Available online at www.sciencedirect.com
ScienceDirect
Physics Procedia 83 (2016) 1279 – 1288
Physics Procedia

9th International Conference on Photonic Technologies - LANE 2016

Optimising process efficiency during remote laser cutting of CFRP by utilisation of a double-scan-head

Hagen Dittmar[a,*], Patrick Herda[a], Peter Jäschke[a], Oliver Suttmann[a], Ludger Overmeyer[a,b]

[a]*Laser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hannover, Germany*
[b]*Institut für Transport und Automatisierungstechnik, Produktionstechnisches Zentrum Hannover, An der Universität 2, 30823 Garbsen, Germany*

Abstract

A double-scan-head was developed combining two pairs of galvo-mirrors into one device. One pair controls the laser beam's position, while the other in this setup is used for a pyrometer. Thus, a pyrometer's optical path can be controlled independently from a laser's path as well as being locked to the same geometrical path during CFRP processing.
Using such a double-scan-head, a comparison between locked pyrometry and independent scanning pyrometry is performed during multi-pass laser cutting on multiple geometries. Carbon fibre reinforced epoxy and PPS are cut with pre-selected threshold surface temperatures ranging from T = 80-120°C to interrupt and optimise the process in order to reduce the material's thermal strain. Both locked and scanning pyrometry are compared based on total processing time, heat affected zone, and the influence of fibre orientation.
The study shows a double-scan-head allows improved process monitoring strategies leading towards more efficient laser material processing in terms of quality and time.

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH

Keywords: laser cutting; pyrometry; process control; HAZ; fibre orientation

1. Motivation / State of Technology

Composite materials are of increasing importance in lightweight applications. Especially in the aviation and automobile industries, fibre reinforced plastics have started substituting metal based structural parts. A recent development is the utilisation of carbon fibre reinforcements which offer an outstanding stiffness-to-weight ratio,

* Corresponding author. Tel.: +49-511-2788-335 .
E-mail address: h.dittmar@lzh.de

1875-3892
Peer-review under responsibility of the Bayerisches Laserzentrum GmbH
doi:10.1016/j.phpro.2016.08.135

Beardmore and Johnson (1986), Chawla (2001). But carbon fibre reinforced plastics (CFRP) are also known for their difficult machinability, which is the reason for research on new processing strategies for handling this class of material. A possible approach is presented by laser machining, Fischer et al. (2015).

Laser technology offers several advantages in comparison to conventional mechanical machining and has got a high potential for automated processing as well. Advantages include contact-free and thus force-free machining and a high geometrical flexibility. On the other hand, laser machining is a thermal process and CFRP exhibits heterogeneous thermal properties due to its composite nature. Thermal conductivity coefficients, glass transition and vaporisation temperatures differ widely between carbon fibres and various utilised matrix systems in CFRP. This leads to the formation of a heat affected zone (HAZ), which is, especially in laser cutting, a prominent criterion for process quality. Thus, achieving a process result with minimal HAZ is most desirable. Therefore, development and reduction of the HAZ has been the topic of several investigations in recent years, Blümel et al. (2015) and Stähr et al. (2014). They evaluated the performance of different laser systems like short and ultra-short pulsed lasers and continuous wave (cw) lasers or focused on the influence of certain process parameters. Finger et al. (2013) reported a decreasing HAZ when utilising a picosecond pulsed near-infrared laser at high pulse repetition frequencies in comparison to a low pulse repetition frequency with an increased fluence at an equal average laser power in both cases. Leone et al. (2013) had been using a nanosecond pulsed near-infrared laser in their experiments and found the HAZ increasing when low scanning velocities were combined with high pulse repetition frequencies, due to the heat accumulation that comes with large pulse overlaps. Negarestani et al. (2010) were observing similar behaviour during their studies. They had investigated the effect of processing gas to the formation of a HAZ and concluded that nitrogen enriched with some oxygen was improving cut quality. They also noted that low pulse energies and high scanning velocities at moderate pulse repetition frequencies lead to desirable process results. Blümel et al. (2014) compared a picosecond, a nanosecond pulsed and a cw laser during CFRP multi-pass cutting. Their results show that increasing the scanning velocity, thus decreasing the pulse overlap, is a mean of reducing the HAZ. However, they also witnessed a slightly different behaviour for the cw laser, when the HAZ, while increasing scanning velocity, reached a minimum and eventually started on increase again. Supposedly, this was due to heat accumulation in between the scanning repetitions. Blümel et al. also mentioned that the so-called loop time, the time the laser needs to return to the same position during multi-pass cutting, was influencing the extent of the HAZ, as it allowed for the heat to dissipate, if the loop time was long enough.

