LASER MACHINING OF CFRP USING A HIGH POWER FIBER LASER – INVESTIGATIONS ON THE HEAT AFFECTED ZONE

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Abstract

Different experimental series were performed using a fiber laser with a maximum output power of P_L=6 kW in order to cut carbon fiber satin weave fabric with either an epoxy (CF-epoxy) or a polyphenylene sulfide (CF-PPS) matrix and different thicknesses. In order to measure the arising heat affected zone (HAZ) micrographs of the samples were prepared and analyzed using digital image processing. The results show that the HAZ converge asymptotically to a minimum value for increasing velocities and increasing power. Furthermore, the maximum measured HAZ for CF-PPS specimens is larger than those of CF-epoxy. As an outlook first results of a preliminary study using a disk laser with a maximum output power of P_L=16 kW are shown.

1 Introduction

Carbon fiber reinforced plastics (CFRP) increased their market share as a lightweight construction material subsequently. Especially within the aerospace industry the percentage on parts made of CFRP increases significantly. The Airbus A350 for example has a rate of over 50 % of CFRP parts. In the automotive sectors CFRP still plays a minor role in the small batch production, upper class cars and for selected parts like engine hoods. The reason for that lies e.g. within the lack of production technologies allowing a flexible and automatable cutting of CFRP with high rates as required in series production of cars and other consumables. The state of the art for cutting of CFRP is milling and abrasive water jet cutting. Both techniques have in common that during the cutting process a force is induced into the material, which can lead to vibrations and delamination [1]. Other disadvantages of the abrasive water jet cutting are the handling of the water circuit and additives as well as the limited ability to process three dimensional parts.

The heterogeneous build-up of CFRP and the different material properties of carbon fibers and matrix material make their processing challenging. The high hardness of the carbon fibers causes high tool wear during the mechanical cutting processes as e.g. milling. In terms of laser cutting as a thermal process the different heat conductivities and deterioration temperatures of fiber and matrix could lead to a distinctive heat affected zone (HAZ). In previous investigations the influence of the HAZ on the mechanical properties of laser cut specimens was discussed [2, 3, 4]. Therefore, it is the aim to minimize the HAZ. Within this paper the authors examined the influence of cutting velocity and laser power on the development of the HAZ for a thermoset and a thermoplastic matrix. These parameters have been identified as parameters with essential effect on part quality in previous investigations [5].

2 Materials and Testing Methods

The experiments were performed with a multi-mode fiber laser with a maximum output power of P_L=6 kW which emits at a wavelength of λ = 1070 nm. The cutting head has a focusing of f = 200 mm and was equipped with a nozzle with a diameter of D = 1.5 mm. Laser and cutting head were connected by a fiber with a diameter of D = 200 µm. During the experiments the cutting head remains at a fixed position with a working distance between nozzle and sample of x = 1 mm. The cutting stroke was realized by a high speed linear axis allowing cutting velocities of up to v = 2 m/s (Figure 1).

