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Correlation between Temperature Field and Heat Affected Zone during Laser Cutting of Carbon Fiber Reinforced Polymers

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Abstract

Due to its ability for wear free 3D-processing and a high degree of automation, the laser remote cutting is a suitable technology for the mass production of carbon fiber reinforced polymers (CFRP) parts in the automotive industry. The heat affected zone (HAZ), which is typical for the laser process, is measured after the cutting process by a time-consuming and expensive preparation of cross sections. A missing in-situ measurement procedure for the cutting quality handicaps the laser processing of CFRP in an industrial application.
The investigation deals with the question, if a relationship between the temperature field around the cutting kerf and the heat affected zone exists. The temperature field is measured by infrared camera while the corresponding HAZ is quantified conventionally by cross section preparation.
The investigation shows that a positive correlation between the temperature field and the HAZ exists. Regarding the typical spreading of the HAZ during laser processing of CFRP, its prediction by measuring the temperature field is possible, independent of the laminates thickness, process parameters and cutting directions. Thus an in-situ measurement of the cutting quality is applicable. An algorithm to predict the HAZ reliable at areas with heat accumulation has to be developed.

Keywords: laser, remote, cutting, cfrp, temperature field, heat affected zone

1. Introduction

Milling and water jet cutting are the common procedures for cutting of CFRP. During milling of CFRP high tool wear due to the abrasive properties of the carbon fibers occurs. By reason of the process forces the cutting edge of the tool displaces the carbon fibers at the surface layers. Frazzles at the laminate surfaces occur, as shown by Hintze and Hartmann, 2013. Abrasive water jet cutting offers comparatively low feed rates and a high effort for handling of the water abrasive mixture. In addition to that, water jet cutting of 3D parts comes with complex and expensive jig tools. The demand for a force free and more cost efficient cutting technology exists.

Therefore, several research groups already focused on the investigation of laser cutting of CFRP and the improvement of the cutting quality. Compared to conventional laser cutting, with a flying optic along the contour, the laser remote cutting enables a significant increase of the cut edge quality due to short interaction time between laser beam and material, which can be reached with a mirror based beam deflection. First investigations were carried out by Klotzbach et al., 2011. The laser remote cutting of a large 3D CFRP part, regarding the mass production of parts in the automotive industry, was considered by Herzog et al., 2014. Today, with multi-kW continuous wave laser systems, heat affected zones in the range of 0.2-0.4 mm and feed rates of 10-15 m/min are achievable for laminate thicknesses <2 mm, shown by Canisius et al., 2014. Due to the high degree of automation, the ability for 3D processing as well as the absence of wear and process forces, the laser remote cutting is a suitable method for mass production in automotive industry.

During the laser cutting of CFRP, the material is removed by vaporization. Compared to the matrix material of the CFRP, the carbon fiber has a high vaporization temperature of 3,825 °C as published by Paufler, 1982. These different vaporization temperatures combined with the large heat conductivity of carbon fibers lead to a heat affected zone (HAZ) at the cutting kerf. In this HAZ, the matrix material is totally vaporized or at least thermally damaged. Today the HAZ is the most important quality characteristic number and gets measured at cross sections of the laminate. This method causes costs of several € per cross section, is time consuming and a destructive test method. Furthermore, the knowledge from one cross section cannot be transferred directly to other positions of the cutting geometry. This fact occurs for example at areas with different fiber orientations and especially at areas with heat accumulation that increases the HAZ. This heat accumulation appears at zones with large energy input on small areas, for example at multiple, neighboring cut bore holes. The evaluation of such areas by cross section doesn't represent a suitable method for mass production of CFRP. Thus a non-destructive in-situ measurement in real time of HAZ is necessary to reduce costs and time during manufacturing. Furthermore, concerning a potential mass production, a real time in-situ measurement enables the component release for following process steps.

2. State of the art

Non-destructive testing of laminate damage of CFRP using an infrared camera is investigated for many years. One of the latest investigations is done by Bossi and Giurgiutiu, 2015. After thermal stimulation the surface temperature gets measured. Typical damages such as delamination and cracks can be detected due to changed head conductivity. The method is relatively fast and often used in the aerospace industry.