Another approach to regulate the extent of the HAZ lies in temperature monitoring and related automatic control routines that are also key steps towards full laser process automation.

A frequently used method for temperature control during laser processing is pyrometry as it allows localised measurements at a sampling rate of up to 50 kHz to be carried out. So far, pyrometry has been used mainly on-axis during laser cutting or laser welding or off-axis at a fixed measuring location, cf. Woo and Lee (2015) and Grabas (2016). As geometries and materials are becoming increasingly challenging to be processed, advanced strategies for temperature control are developed. One strategy for such a control during laser remote processing includes the utilisation of a double-scan-head. It has been shown by Dittmar et al. (2015) that such a device would offer increased flexibility, because with only a small deviation in the angle of incident, the pyrometer is able to take measurements either locked to the laser beam's position or in its close proximity as well as completely independent.

In this article, pyrometer measurements are performed with a double-scan-head during remote laser cutting. Different strategies are pursued for temperature control, demonstrating that this type of device is capable to significantly increase process efficiency in terms of optimised processing time and reduced heat affected zone during laser cutting of CFRP.

Nomenclature

A_C	coupon size
α_{tc}	angle of incidence (tc = thermographic camera)
$d_{EP, PPS}$	thickness (EP = epoxy, PPS = polyphenylenesulfide)
$E_{P, max.}$	pulse energy (max. = maximum pulse energy)
$f_{P, max.}$	pulse repetition frequency (P, max. = for maximum pulse energy)
L	length of cut
$l_{fp,l,tc}$	distance (fp = focal plane, l = line, tc = thermographic camera)
λ	wavelength
$P_{L, max.}$	laser power (max. = maximum internal laser power)
$T_{cool, hot}$	surface temperature (cool = low threshold, hot = high threshold)
t	processing time
τ	pulse duration
θ	main fibre orientation
$v_{L, pl, pi}$	scanning velocity (L = laser, pl = locked pyrometry, pi = independent pyrometry)
$Ø_{fp}$	laser beam diameter (fp = focal plane)
#	number of repetitions

2. Experimental

The investigation was performed on two carbon fibre reinforced composite materials. One material was a polyphenylenesulfide (PPS) with satin-woven fibres and a thickness of d_{PPS} = 1.3 mm, while the other was an epoxy resin with twill-woven fibres and a thickness of d_{EP} = 1.1 mm. Coupons were cut from plates of these materials with a final dimension of A_C = 70 x 20 mm². The coupons were cut in three directions relative to main fibre orientation θ: θ = (0°, 45°, 90°) for the satin-woven PPS. For twill-weave θ = 0° and 90° are symmetric. Therefore, epoxy coupons were only cut in θ = (0°, 45°), cf. figure 1.

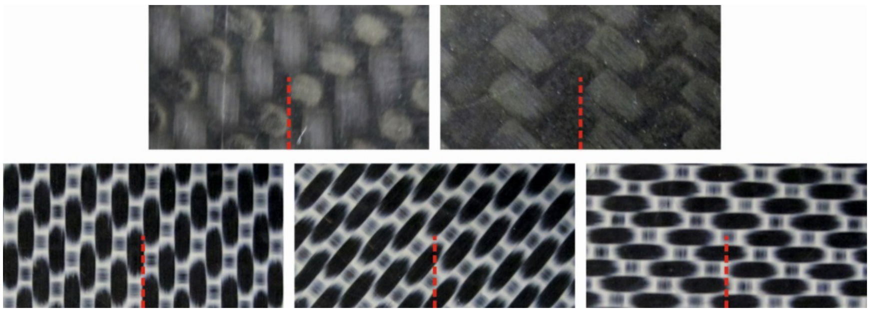

Fig. 1. Top: Epoxy coupons with cut directions (red) in 0°/90° and 45° relative to main fibre orientation. Bottom: PPS coupons with cut directions in 0°, 45° and 90° relative to main fibre orientation.

