Document Version
Final published version

Licence
CC BY-NC-ND

Citation (APA)
Jongbloed, B. C. P., Asfew, K. N., Teuwen, J. J. E., & Peeters, D. M. J. (2024). The challenges with fast heating rates in the processing of thermoplastic composites. In *Proceedings of the International Conference and Exhibition on Thermoplastic Composites* (2024 ed.). ITHEC.

The challenges with fast heating rates in the processing of thermoplastic composites

B. Jongbloed, K. Asfew
Smart Advanced Manufacturing XL (SAM XL), Delft, the Netherlands
J. Teuwen, D. Peeters
Delft University of Technology, Delft, the Netherlands

Abstract:
To meet high production rate demands for single-aisle aircraft, this paper looked into automated fiber placement for composite parts and continuous ultrasonic welding for fast assembly, both leveraging rapid heating rates. We highlighted some of the challenges and opportunities in manufacturing thermoplastic composites with these advanced methods. Fast heating can change the microstructure of tapes (increased voids and surface roughness) prior to consolidation. Due to the high temperature and fast speeds, limited consolidation times are available to cool down effectively or resolve the changed microstructure, resulting in poor quality (intimate contact). This could be measured in the cooling phase, through a reduced cooling rate with tapes with low intimate contact.

Keywords: continuous ultrasonic welding, laser-assisted fibre placement, Humm3

Introduction

Thermoplastic composites are promising for their potential to reduce the weight of the next generation aircraft as compared to the aluminium baseline. To reach the high production rates needed for the production of single-aisle aircraft, automated techniques are needed to produce parts and for the assembly. This paper will highlight automated fibre placement as a potential method for producing composite parts, and will introduce continuous ultrasonic welding (CUW) as a promising joining technique for short cycle times for the assembly. All these techniques are governed by fast heating rates. The goal of the paper is to highlight insights and challenges into manufacturing processes with fast heating rates for thermoplastic composites.

Continuous ultrasonic welding

Continuous ultrasonic welding consists of a heating/vibration phase and a cooling/consolidation phase. During the heating phase high-frequency low-amplitude mechanical vibrations are introduced by a sonotrode, generating heat at the welding interface due to surface and viscoelastic friction. After the heating phase, the material is consolidated under the pressure of a consolidator during the cooling phase.

SAM XL developed a robotic continuous ultrasonic welding setup shown in Fig. 1. The setup consists of a custom linear track from Vansichen together with industrial KUKA robot. The robot was equipped with an in-house developed end effector. To ensure that the to-be-welded materials are in contact before entering into the heating phase, the end effector is equipped with a compactor ahead of the sonotrode.

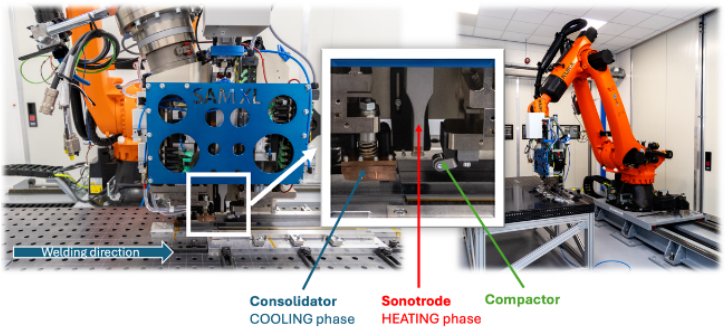

Fig. 1: *Robotic set-up at SAM XL*

The transition from a stiff bench welder with an XY table in a laboratory setting as described in [1] to a more flexible industrial robot makes it challenging to simultaneously align the compactor, sonotrode and consolidator with respect to the to-be-welded materials to ensure perpendicularity. For the bench welder in [1] the consolidator was rigidly connected to the force application platform transferring the load to the consolidator. To simplify the required alignment, compliance was introduced by connecting the consolidator via a universal joint shown in Fig. 2 config. 1. However, the introduction of this universal joint resulted in heat built up in the consolidator (see Fig. 4 A). Therefore, the capacity to transfer heat away from the weld was lost, significantly increasing the temperature of the top adherend surface (see Fig 4 B) and presumably also of the welding interface. This is a significant problem as overheating of the adherends might occur and changing thermal boundaries are introduced making it challenging to control the welding process and get a uniform weld quality.