A potential in-situ measurement procedure for the HAZ at the surface of a CFRP laminate was investigated by Freitag et al., 2012. The time dependent dimension of the HAZ during drilling using a pico-second laser system was measured. The used laser system has a power of about 22 W, a pulse duration of 8 ps, a wavelength of 515 µm and a repetition rate of 800 kHz. The development of the HAZ was determined with a high speed camera with a resolution of 1,064 x 642 pixel and frame rate of 800 fps. The illumination of the image section is realized with a diode laser at a wavelength of 808 nm. By filtering this wavelength, the formation of the HAZ can be measured during the cutting process.

Niino et al., 2014 investigate the interaction zone during laser cutting of a short fiber reinforced thermoplastic material. For that purpose a solid state laser with a power of 1 kW and a wavelength of 1.09 µm is used. Via infrared camera a temperature of 500 °C at the cutting kerf could be measured. This value gets validated based on the evaporation temperature of the matrix material of 470 °C.

Muramatsu et al., 2014 investigated the relationship between the HAZ of laser cutting and the stress condition during static and dynamic stress test. A CO_2-laser, two single mode lasers and a diamond cutter are used for the preparation of the tensile specimen. The stress induced heating of the sample gets measured with an infrared camera. It could be shown that the zones with reduced stresses correlates with the heat affected zone of the laser process.

Bluemel et al., 2013 used thermocouples to measure the temperature field around the kerf during laser cutting of CFRP. These thermocouples are placed in a distance of 1.4-50 mm beside the cutting kerf. Due to their small diameter of 0.41 mm, a little influence to the fiber orientation can be realized. A triple exposure lead to a reduced heat input compared to a single exposure for complete cutting the laminate.

An in-situ measurement of the HAZ based on thermography during laser cutting of CFRP doesn't exist.

3. Experimental Setup, Material and Method

3.1. Material

For the investigated process a carbon fiber reinforced epoxy is considered. The laminate is composed of six layers of unidirectional non-crimp fabric, each with a grammage of 200 g/m² and an identical fiber orientation. The final laminate has a thickness of about 1.5 mm. The used resin CHS-EPOXY 404 is processed in combination with the hardener TELALIT 0420 in vacuum infusion. After a curing time of 24 hours at ambient temperature and 1 hour at 70 °C the laminates have a fiber volume content of 43.2 %.

3.2. Experimental setup

The investigations are executed with a Trumpf TruDisk 6001 multi-mode continuous wave disk laser with a laser power of 6 kW at a wavelength of 1.03 µm. The scanning optic Trumpf PFO 33 is used to enable a laser remote cutting process under surrounding atmosphere. The infrared camera is an IRCam Equus 81kM MCT. This camera system works at a spectral range of 3-5 µm and with a resolution of 256 rows and 320 columns. The infrared camera is installed with a working distance of 550 mm to the cutting kerf and an angle of 45 degrees toward the surface of the laminate.

For the measurement of temperatures at the CFRP laminate a calibration of the infrared camera to the material is executed. For this purpose a pure matrix sample, a dry carbon fiber non-crimp fabric, the laminate and a black body are placed in an oven with controlled temperature. The exact measurement of the temperature is done with a thermocouple. After stabilization of different temperatures, from ambient temperature up to the evaporation temperature of the matrix material of 320 °C, the door of the oven is opened instantaneously and the surface temperature gets measured by the infrared camera. With this approach the measurement of the sample temperature during laser cutting can be executed.

3.3. Method

The Figure 1 shows the measured counts with infrared camera during and after laser cutting. Figure 1 (a) shows the measured counts during laser cutting. The process emissions nearly hide the total visual field of the infrared camera. After the laser exposure, the process emissions are removed by exhaust system to the top left side of the visual field (b). The measurement of the transient count field starts with the first emission-free frame (c). The total removal of the process emissions is necessary to avoid measuring errors caused by radiation reflection of the emissions at the laminate surface. These reflections can be misinterpreted as laminate temperatures by the used algorithm (equations 2-4). After starting the measurement, the transient count field gets measured for every camera frame up to a time of t = 30 s.