The machining setup consisted of a Newson NV “RhothorTwin Head Pyro” double-scan-head with “Elevathor” focus shifter, a Sensortherm GmbH pyrometer “Metis HI 18”, an InfraTec thermographic camera “PIR uc 180”, a cross-jet with nitrogen supply, an exhaust system and a fixture for the material coupons. The utilised laser was a JenLas fiber ns 40 by Jenoptik AG, cf. table 1 for general specifications. Material processing was performed in a laser-safe laboratory work station.

Table 1. Specifications of JenLas fiber ns 40.

Property	Symbol	Value	Unit
Wavelength	λ	1064	nm
Max. laser power	$P_{L, max.}$	40	W
Max. pulse energy	$E_{P, max.}$	1.33	mJ
Pulse repetition frequency for max. pulse energy	$f_{P, max.}$	30	kHz
Pulse duration at 30 kHz	τ	<40	ns
Laser beam diameter in focus plane	$\varnothing_{fp}$	260	µm

The RhothorTwin Head Pyro consists of two pairs of galvanometric mirrors providing independent beam paths for two optical systems. In this experimental setup one half of the Rhothor was used by the laser beam, whereas the pyrometer was mounted in front of the other half's aperture. Thus, the pyrometer was enabled to detect temperature radiation independent of the laser beam's position. The thermographic camera was positioned off-line at a distance of approx. l_{tc} = 400 mm and at an angle of approx. α_{tc} = 45°.

The material coupons were positioned in the focal plane l_{fp} = 305 mm below the double-scan-head. Adjacent to the coupons are placed cross-jet and exhaust. They were setup in a way that nitrogen from the cross-jet would be blown above the coupons into the exhaust supporting evacuation of particles and fumes. The machining setup is presented in figure 2.

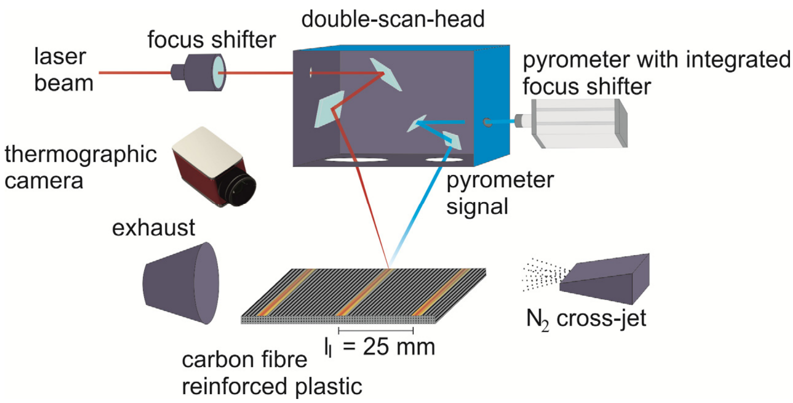

Fig. 2. Machining setup.

In order to optimise the effectiveness of remote laser cutting on different CFRP, two different strategies for a pyrometry based process control were evaluated: locked-mode and independent-mode. In locked-mode the pyrometer's measuring spot was strictly linked to the laser spot, whereas independent-mode allowed individual movements of both spots. Samples contained a test geometry of three parallel lines of length L = 20 mm that were spaced l_l = 25 mm apart. The middle line was centred below the double-scan-head. These three lines were cut into both materials at θ = (0°, 45°) and in case of PPS also at θ = 90° of the main fibre orientation. All cuts were monitored by the thermographic camera for comparison.

Table 2 states the utilised processing parameters. The scan job was programmed to finish cutting the lines consecutively.

Table 2. Utilised processing parameters.

Property	Symbol	Value	Unit
Laser power	P_L	28	W
Pulse repetition frequency	f_P	30	kHz
Laser scanning speed	v_L	400	mm/s
Pyrometer scanning speed in locked-mode	v_{pl}	400	mm/s
Pyrometer scanning speed in independent-mode	v_{pi}	9000	mm/s
Number of scanning repetitions per line	#	2000	-

First, the two materials were cut without pyrometric measurements as a reference.

During locked-mode pyrometry, the pyrometer was detecting the surface temperature at the laser's current position. In case of the surface temperature T rising past a defined threshold temperature T_{hot}, processing would pause until the temperature dropped below a second threshold temperature T_{cool}, and then continue cutting the line.

