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Determination of corresponding temperature distribution within CFRP during laser cutting

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Abstract

Laser cutting of carbon fiber reinforced plastics as a thermal process results in a thermal load on the material. Due to the high thermal conductivity of carbon fibers, residual heat is conducted along the fibers, away from the laser interaction zone. Common temperature measurement techniques, such as pyrometry and infrared thermography only allow for observation of the temperature development on the surface of the material. In order to achieve information about the temperature distribution within the material during the cutting process, thermochromes and thermocouples were implemented during the laminating process of CFRP. The cutting tests were performed with a single mode fiber laser emitting a continuous wave and at a wavelength of λ = 1080 nm.

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Keywords: laser cutting; temperature distribution; thermochrome; thermocouple

1. Motivation

Automatable, efficient and precise processing of carbon fiber reinforced plastics (CFRP) is of high importance for the production of parts within industrial sectors, such as aerospace and automotive. The cutting and trimming of parts is a fundamental step in many production lines. Here, lasers can be used, with the advantages of being contact-free, fast and automatable. Laser cutting as a thermal process can lead to distinctive heat affected zones, due to the difference in sublimation temperatures between carbon fibers and matrix material [Jaeschke et al., 2012; Bluemel et al., 2012]. Additionally, the carbon fibers have a high

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thermal conductivity, which can be two orders of magnitude greater than the conductivity of the matrix material [Freitag et al., 2012]. Common techniques to measure and visualize the temperature development during the cutting process are pyrometry and infrared thermography. Both techniques allow the observation of the temperature fields on the surface, but not inside the material. In order to address this issue, different techniques have been evaluated. One technique for the temperature detection is using thermal paints which contain thermochromes. The color change of the thermochromes due to the passing of a specific threshold temperature can be used as an optical indicator for temperature distribution. This color change is irreversible, and the analysis is performed after the thermal process. An alternative to thermochromes are thermocouples, which enable continuous measurement in a specific temperature range of the present temperature during processes [Bernhard, 2004; Körtvélyessy, 1987]. Thermochromes provide the possibility to measure the internal temperature by placing thermochromes into the matrix material before lamination. Thermocouples can be placed between two layers of carbon fiber fabric during the laminating process. While thermochromes allow temperature detection for volumes and areas of the CRFP, thermocouples deliver a value for a defined small area around the thermocouple.

2. Experimental

For the investigation of the temperature distribution within the CFRP laminate during the laser cutting process, thermocouples and thermochromes were placed into self-made CFRP laminates. The laminates consist of the 5 harness satin weave fabric G0926 from the company Hexcel Corporation with a thickness of d = 0.38 mm. The composition of the epoxy matrix is shown in Table 1.

Table 1. Composition and curing temperature of the epoxy matrix

Resin	Hardener	Mixing ratio	Curing temperature
Epoxy resin L	EPH161 (VE 3261)	100:25	110°C for 10 hours

Each fabric layer of the multi-layered laminates was placed with the same orientation. The CFRP was laminated in a metal form, which allows laminates with dimensions up to 200 mm x 200 mm to be produced. The laminated samples were cured at room temperature for $t_c = 24$ h before being tempered in an oven at $T_T = 110°C$ for $t_T = 10$ hours. Due to the tempering process the epoxy matrix has a heat resistance of T = 140°C. The final thickness of the CFRP varies between d = 0.8 mm and d = 0.85 mm.

For the experiments using thermochromes, a thermal paint containing thermochromes was mixed into the resin. To allow a sufficient contrast between carbon fibers and matrix material a ratio of 10% thermal paint were mixed into the epoxy resin. Depending on the characteristics of the thermal paint, certain storage or curing temperatures have to be taken into account (Table 2). Some thermochromes can change their color if they are exposed to a certain temperature for a long time. In case of the thermal paint SC155 the safe temperature with a value of T = 46°C is located below the curing temperature of T = 110°C. To evaluate the possible color change, tempered and non-tempered samples were manufactured with SC155. No significant differences in the color could be detected at the surface of the laminates and so the cutting experiments were carried out with the tempered samples due to the higher heat resistance of the material.