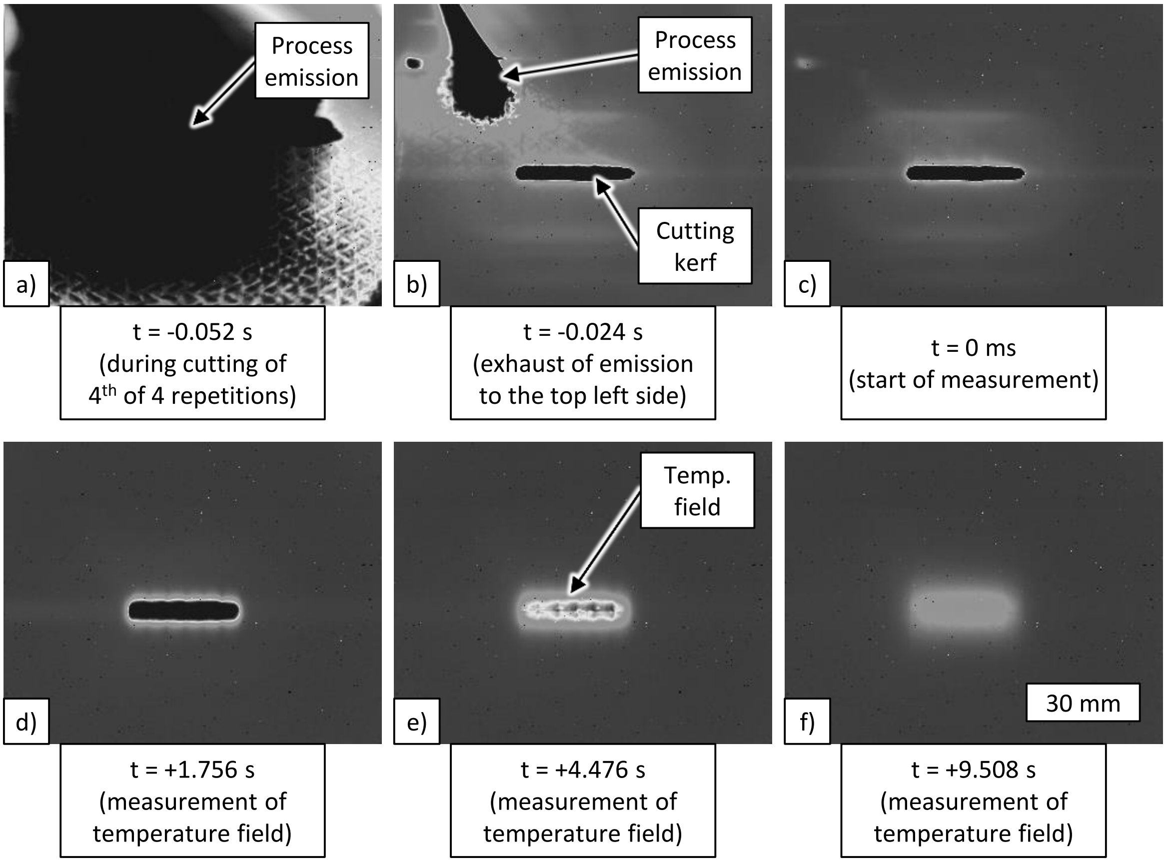

Fig. 1. Measured counts with infrared camera during and after laser cutting, laser power 6 kW, scan speed 1.4 m/s, exposure repetitions 4, cutting direction 90° (perpendicular to fiber orientation)

The relationship between the samples temperature and the measured counts is described by a modified Stefan-Boltzmann equation:

$$C(T)-c_1=c_2(T-c_3)^{(4+c_4)} \quad (1)$$

C equates the measured counts and T equates the corresponding temperature. Using four fitting parameters c_1, c_2, c_3 and c_4 is necessary to minimize the sum of error squares between measured data and this fitting equation to a suitable value. A little deviation between measured data and fitting equation is especially necessary to measure temperatures that are slight above the ambient temperature. In this range comparatively large temperature changes lead to small changes of the measured count, because of the exponential relationship. The parameters could be found to c_1 = 1,199 [-], $c_2 = 1.165 \cdot 10^{-15}$ [$K^{-6.982}$], c_3 = 32.79 [K] and c_4 = 2.982 [-].