The second strategy was independent-mode, when the pyrometer was able to not only detect temperature radiation at the laser beam's position (at $v_L = 400$ mm/s), but also at other positions. In this mode of operation, the pyrometer would scan all three lines at $v_{pi} = 9000$ mm/s during laser processing and detect their surface temperatures. Whenever the current processed line would get too hot, the laser beam would pause processing that line and continue to process whichever line was not finalised yet and had a surface temperature below T_{cool}, cf. figure 3. If no such line would be available, laser processing would pause until T_{cool} was reached on any of them or all lines were finished. This allows a quicker processing of multiple geometries.

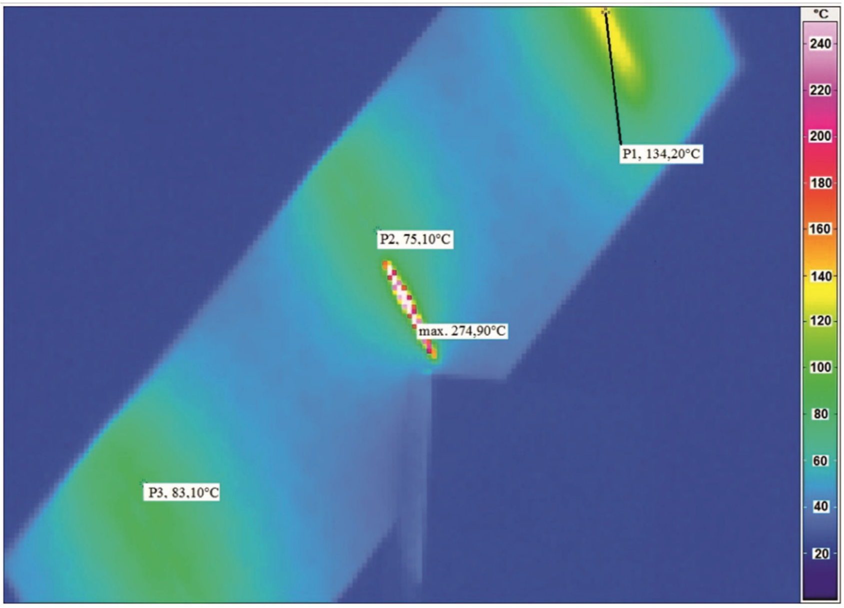

Fig. 3. Picture taken by thermographic camera in independent-mode. Because of P1 exceeding the threshold temperature, the laser jumped to P2, because P3 is still above T_{cool}.

For the experiments three different temperatures were set for threshold temperature T_{cool}, according to table 3. The threshold temperature to pause processing was selected to be $T_{hot} = T_{cool} + 40$ °C.

Table 3. Threshold temperatures.

T_{cool}	T_{hot}
80 °C	120 °C
100 °C	140 °C
120 °C	160 °C

The two control strategies, locked- and independent-mode, were compared in terms of processing time t and size of the HAZ. The processing time t was recorded by the scanner program and the HAZ was evaluated using cross-section analysis. The HAZ is the sum of the affected area both left and right of the cut groove, cf. figure 4. Both criteria were investigated for the influences of threshold temperature and of fibre orientation.

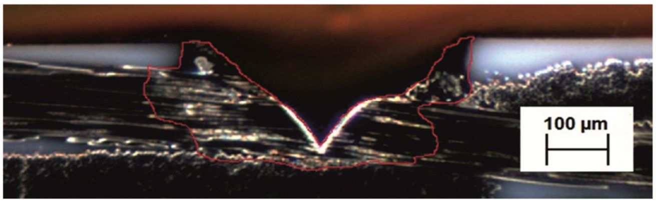

Fig. 4. Cross-section of PPS sample with marked HAZ (red).

3. Results

First, the reference samples were produced. All five samples, two epoxy and three PPS, were processed without temperature control. Therefore, heat accumulation was intense and lead to extensive HAZ > 10 mm² while on the other hand processing time $t = 6$ min was rather fast compared to the samples that were temperature controlled. All reference samples' data are included in figures 5 to 8.

The temperature controlled epoxy samples showed HAZ between 0.06 and 0.12 mm², about 1 % of the HAZ of the references. Figure 5 depicts the HAZ for epoxy samples and compares control modes, the threshold temperatures and main fibre orientation.