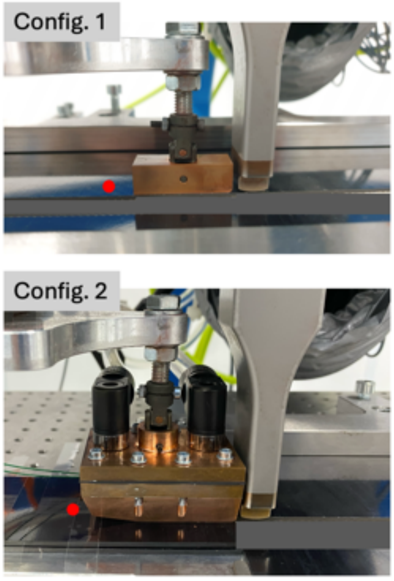

***Fig. 2:** Different configurations of the ultrasonic welding set-up*

To mitigate the heat build-up within the consolidator over the length of the weld, an actively cooled consolidator was developed [2] through which a coolant flows, as shown in Fig. 2 config. 2. The temperature of the cooled consolidator remains at a low constant value during the welding process shown in Fig. 4 [1], and the temperature of the top adherends surface remained constant and was significantly cooler compared to the not-cooled consolidator config. 1. This indicates that the cooled consolidator ensures more stable thermal boundary conditions compared to the non-cooled consolidator, which has been seen to result in uniformly welded seams.

Laser-assisted fibre placement

LAFP, schematically shown in Fig. 3, can roughly be split into three stages: heating, compaction and cooling. First the material is heated to above the processing temperature, after which there is a small shadow zone before the material is compacted by the compaction roller. Finally, the tape is cooling down without pressure after the compaction roller has passed. While only in the first phase the material is heated, the effects of the heating have to be 'erased' during the compaction phase, and the cooling phase may give some information on how well this erasing has gone. Hence, all three stages will be discussed.

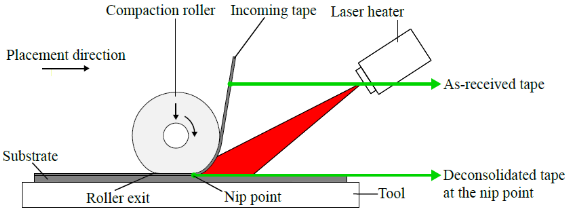

***Fig. 3:** Schematic of LAFP*

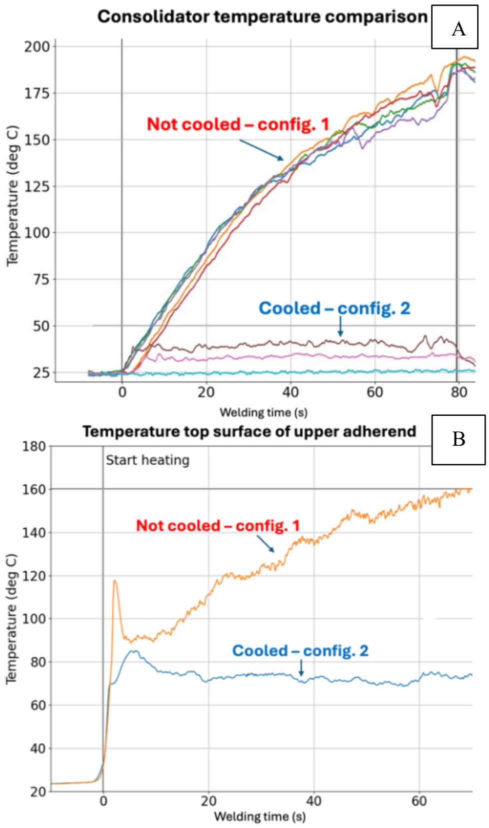

***Fig. 4:** Time-temperature graphs for different configurations taken from* [2] for a weld made on UD CF/LMPAEK

For the study on the heating phase, the tape was kept stationary in the set-up shown in Fig. 5, showing the VCSEL (Vertical Cavity Surface Emitting Laser) that is used to heat up the sample. Also the thermal camera and laser line scanner are shown, where the latter is aimed at the 'simulated nip point': the point where the material is expected to reach its highest temperature, aimed to be around 400°C, the processing temperature of CF/PEEK.

The results of the test were unexpected: it was shown that even if the material was not heated to its melting temperature (T_m), but only slightly above its glass transition temperature (T_g), there was already an increased void content. Hence, the microstructure of the tape already changes when T_g is reached. This effect is also observed in Fig. 6, where the temperature and out of plane deformation (as function of the material thickness) are shown at the simulated nip point. It can be clearly observed that the deformation suddenly increases when T_g is reached. Furthermore, a clear link between deformation and temperature can be seen: the higher the temperature, the higher the deformation.