Table 2. Characteristics of the used thermal paint [TMC Hallcrest, 2012]

Paint name	Color change temperature T_c [°C]	Highest Temperature without change T [°C]	Original color	Indication color
SC155	155	46	blue	green
SC240	240	170	yellow	red / brown
SC447	447	170	green	salmon pink

The experiments with thermocouples were performed with nickel-chrome / nickel Type K wires with a diameter of $D = 0.41$ mm, including the $d = 0.08$ mm thick PTFE PFA insulation [Omega, 2012]. The thermocouples were welded together using an electrical thermocouple welder, in order to assure small welding marks and good contact between the wires. The chosen thermocouples have a maximum measuring temperature of $T_{max} = 1250$°C, with a failure tolerance of $\Delta T = 2.2$°C or $\Delta T = 0.75\%$, respectively. The thermocouples were placed between two layers of fabric with an increasing distance s from the cutting edge.

The cutting tests were performed with a Rofin FL 010 S single-mode fiber laser with a maximum output power of $P_L = 1000$ W, emitting continuous wave at a wavelength of $\lambda = 1080$ nm, and using a laser scanning system with an F-theta optic with a focal length of $f = 330$ mm. The corresponding focal diameter is $D_f = 80$ µm. During preliminary test the maximum cutting velocity for reliable cutting results were investigated for one and three repetitions and for a constant laser power of $P_L = 500$ W. The cutting investigations were performed with two different sets of parameters shown in Table 3.

Table 3. Process parameters for the cutting tests

Laser power P_L [W]	Scanning velocity v [m/s]	Number of repetitions
500	0.02	1
500	0.16	3

3. Results and Discussion

The density of thermochromes on the surface of the produced samples was visual uniform (Fig. 1), so that the authors decided that the samples will fit for the described test. As a start the surface next to the cutting edges was examined concerning color changes of the thermochromes induced by an increase of the temperature due to the laser radiation, flames or plasma. In Fig. 2 a change from the original color to the indication color is shown for the SC155 (left) and the SC240 (middle). For the thermal paint SC447 (right) no clear color change can be detected. This leads to the assumption that regions where the threshold temperature of T = 447°C was reached the matrix material is damaged too much.