It shows that the HAZ is slightly smaller for samples that have been cut at $\theta = 45°$. Comparing locked- and independent-mode at different threshold temperatures T_{cool} shows a tendency for smaller HAZ when utilising the independent-mode. However, a significant difference when comparing threshold temperatures does not become obvious.

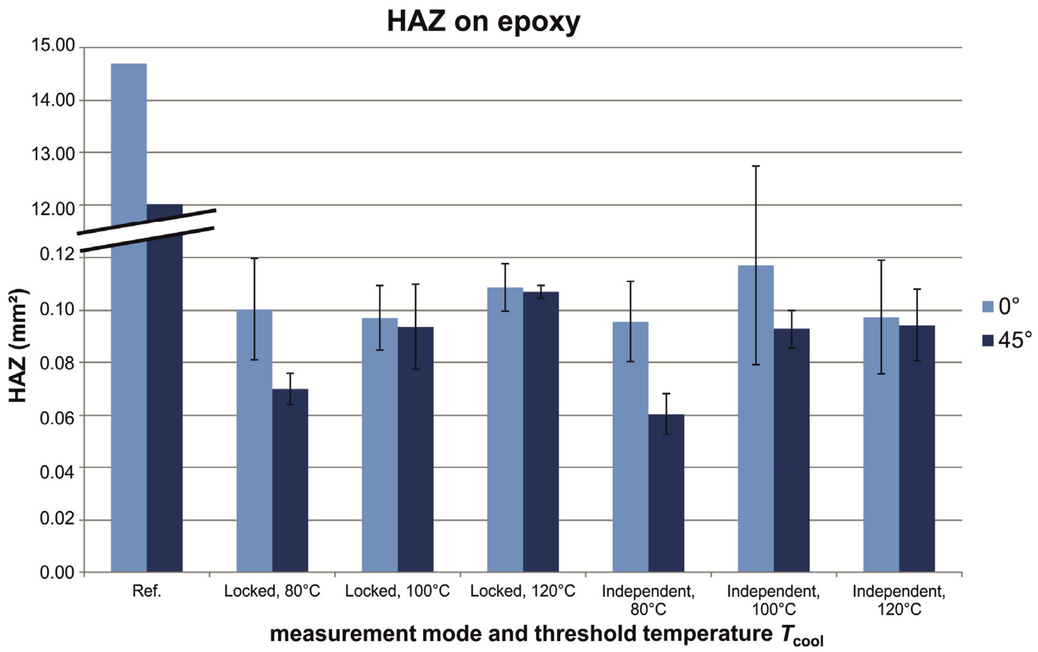

Fig. 5. Comparison of HAZ on epoxy samples in relation to pyrometry mode, threshold temperature, and fibre orientation.

While the HAZ is significantly improved due to the utilisation of temperature control, it also has a huge impact on overall processing time *t*. Figure 6 shows the processing time *t* for the epoxy samples in relation to pyrometry mode, threshold temperature and fibre orientation.