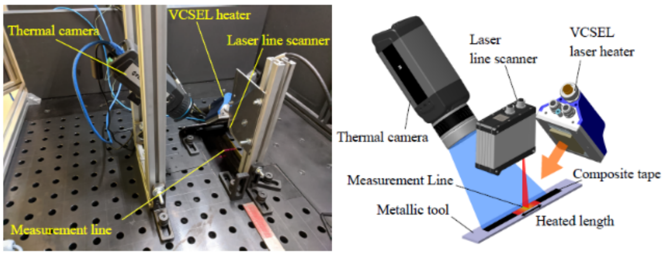

Fig. 5: *Schematic of static test set-up (laser)*

This has two reasons: one, once the deformation is sufficiently high, the contact with the aluminium tool is lost, reducing the heat transfer on the bottom side of the tape; two, the higher the deformation, the closer the tape comes to the laser. This shows that hot spots are being exacerbated: once the deformation starts, it becomes easier to heat up, heating the tape up even more.

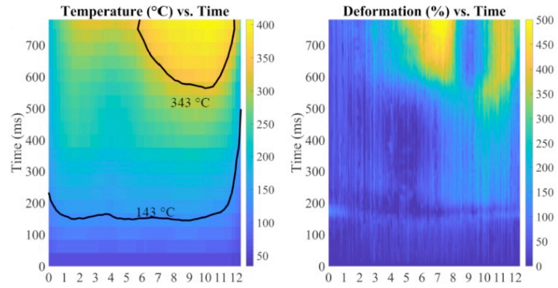

Fig. 6: *Time vs temperature results and time vs out-of-plane deformation*

Next, we looked into how the effects that occur during heating can be resolved during compaction: often, the contact development is modelled using the roughness of the as-received tapes [3, 4], while we found that the tape after heating is significantly different.

To investigate this, we designed a set-up that can mimic the roller going over the tape in the laser enclosure. When using this set-up, we could investigate whether the effects of heating were fully reversed or not. As shown in Fig. 7, increasing the speed and pressure both have a positive effect on the surface roughness (i.e., lower surface roughness), but the as-received state cannot be fully recovered. The same results was found for other descriptors as well. Finally, we also looked at the cooling phase. This was done with a thermal camera placed behind the compaction roller. By changing the pressure, and keeping the temperature after heating constant, different levels of degree of effective intimate contact were achieved. As can be seen in Fig. 8, the model built to simulate the cooling was only matching when the effect of the intimate contact was taken into account. This shows that the thermal contact resistance, and thus the cooling rate, is dependent on the degree of effective intimate contact, and could in the future be used as a quality indicator.