The Figure 2 (a) shows the counts measured by the infrared camera after the laser exposure and directly after removing the process emissions with an exhaust system for the time t = 0 s (compare Figure 1). The cutting kerf is cut with a laser power of 6 kW, a scan speed of 1.4 m/s and 4 exposure repetitions. This parameter leads to a complete through cut at the investigated material.

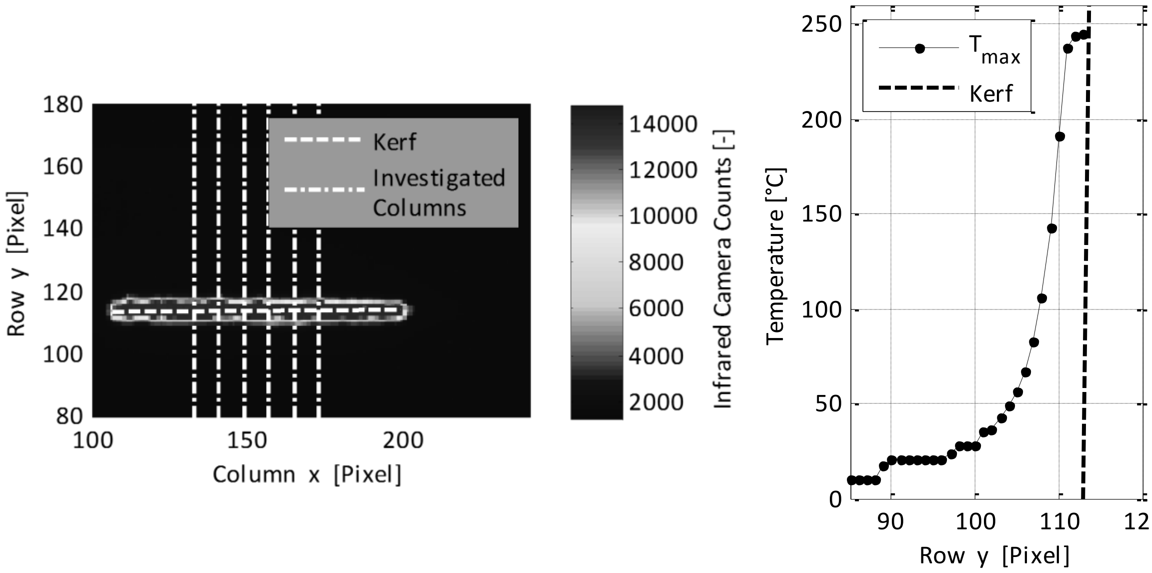

Fig. 2. (a) Measured counts with infrared camera at a single cutting kerf, laser power 6 kW, scan speed 1.4 m/s, exposure repetitions 4, cutting direction 90° (perpendicular to fiber orientation), time t = 0 s
(b) T_{max} perpendicular to the cutting kerf, t ∈ [0, 30 s], quantity of investigated columns n = 21 (columns 1, 5, 9, 13, 17 and 21 are shown)

The position of the cutting kerf and the positioning of the investigated columns automatically take place by the developed algorithm. The position of the cutting kerf gets determined based on the highest count values that occur in the visual field. The investigated columns C_{Inv} are placed symmetrically on both sides starting from the half kerf length.