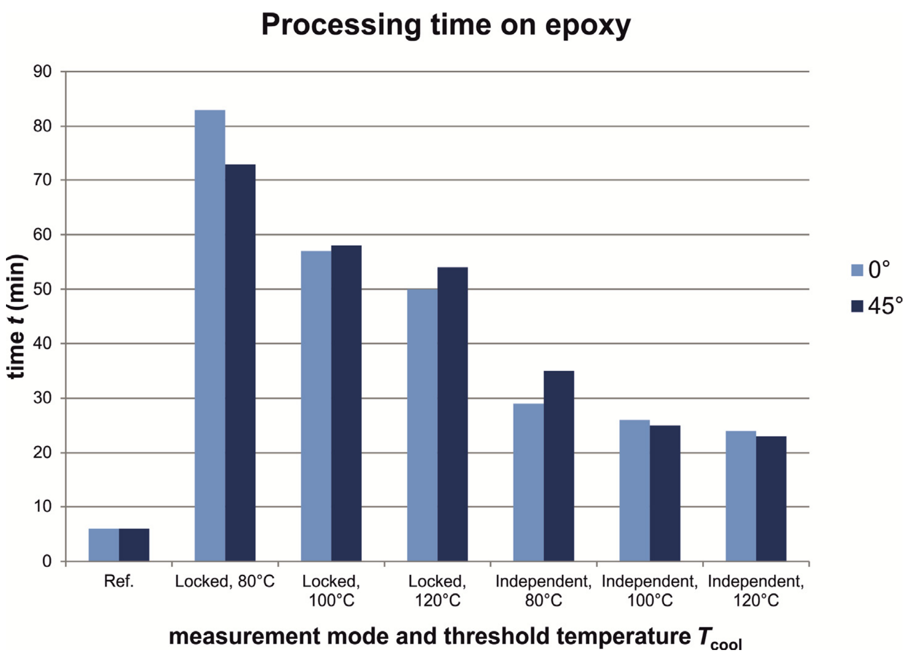

Fig. 6. Comparison of processing time *t* on epoxy samples in relation to pyrometry mode, threshold temperature, and fibre orientation.

Evaluating the processing time, the diagram shows that the independent-mode was at least two times faster than locked-mode within the same threshold temperature regime. With rising threshold temperature T_{cool} the overall processing time t is decreasing. However, a clear correlation between fibre orientation and time t is not possible.

The PPS samples contained a satin-woven carbon fibre fabric. Therefore, PPS samples were cut at $\theta = 90°$ in addition to $\theta = (0°, 45°)$. During the experiments HAZ were generated that were slightly larger than for the epoxy based samples with areas of approx. 0.08 to 0.16 mm². Similar to the epoxy samples, this is about 1 % of the references' HAZ.

Figure 7 shows the HAZ generated on PPS in dependence of the pyrometry mode, the threshold temperature T_{cool} and the main fibre orientation θ. It can be seen that the HAZ is increasing with a rising threshold temperature for both locked- and independent-mode pyrometry, although the increase is comparably small for the independent-mode. Again, a clear correlation between fibre orientation and size of HAZ is not detectable.Similar to the epoxy samples, processing time t is significantly affected by the applied temperature control strategy. Figure 8 shows the data recorded for processing the PPS samples utilising the two pyrometry modes in regard to threshold temperature and main fibre orientation. As before, a clear correlation between processing time and fibre orientation does not become obvious, but again independent-mode is significantly faster than locked-mode and at an almost constant processing time, whereas the laser cutting process becomes faster in locked-mode at increasing threshold temperatures, still requiring about twice the time of the independent-mode at a threshold temperature T_{cool} = 120 °C.

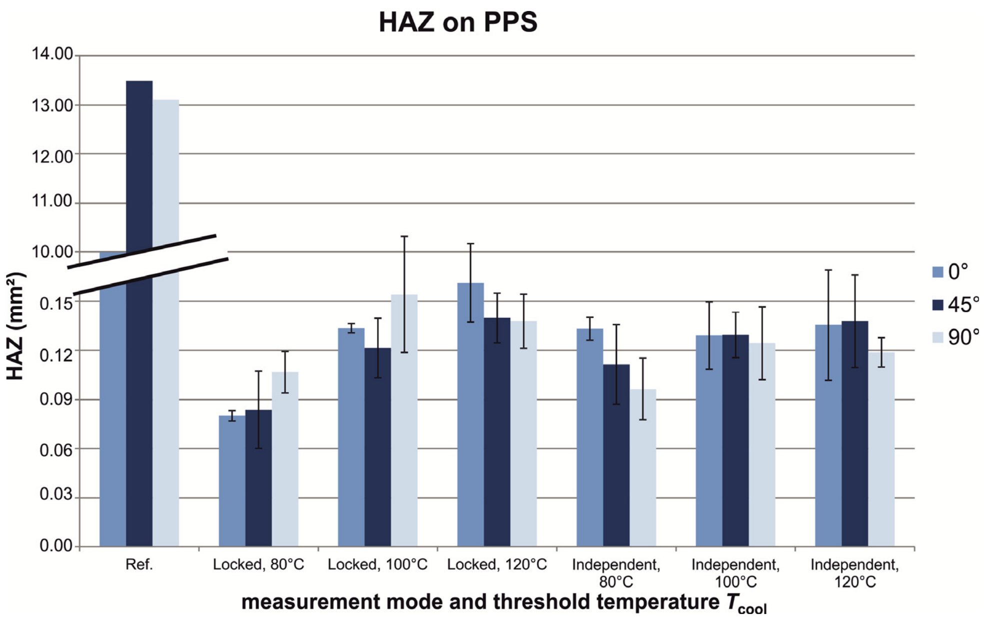

Fig. 7. Comparison of HAZ on PPS samples in relation to pyrometry mode, threshold temperature, and fibre orientation.