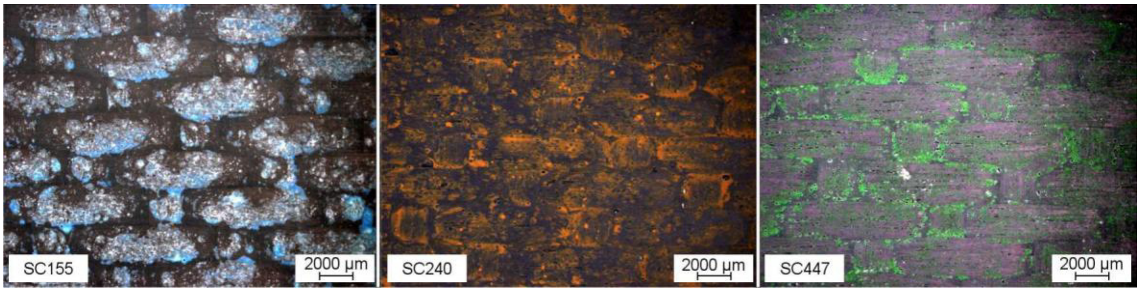

Fig. 1. Distribution of thermochromes on surface of manufactured samples

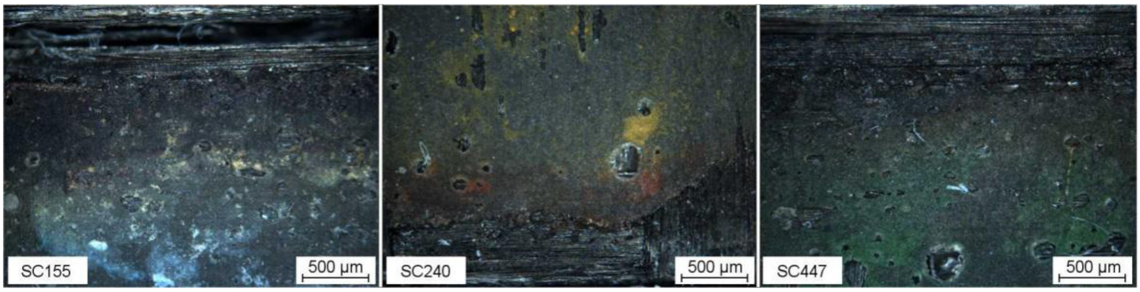

Fig. 2. Color change on the sample surface due to reach of threshold temperature of the thermochromes after laser cutting

The distribution of thermochromes within the CFRP laminate is not homogenous, although the matrix material contains 10% thermal paint. Fig. 3 displays chosen micrographs of cuts where thermochromes can be seen next to the cutting region. The cutting edge is placed at the left edge of the picture. In these micrographs it is shown that a detection of threshold temperatures within CFRP by help of thermochromes is possible, in general. Due to the non-uniform distribution of the thermochromes it was not for all performed cuts possible to detect a temperature, if not enough thermochromes where visible within the region of the micrograph (Fig. 4).