To quantify the thermal load of the laminate as consequence from cutting, several parameters get measured and calculated after the laser exposure and directly after removing the process emissions from the visual field of the infrared camera, starting at time t = 0 s.

$$T_{Inv,mean}(t,R)=\frac{1}{n}\sum_{i=1}^{n} T(t,R,C_{Inv,i}) \qquad (2)$$

Where $T_{Inv,mean}$ is the average temperature for all investigated columns C_{Inv}, t is the time, R is the row, n is the quantity of investigated columns and T is the temperature as a function of time as well as rows and columns.

$$T_{max}(R)=\max_{t} T_{Inv,mean}(t,R), \qquad \text{with} \qquad t \in [0, 30\ s] \qquad (3)$$

Here T_{max} is the maximum temperature for the investigated time range after cutting and exhaust. R is the row.

$$L_T=\sum_{k=1}^{m} T_{max}(R_k), \qquad \text{with} \qquad R_k=R_{Kerf} - k \tag{4}$$

Here L_T is the thermal load of the laminate due to laser cutting the kerf and m is the number of investigated rows. R_{Kerf} equates the row of the position of the kerf.

The described procedure in this chapter replaces one of several possibilities to get information about the thermal load of the laminate. The most obvious possibility to measure the heat affected zone is the measurement of the largest distance of the isothermal line of the evaporation temperature of the matrix material. This procedure has the disadvantage that this isothermal line occurs typically just for a few 10 ms after the exposure. Due to the fact, that a few 10 ms has to be spent to remove the process emissions from the visual field of the camera, as mentioned above, the isothermal line can disappear before starting the measurement. Furthermore the recommended resolution of this zone cannot be achieved without reducing the visual field of the infrared camera clearly below the working area of the laser scanner. For this reason a comparatively large area is considered as described above. The hypothesis that a correlation between this far field and the HAZ exists is proposed.

4. Results and Discussion

4.1. Emission coefficients

Based on the setup for the calibration of the infrared camera described above, the emission coefficients get determined. A black body is used as reference with an estimated emissivity of $\varepsilon = 1$. The values for the laminate, the pure matrix material as well as the non-crimp fabric are measured as follows:

Table 1. Emission coefficients of the investigated materials

Material	Value	Unit
Black body	1	-
Laminate	0.888	-
Matrix material	0.925	-
Non-crimp fabric	0.779	-

4.2. Correlation between the thermal load of the laminate and the heat affected zone

Figure 3 shows the measured values to determine the heat affected zone. Both areas of the HAZ as well as the laminate thickness get measured. The mean width of the HAZ is then given by:

$$HAZ=\frac{1}{2}\cdot\frac{1}{d}\cdot(A_{HAZ\,1}+A_{HAZ\,2}) \tag{5}$$

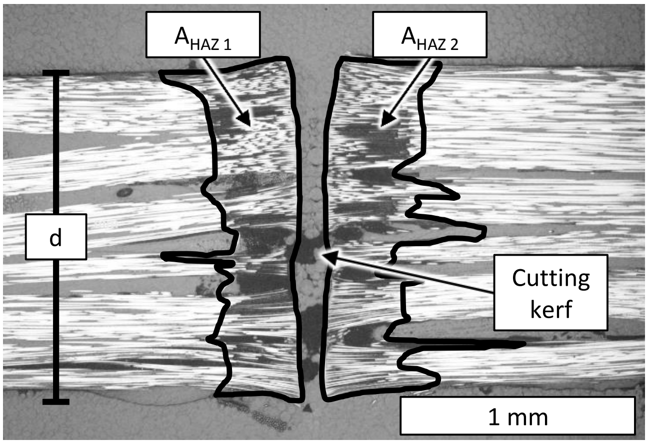

Fig. 3. Areas of the heat affected zones at both sides of the cutting kerf

The Figure 4 shows the measured HAZ across the measured thermal load. The HAZ gets measured by cross section as shown in Figure 3 using Equation 5. A database of 4 cross sections per parameter is used. The thermal load is measured with a quantity of investigated columns of n = 21, a time range of t = 0…30 s and for a number of investigated rows of m = 35.