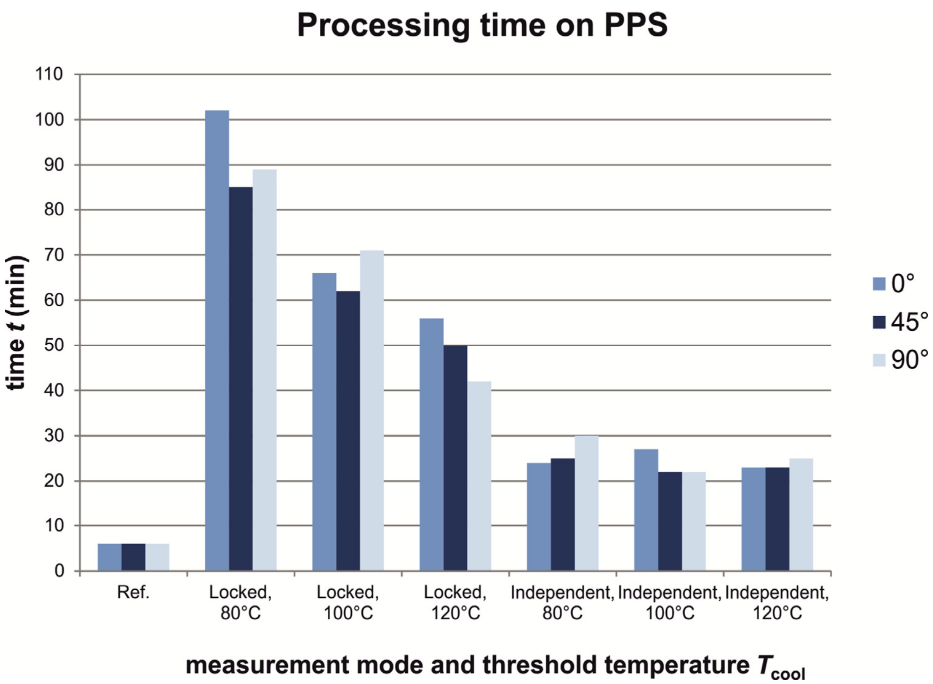

Fig. 8. Comparison of processing time *t* on PPS samples in relation to pyrometry mode, threshold temperature, and fibre orientation.

4. Discussion and conclusion

On-axis-pyrometry is a common technique to control surface temperature during laser material processing. In this study a double-scan-head was used to introduce an alternative procedure. The double-scan-head allows two different ways of monitoring the laser process. Either by synchronised movement of laser beam and pyrometer measuring spot in a so-called locked-mode or by independently controlling those two systems.

The locked-mode closely resembles the conventional on-axis-pyrometry with the ability to use different optical coatings perfectly fit for the individual paths of laser and pyrometer, but with a small deviation of the angle of incidence of the two optical paths on the target. During laser processing of CFRP, this locked-mode was compared with the independent-mode. In independent-mode, it was possible to control temperatures on multiple geometries, while the laser would continue processing one of those geometries. This was realised by increasing the pyrometer's scanning velocity by an order of magnitude. Thus, the pyrometer would do several temperature scans on all geometries and decide, based on the detected temperatures, whether a geometry was cleared for processing or needed to continue cooling down. The comparison of these two modes focused on the HAZ and processing time during laser cutting of carbon fibre reinforced epoxy and PPS. Those two process characteristics were investigated in dependence of fibre orientation and threshold temperature.

This study demonstrated that the ability to independently scan all geometries, while processing one of them, allowed to significantly reducing processing time in comparison to locked-mode pyrometry. Depending on the threshold temperature, processing time was improved by approx. factor 2 to 4 in comparison to locked-mode. In regard to the reference sample, this would still be about three times slower at T_{cool} = 120 °C, but the results also showed that both pyrometry modes significantly raised process quality in terms of HAZ by approx. two orders of magnitude in relation to the reference sample. Thus, process efficiency was clearly improved.