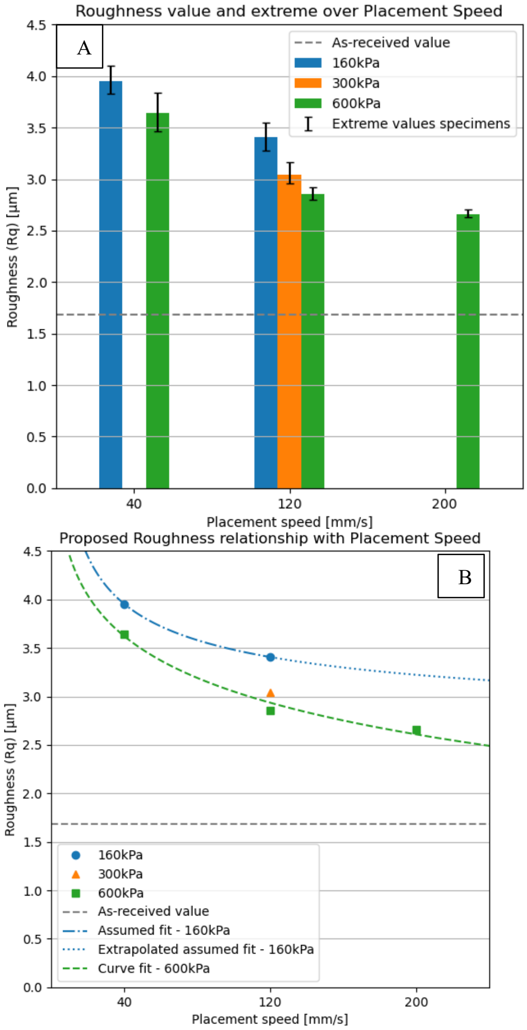

Fig. 7: *Roughness vs pressure after consolidation*

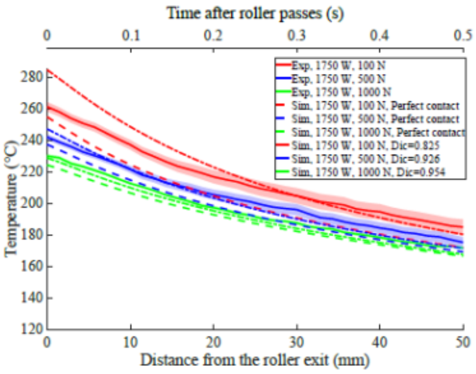

Fig. 8: *Temperature vs distance after the roller*

Humm3 heating

Lasers and infrared heaters are common heat sources for processing composite materials. An innovative pulsed broadband heat source that provides rapid temperature changes without the safety constraints of class 4 lasers is the Humm3®, developed by Noblelight Ltd. Its heat profile is controlled by three programmable parameters: voltage, pulse width, and frequency. This study varied these parameters to examine their impact on the thermal response of CF/LM-PAEK tape. Experiments ensured that different combinations of pulse width and frequency (Tab. 1) delivered similar heating energy.

Tab. 1: *Process settings of the Humm3 used for the experimental runs*

Voltage (V)	Frequency (Hz)	Pulse width(msec)	Heating time(sec)
180	120	1.5	1.0
170	90	2.0	1.0
160	60	3.0	1.0

Nine experimental runs (5 replicates each) were conducted using a static setup (Fig. 9) consisting of the Humm3 head, thermal camera, and tape monitoring temperature evolution of the heated area.

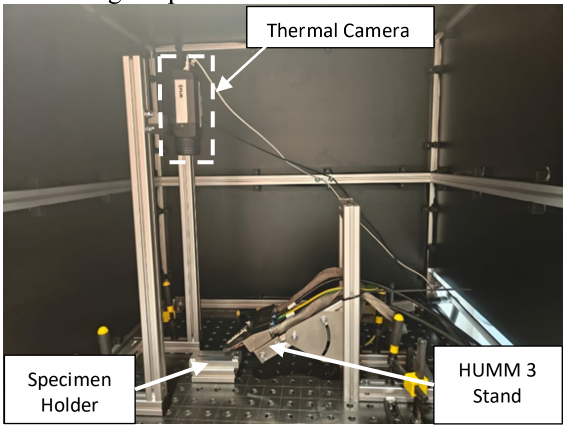

Fig. 9: *Setup for static AFP experiments (Humm3)*

The heated length of the specimen was kept constant for all experiments. The line region of interest (ROI) was cantered in the heated zone during postprocessing (Fig. 11(A)). The average temperature of the line ROI within the heated zone was recorded and analysed.

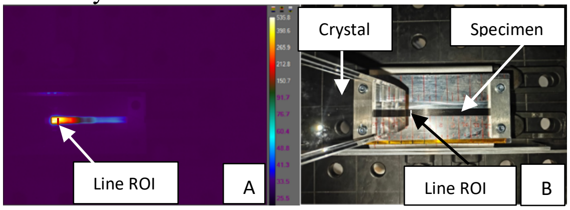

Fig. 10: *Thermographic image of the heated zone and the line ROI (A), Physical setup of the heated area*

The average temperatures from all experimental runs are shown in Fig 11. The results indicate that voltage significantly influences the thermal response of the composite specimen. When similar total energy was supplied, different combinations of pulse width and frequency did not significantly affect the thermal response. Another finding is the significant variation in thermal response among specimens within each run. This variation is due to local differences in fibre concentration within the composite tape. Areas with higher fibre concentration, which absorb more radiative heat, heat up more intensely, leading to inconsistencies in the thermal response.

Fig. 11: *The average temperature of the line ROI of the experimental runs*

Conclusion

We investigated manufacturing processes with fast heating rates and identified a few challenges from which the following conclusions could be drawn:

An actively cooled consolidator is key for CUW when stable thermal boundary conditions are needed and to ensure a relatively constant temperature for the top adherends' surface.

In AFP, local microstructure and fibre distribution have an effect on the laser or Humm3 absorption and heating, leading to local hot spots.

The voids and roughness appearing during the heating phase can partially be resolved by the consolidation phase, mainly limited by the short consolidation time. The resulting effect of reduced intimate contact can be measured in the cooling phase through a reduced cooling rate, which can be used as a quality indicator.

References

[1] B. Jongbloed, "On the use of a rounded sonotrode for the welding of thermoplastic composites," Journal of Advanced Joining Processes, vol. 7, no. 100144, 2023.

[2] N. v. Nierop, "Actively cooled consolidator project," internship report SAM XL, Delft, 2023.

[3] Lee WI, Springer GS. A model of the manufacturing process of thermoplastic matrix composites. J Compos Mater 1987; 21: 1017–1055.

[4] Yang F, Pitchumani R. A fractal Cantor set based description of interlaminar contact evolution during thermoplastic composites processing. J Mater Sci 2001; 36: 4661–4671.