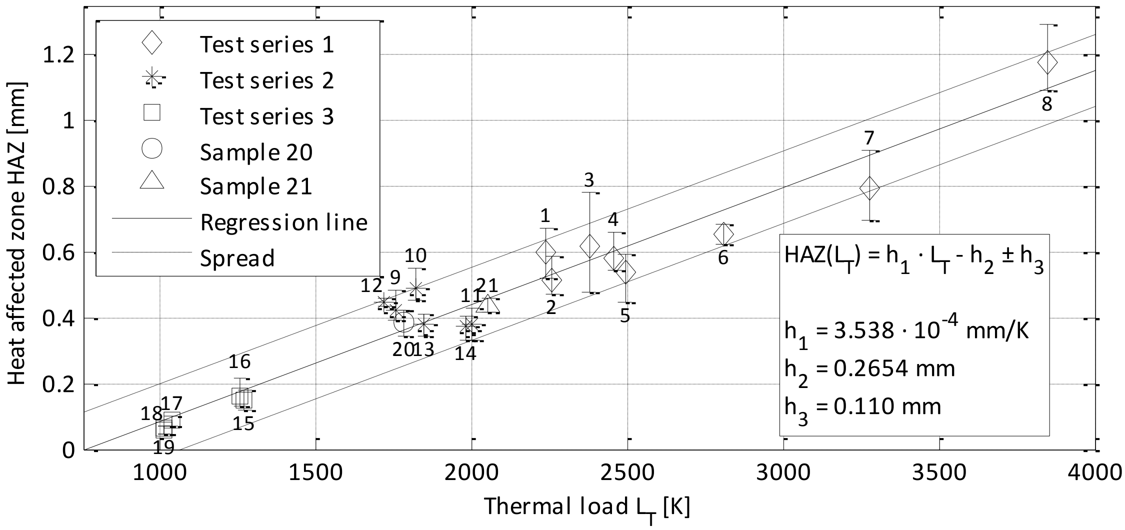

Fig. 4. Relationship between thermal load and heat affected zone, t ∈ [0, 30 s], n = 21, m = 35

Five test series are executed during the investigations as shown in Table 2. Test series 1 is characterized by a constant energy per unit length at varied exposure repetitions and scan speeds. Test series 2 is characterized by a minimized energy per unit length for the chosen exposure repetitions. Minimizing the energy per unit length by keeping the cut through is the typical procedure to reduce the heat affected zone during laser remote cutting, as described by Canisius et al., 2015. Test series 3 is characterized by cutting parallel to fiber orientation. Sample 20 is characterized by cutting with an angle of 45° to the fiber orientation. The investigation of the influence of the fiber orientation to the HAZ and the thermal load is important to transfer the procedure to multi-axial laminates. With increasing the number of layers of sample 21 the influence of the laminates thickness is investigated. This test is also important regarding the transferability of the procedure to varying laminates.

For the 21 investigated samples a linear correlation between the thermal load and the heat affected zone exists. The spreading of the values around the regression line is caused by the typical huge irregularity of CFRP laminates, which cause significant variations of the fiber volume content, the heat conductivity, heat capacity and the emission coefficient (compare Table 1). Variable heat conductivity enlarges the spreading of the measured thermal load and of the occurring heat affected zone, while a variable heat capacity and emission coefficient especially influences the measured heat load. These spreading can be seen at the identical parameters 1, 2 and 3 as well as 11 and 12. In general the HAZ shows a significantly larger relative spreading compared to the thermal load. This occurs because of the much larger database for the calculation of the thermal load of n = 21 investigated columns and m = 35 investigated rows, which equates 735 considered pixel per frame, as well as a considered time range of 0…30 s. This large database typically leads to comparatively small spreading of the thermal load due to averaging.