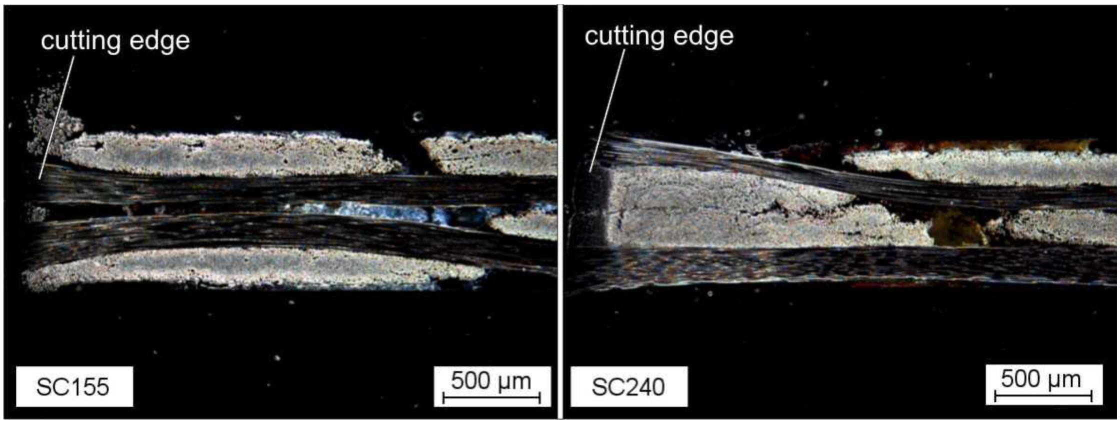

Fig. 3. Micrographs of laser cuts with visible color change of thermochromes

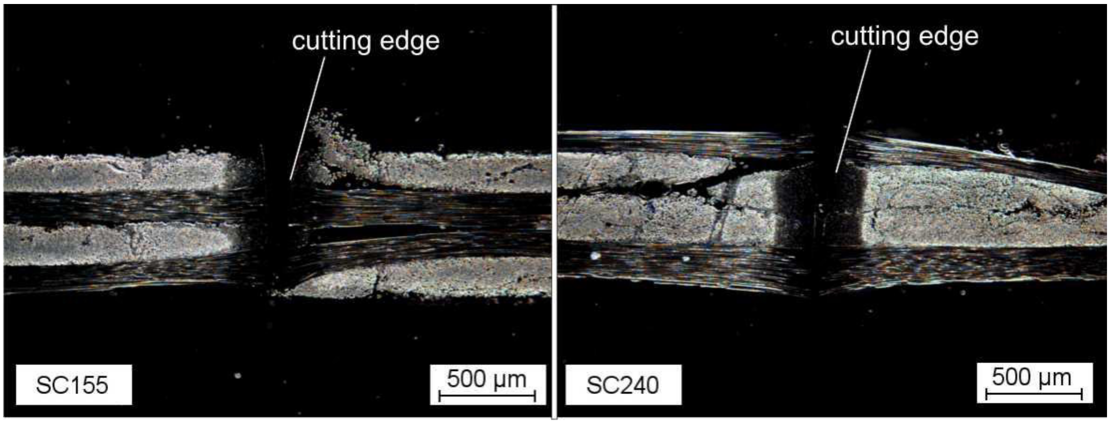

Fig. 4. Micrographs of laser cuts without visible color change

The thermocouples provide the possibility to measure the heating due to the laser cutting process, as well as the cooling due to the heat dissipation along the carbon fibers. The distance between the middle of the cutting kerf and the thermocouple is defined as distance s. Different effects can be observed, plotting the temperature T in a distance of s = 1.55 mm for cuts with one repetition and s = 1.4 mm for 3 repetitions depending on the time (Fig. 5). The zero-point of the time is defined at the point of maximum temperature. This enable a better comparison of the two described cutting strategies concerning temperature profile. The temperature increases to the maximum measured value in a short period of time, relative to the cooling time for both cuts. Whereas an intersection with a comparable slow rise of the temperature is given between room temperature and abrupt temperature rise. This temperature profile is influenced by the temperature rise which the thermocouples measure as soon as the laser interacts with the material. When the laser spot draw nearer to a position rectangular to the thermocouple the temperature increases with a high slop. The temperature development for the cut with 3 repetitions contains only one temperature peak, although the laser beam passed the thermocouple three times. The reason for that can be either the small process time together with the limitations of the response time of the experimental setup or the mechanism of heat conduction. The process time t_p it takes to perform a cut is calculated using the number of repetitions r, cutting speed v, the jump speed v_j, the length of the cut x and the formula (1). The process time for the cut with three repetitions is $t_p = 2.5$ s and for the cut with one repetition it is $t_p = 6.25$ s. The shorter process time can be one reason for the different temperature distribution till the maximum temperature is reached.

$$\Delta t = r \cdot \left(\frac{x}{v} + \frac{x}{v_j} \right) \tag{1}$$

Comparing the maximum temperature of these two cutting strategies, a difference of ΔT = 43°C between one and three repetitions can be identified. Due to the lower maximum value the temperature for three repetitions reaches significantly faster room temperature.

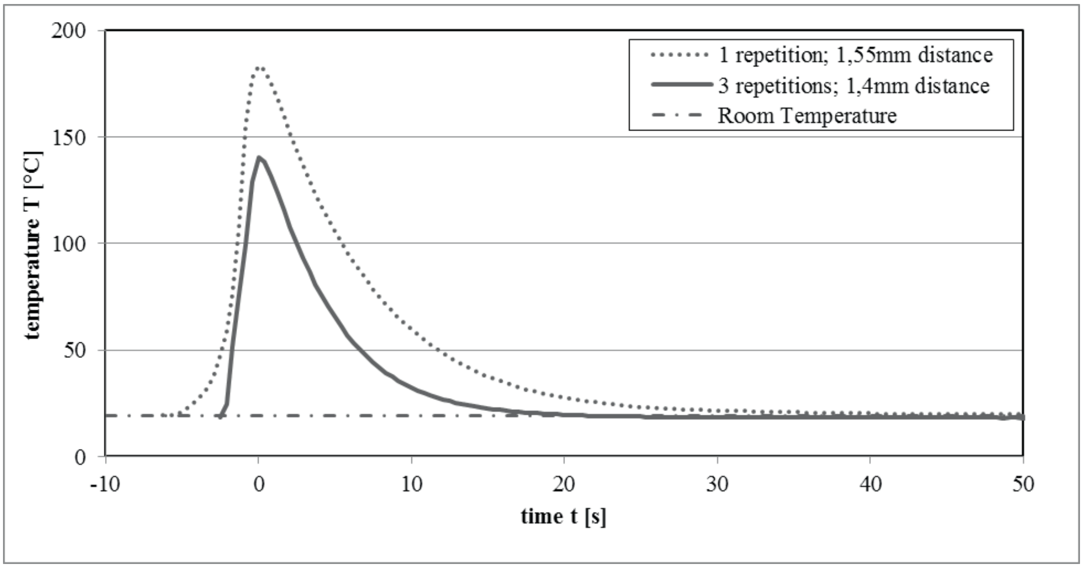

Fig. 5. Temperature T within CFRP depending on the time t for cuts with one and three repetitions

