Ultrasonic Resin Flow and Cure Monitoring

N. Liebers[1]*, D. Bertling[1]

[1] *German Aerospace Center (DLR), Lilienthalplatz 7, 38108 Braunschweig, Germany.*
**Corresponding author (Nico.Liebers@dlr.de)*

Keywords: Ultrasonic Sensors, Flow front monitoring, Thickness monitoring, Cure monitoring, Experimental.

Introduction

The resin injection and cure processes are crucial manufacturing steps for composite materials with high impact on the part quality and properties. But both processes are sensitive to deviations in raw materials and process parameters [1,2]. By monitoring the process evolution and current part state with suitable process monitoring sensors and systems, potential irregularities can be identified and evaluated. If necessary, corrective actions can be undertaken, where the sensor input can serve as input in a closed-loop control. Next to process control such sensors can be used to speed up the process design phase and evaluate process models.

Low cost ultrasonic sensors for process monitoring

Ultrasound based sensors on one hand do not require direct contact to the part offering the advantage that part surface and mold remain unaffected and simplifying the sensor integration [3]. On the other hand almost all of the most crucial process parameters can be obtained by signal analysis. The DLR has developed simplified and low cost sensors which enable the integration of a dense sensor network into the mold [4,5]. Compared to conventional ultrasound transducers (Figure 1), the sensor housing was removed. The unstable acoustic coupling between the sensor housing (delay line) and mold was identified as critical for a robust monitoring system.

The sensors are applied on the outer side of the mold (Figure 1 and Figure 2), from where the sound waves propagate through the wall and then interact with the part.

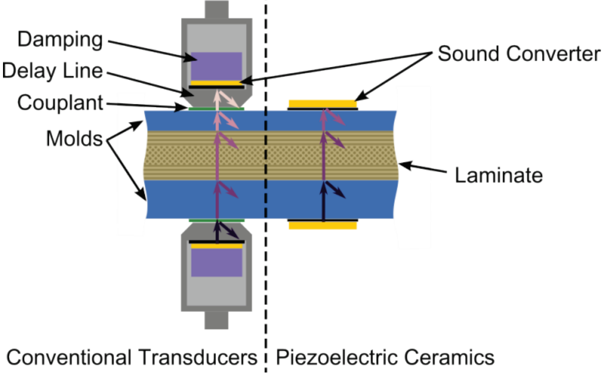

Figure 1: *Scheme of conventional ultrasound transducers and tool mounted piezoelectric elements for process monitoring with comparison of interfaces in sound propagation path.*

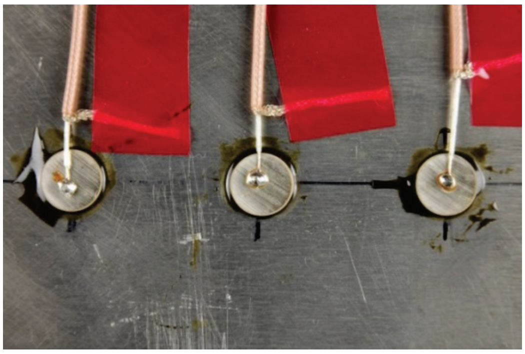

Figure 2: *Photo of adhesively mounted piezoelectric sensors onto mold.*

Flow Front Monitoring

By analyzing the pulse-echo signal, where the same sensor acts as sender and receiver, the resin arrival at the interface between mold and part can be detected (Figure 3). Before resin arrival the sound waves are nearly completely reflected, while on resin arrival the amplitude of the reflected signal is decreasing (Figure 4 upper graph) as now parts of the sound signal propagates into the laminate.

Using the transmission mode with a separate receiver in the opposing mold (Figure 3) the time where the volume between the sensors is impregnated can be derived. During the impregnation of this volume the transmission amplitude is increasing (Figure 4 lower graph).

Combining the information the flow front shape and impregnation mechanics can be derived. Not only the arrival time, also the flow speed and even its direction can be derived by further signal processing as both duration and shape of the amplitude change depend on the impregnation speed and direction.

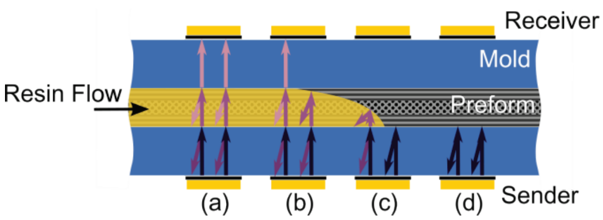

Figure 3: *Scheme of working principle of ultrasonic flow front monitoring*

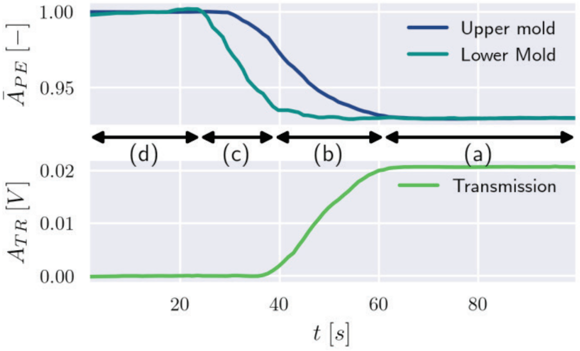

Figure 4: *Top: Normalized pulse-echo signal amplitudes during passing of flow front Bottom: Transmission amplitude*

Degree of Cure and Laminate Thickness Monitoring

The degree of cure can be derived from measuring the sound velocity, which depends on the part's elastic modulus. Any increase in elasticity hence leads to an increase in sound velocity. For high degrees of cure there is a linear relation to the sound velocity. Also the gelation and vitrification can be extracted from characteristic points in the sound velocity curve progression.

Finally the laminate thickness can be derived from the time of flight of the sound signal through the part. This is the most challenging parameter to calculate, as the time of flight is not only depending on the thickness, but the current sound velocity. The latter depends on cure as well as the fiber material and volume content as well as the temperature. These have to be compensated by calibration and special sensor arrangements [6].

References

[1] Mesogitis TS, Skordos AA, Long AC. Uncertainty in the manufacturing of fibrous thermosetting composites: A review. *Composites Part A: Applied Science and Manufacturing* 2014;57:67–75.

[2] Devillard M, Hsiao K-T, Advani SG. Flow sensing and control strategies to address race-tracking disturbances in resin transfer molding—part II: Automation and validation. *Composites Part A: Applied Science and Manufacturing* 2005;36(11):1581–9.

[3] Konstantopoulos S, Fauster E, Schledjewski R. Monitoring the production of FRP composites: A review of in-line sensing methods. *Express Polymer Letters* 2014;8(11):823–40.

[4] Liebers N, Schadow F, Raddatz F. Monitoring of a manufacturing process (EP2657801); 2013.

[5] Liebers N. Effective and flexible ultrasound sensors for cure monitoring for industrial composite production. DLRK Berlin; 2012.

[6] Liebers N. Autoclave Infusion of Aerospace Ribs Based on Process Monitoring and Control by Ultrasound Sensors. ICCM Copenhagen; 2015.