Table 2. Parameters of the investigated test series and samples

Test series	sample	laser power [kW]	scan speed [m/s]	exposure repetitions [-]	energy per unit length [kJ/m]	layers [-] / laminate thickness [mm]	cutting direction [°]
No. 1	1	6	0.180	1	33.3	6 / 1.5	90
	2	6	0.180	1	33.3	6 / 1.5	90
	3	6	0.180	1	33.3	6 / 1.5	90
	4	6	0.360	2	33.3	6 / 1.5	90
	5	6	0.720	4	33.3	6 / 1.5	90
	6	6	1.440	8	33.3	6 / 1.5	90
	7	6	2.880	16	33.3	6 / 1.5	90
	8	6	5.760	32	33.3	6 / 1.5	90
No. 2	9	6	0.260	1	23.1	6 / 1.5	90
	10	6	0.600	2	20.0	6 / 1.5	90
	11	6	1.400	4	17.1	6 / 1.5	90
	12	6	1.400	4	17.1	6 / 1.5	90
	13	6	3.500	8	13.7	6 / 1.5	90
	14	6	3.500	8	13.7	6 / 1.5	90
No. 3	15	6	0.260	1	23.1	6 / 1.5	0
	16	6	0.600	2	20.0	6 / 1.5	0
	17	6	1.400	4	17.1	6 / 1.5	0
	18	6	3.500	8	13.7	6 / 1.5	0
	19	6	9.000	16	10.7	6 / 1.5	0
-	20	6	3.5	8	13.7	6 / 1.5	45
-	21	6	2.63	8	24.4	8 / 2	90

Based on the investigated samples the following Equation 6 is introduced to measure the HAZ non-destructive by infrared camera:

$$HAZ\ (L_T)= h_1 \cdot L_T - h_2 \pm h_3 \tag{6}$$

The constants given in Table 3 enable the quantitative determination of the HAZ. The spread value $h_3 = \pm 110$ µm is comparatively large, because optimized laser remote cutting processes ensure a HAZ of about 200 µm and lower, as shown by Canisius et al., 2015. For processes with HAZ in this range the shown procedure for non-destructive measurement has a relative large uncertainness.

Table 3. Constants for the non-destructive measurement of the HAZ

Constant	Value	Unit
h_1	$3.538 \cdot 10^{-4}$	mm/K
h_2	0.2654	mm
h_3	0.110	mm

The procedure gets more reliable for thermal loads that stay in relationship to HAZ with several tenth mm of HAZ. Such HAZ typically occur for laminates with a thickness of several mm. Then the spreading gets relative low compared to the absolute value of the HAZ. Nevertheless the procedure can be used to detect exceeding of maximum acceptable HAZ. Due to the non-destructive function, the integration of an in-situ quality insurance system based on the procedure mentioned above to an industrial series production is possible.

Reducing the energy per unit length for a cut through reduces the HAZ, as shown by Canisius et al., 2015. For industrial series production it can therefore be expected, that a control of the energy per unit length – to the lowest possible value keeping the cut through – will be used sooner or later. Then the laser machine automatically sets the energy per unit length to ensure the cut through along the entire cutting geometry. This makes the automatable detection of exceeding maximum acceptable thermal loads and HAZ necessary. In this context the developed procedure for in-situ measurement of the HAZ by infrared camera could be used.

A further application for the developed procedure is the measurement of the HAZ at zones with heat accumulation, for example at multiple, neighboring cut bore holes. Due to the complexity and quantity of influences of processes with heat accumulation, the destructive quantification of HAZ based on cross sections is not suitable.

The chosen time of $t = 0 \ldots 30$ s represents a time range, that exceeds an acceptable duration for an in-situ quality insurance system. The area below the maximum temperature curve T_{max}, which equates the thermal load (compare Equation 4), reaches at least 95 % of its final value in a time range of $t < 1$ s. Therefore the needed time range for the measurement of the HAZ can be reduced significantly.

5. Conclusions and Outlook

A method for the calculation of the thermal load of laminates around the kerf during laser cutting of CFRP based on infrared camera is developed. Based on a calibration of the infrared camera to the laminate, this thermal load gets measured concerning the transient temperature field around the kerf. The relationship between thermal load and heat affected zone is investigated and a linear correlation could be found, independent of laser parameters, cutting orientation and thickness. Concerning the typical spreading of material properties and cutting results of CFRP, an equation to measure the HAZ in-situ and non-destructive is proposed. The procedure can be used for an automatable detection of exceeding maximum acceptable HAZ. This is especially necessary for industrial series production. Furthermore a procedure has to be developed for the measurement of the HAZ at zones with heat accumulation, for example at multiple, neighboring cut bore holes, because a destructive measurement based on cross sections is not suitable.

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