In Fig. 6 the maximum temperature T_{max} detected depending on the distance s from the cutting zone for cuts with one and three repetition is shown. The temperature decreases with increasing distance s between thermocouple and cutting edge. Comparing the results of one repetition with the results of three repetitions a difference in the temperature distribution can be observed. While for three repetitions in a distance of s = 17.5 mm the maximum temperature has a value of T_{max} = 19.8°C, which matches room temperature, the maximum temperature for cuts with one repetition in that distance has a value of T_{max} = 31.5°C.

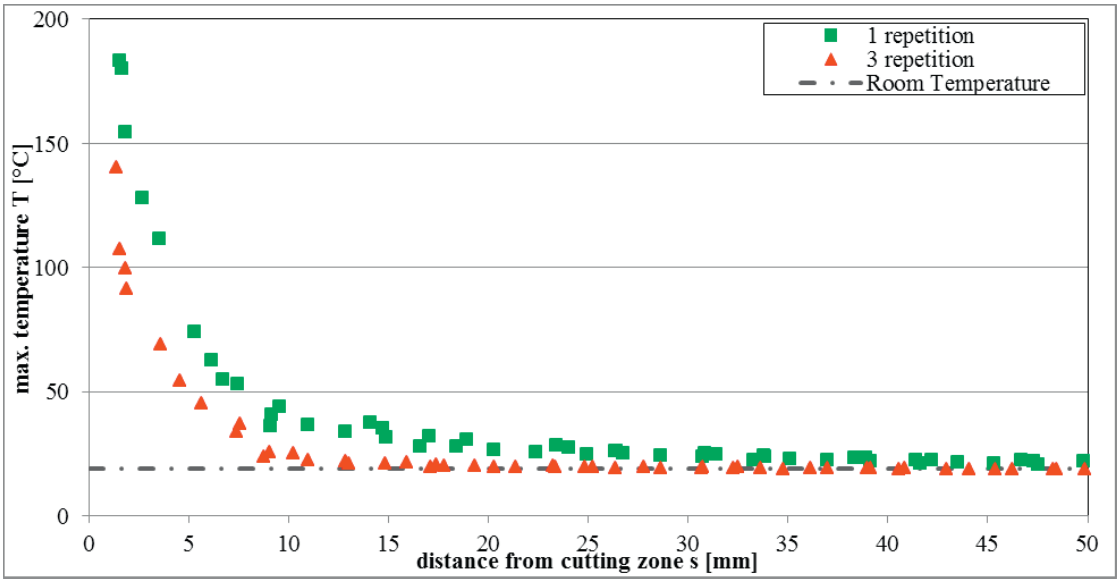

Fig. 6. Max. Temperature T within CFRP depending on the distance s to the cutting edge for cuts with one and three repetitions

4. Conclusion

The thermochromes allow visualizing the temperature distribution within the CFRP concerning the reaching of the specific threshold temperature while thermocouples allow monitoring the temperature at a specific point online.

One drawback of thermochromes is that it is only possible to identify the regions where a specific temperature was exceeded; the exact temperature magnitude distribution cannot be measured. The detectable threshold temperatures are limited by the available thermochromes. Furthermore it is not reproducible with the chosen analysis method that a recognizable amount of thermochromes is placed next to the cutting region. As another analysis method thin sections will be used in future in order to enable a better optical analysis.

Thermocouples allow a time dependent measuring of the temperature within the CFRP but the response time is limited by the used measuring equipment. Altogether thermocouples show great potential to enable a better understanding of the temperature distribution within CFRP during laser processing.

Continuative experiments are planned correlating the temperature which is measured by thermocouples with the surface temperature detected by infrared thermography. Furthermore the gained results will be the base for a temperature distribution model.

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