It was shown that the HAZ size was mainly affected by the threshold temperature. Since a higher threshold temperature would allow more heat to be stored in the surface before the process was paused, the material is more likely to receive a bigger HAZ. While the epoxy samples' HAZ seemed to show a small dependence on fibre orientation with cuts performed at an angle of θ = 45° having a slightly smaller HAZ in comparison to those cut at

$\theta = 0°$, this could not be witnessed on the PPS samples. This might be due to the asymmetric type of weave. In order to investigate the effect of fibre orientation on the development of a HAZ more closely, experiments need to be conducted that also consider an exact and reproducible placement of geometries on defined fibre locations.

The investigation shows the double-scan-head is able to support advanced temperature control strategies during laser material processing.

Acknowledgements

This research was conducted within the EraSME project “A’Quilaco – Advanced online quality and process control for high speed laser machining of composites” and was supported by the Federal Ministry for Economic Affairs and Energy (BMWi) on the basis of a decision by the German Bundestag (KF2186414AB3).

The authors would like to express their gratitude to Mrs K. Delaey and Mr M. Van Biesen at Newson NV for providing the RhothorTwin Head Pyro double-scan-head as well as to Dr H. Kriz at Sensortherm GmbH for providing the pyrometer Metis HI 18 used in these experiments.

References

Beardmore, P., Johnson, C. F., 1986. The potential for composites in structural automotive applications, Composite Science and Technology 26 (4), p. 251-281.

Blümel, S., Jäschke, P., Suttmann, O., Overmeyer, L., 2014. Comparative study of achievable quality cutting carbon fibre reinforced thermoplastics using continuous wave and pulsed laser sources, Physics Procedia 56, p. 1143-1152.

Blümel, S., Stähr, R., Jäschke, P., Suttmann, O., Overmeyer, L., 2015. Correlation of internal and surface temperatures during laser cutting of epoxy-based carbon fibre reinforced plastics, Journal of Reinforced Plastics and Composites 34, p. 662-671.

Chawla, K. K., 2001. Composite Materials, Springer, ISBN 978-0-387-98409-4.

Dittmar, H., Wippo, V., Jäschke, P., Kriz, H., Delaey, K., Suttmann, O., Overmeyer, L., 2015. Temperature monitoring independent of laser-beam-position during laser transmission welding of fibre reinforced thermoplastics, Lasers in Manufacturing Conference. Munich, Germany, paper 178.

Finger, J., Weinand, M., Wortmann, D., 2013. Investigation on processing of carbon fiber reinforced plastics using ultrashort pulsed laser radiation with high average power, In: Proceedings of 32nd International Congress on Applications of Lasers & Electro-Optics (ICALEO), Miami, USA.

Fischer, F., Kreling, S., Blass, D., Stähr, R., Blümel, S., Jäschke, P., Dilger, K., 2015. Laser material machining of CFRP – an option for damage-free and flexible CFRP processing?, in “Machinability of Fibre-Reinforced Plastics”. In: Davim, J. P. (Ed.), Advanced Composites, de Gruyter, Berlin/Boston, p. 1-30.

Grabas, B., 2016. Pyrometric temperature measurements with a miniature cavity used as a blackbody in the calorimetric method for determining absorbed laser energy, Experimental Thermal and Fluid Science 74, p. 100-109. DOI:10.1016/j.expthermflusci.2015.11.022

Leone, C., Papa, I., Tagliaferri, F., Lopresto, V., 2013. Investigation of CFRP laser milling using a 30W Q-switched Yb:YAG fiber laser: Effect of process parameters on removal mechanisms and HAZ formation, Composites Part A: Applied Science and Manufacturing 55, p. 129-142.

Negarestani, R., Li, L., Sezer, H. K., Whitehead, D., Methven, J., 2010. Nano-second pulsed DPSS Nd:YAG laser cutting of CFRP composites with mixed reactive and inert gases, International Journal of Advanced Manufacturing Technology 49, p. 553-566.

Stähr, R., Blümel, S., Hansen, P., Jäschke, P., Suttmann, O., Overmeyer, L., 2015. The influence of moisture content on the heat affected zone and the resulting in-plane shear strength of laser cut thermoplastic CFRP, Plastics, Rubber and Composites 44(3), p. 111-116.

Woo, W.-S., Lee, C.-M., 2015. A study of the machining characteristics of AISI 1045 steel and Inconel 718 with a cylindrical shape in laser-assisted milling, Applied Thermal Engineering 91, p. 33-42.