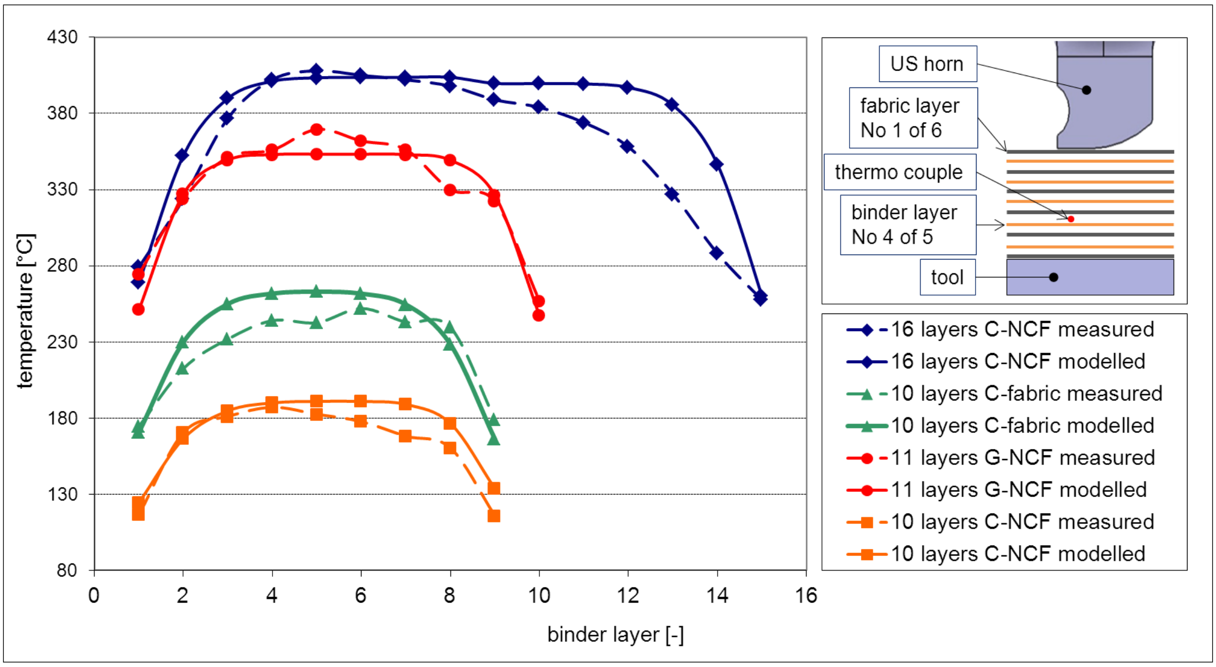


**Figure 3.** Results of temperature profile measurements (dashed line) and according profile models (solid lines) for different material/welding configurations; top right: Setup example

Measurements have been conducted in every interlayer between two fabric layers; the modelled points have been calculated in the according depth of the laminate.
The direct comparison revealed an average deviation of 15.6 °C (14%). The comparison of measuring points close to the surfaces (important for estimating the skin effect) revealed an average deviation of 15.8 °C, whereas points closer to the laminate thickness center could be predicted with an average deviation of 12.5 °C.

## 4 Conclusion

A simple thermodynamical model to predict the temperature profile in a preform laminate during an ultrasonic welding cycle has been proposed. Its accuracy has been assessed by

comparison with measurements in the laminate; an average accuracy of 15.6 °C (14%) could be determined for temperature profiles with peak temperatures between 200 and 400 °C.
This accuracy has to be judged against the background of its intended use.
The binder activation process is an auxiliary process and the created bonds are not meant to actually carry loads in the part. Therefore the process window for the activation of the binder polymers usually is relatively large; e.g. for the used Copolyamide veil a temperature range between 90 °C and 150 °C is considered applicable [12].
The proposed model (implemented in an easy-to-use spreadsheet program) serves to easily change all main process parameters and directly see the effect. This significantly enhances the chance to instantly define the right set of parameters thus reducing time consuming measurements ("first time right"). It is recommended however to validate the final set of parameters before implementing it into the final process.

**References**


[1] Weimer, C., Mitschang, P.: *Preformverfahren* in „Handbuch Verbundwerkstoffe" edited by Neitzel, M., Mitschang, P. München: Carl Hanser Verlag, p. 73-104, 2004
[2] Internet: Homepage EU-project "Clean Sky": www.cleansky.eu
[3] Asareh, M. et al.: *Investigation of Preform Manufacturing Techniques using Novel Binder coated carbon fibre tows*, Proceedings of *ECCM* 2009
[4] Ageorges, C., L. Ye, M. Hou: *Advances in fusion bonding techniques for joining thermoplastic matrix composites: a review*; Composites, Part A; Article; 2001
[5] Grewell, D. et al. *Plastics and Composites Welding Handbook*, Carl Hanser Verlag, 2003
[6] Zongbo Zhang et al.: *Study on Heating Process of Ultrasonic Welding for Thermoplastics*, Dec. 2009
[7] Weiland, F., Weimer, C., Mitschang, P.: *Ultrasonic Welding of Carbon Fiber Preforms: Process and Mechanisms* in "Proceeding of *International SAMPE Conference"*, Long Beach, California (2011)
[8] Weiland, F., Beier, U., Weimer, C., Mitschang, P.: *Ultrasonic Welding Application in Preform Automation* in "Proceeding of *European SAMPE Conference"*, Paris, France, 2011
[9] Yamashita Yoshihiro et al.: *Effective Thermal Conductivity of Plain Weave Fabric and its Composite Material Made from High Strength Fibers*. "Journal of Textile Engineering", Vol.54, No.4, 2008
[10] Herwig, H.: *Wärmeübertragung A-Z*, VDI-Buch, Springer-Verlag GmbH, März 2000
[11] Polifke, W., Kopitz, J.: *Wärmeübertragung: Grundlagen, analytische und numerische Methoden*, Pearson Studium; 2., aktualisierte Auflage. Januar 2009
[12] Beier, U.: *High Performance fibre-reinforced composites prepared by a novel preform manufacturing routine*, Technisch wissenschaftlicher Bericht, 2010