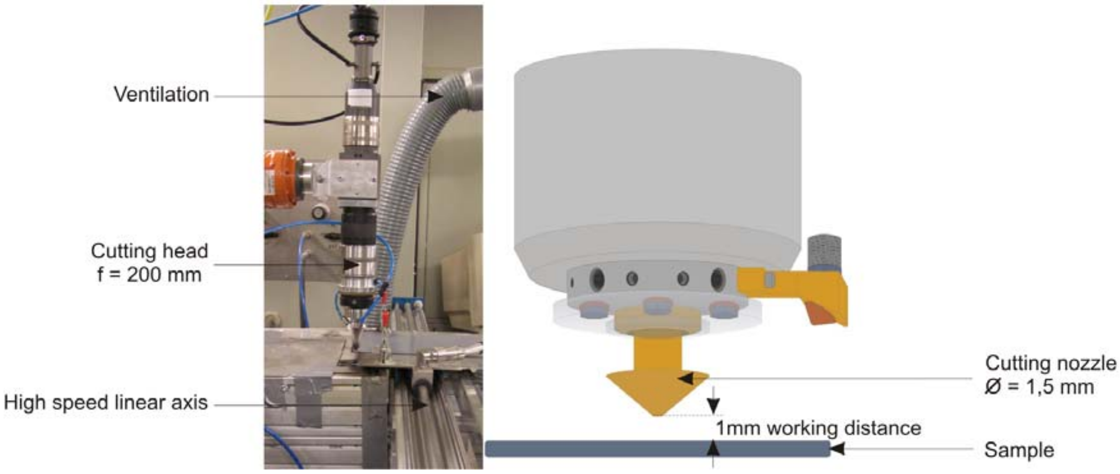


Figure 1. Experimental set-up

The investigated CFRP were based on fabrics with satin weave structure (Figure 2) and different matrix materials. The orientation of the different layers was 0° / 90° and the thickness of the samples varied between d = 1.0 mm and d = 3.2 mm (Table 1). The used matrix materials are the thermoset epoxy and the thermoplastic polyphenylene sulfide (PPS). For the CFRP with epoxy matrix (CF-epoxy) thicknesses from d = 1.1 mm to d = 3.1 mm are investigated concerning the development of the HAZ for increasing cutting velocities and laser power. For fabric with thermoplastic PPS matrix (CF-PPS) configurations were chosen enabling a comparison of the different matrices for the same fabric (Table 1). Due to different suppliers the samples for the fabric with thermoplastic PPS matrix (CF-PPS) and CF-epoxy are not available with identical thicknesses. The variance between the different configurations of CF-epoxy and CF-PPS is d = ±0.1 mm. The results of the experiments were compared in order to give a general overview of the cutting results for CF-epoxy and CF-PPS with similar build-up and identical laser parameters.

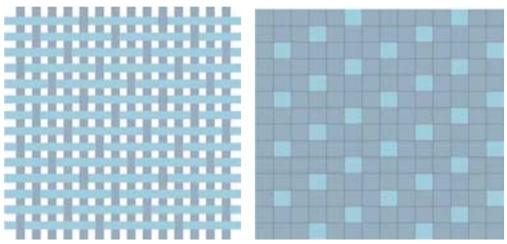


Figure 2. Structure of 5-harness satin weave fabric

CF-epoxy	Thickness [mm]	1.1	2.1	3.1
	Number of Layers	3	6	9
CF-PPS	Thickness [mm]	1.0	2.2	3.2
	Number of Layers	3	7	10

Table 1. Sample configuration for both matrix materials

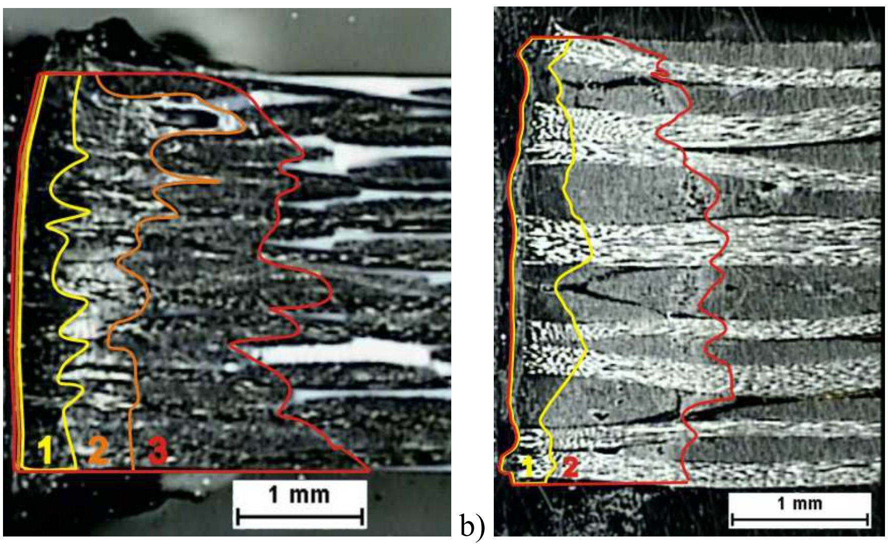
In preparation of the experimental series cuts were performed with different focus positions in order to investigate the best alignment for preferably parallel cutting edges over the height of the sample.

Comparable experimental series were performed varying the cutting velocity for a constant laser power and material thickness. The used cutting gas was nitrogen with a pressure of $p = 9 \times 10^5$ Pa. At the beginning of each experimental series cuts were performed for cutting velocities of v = 0.5 m/min and v = 1 m/min. Afterwards the velocity was increased in steps of $\Delta v = 1$ m/min until no cut occurred. For each matrix material experimental series were performed determining the maximum cutting velocity for three different material thicknesses. For each material thickness the laser power was varied from P_L=1 kW to P_L=5 kW.

The determination of the HAZ was carried out by computer aided measurements. The first step is the generation of micrographs followed by pictures realized with bifocal microscopy. By help of a computer program the area of the HAZ for each side of the cut was measured (Figure 3). With these values an average value for the size of the HAZ is calculated. By dividing these values by the corresponding material thickness an average width of the HAZ is calculated (1).

$$\text{Average width HAZ} = \text{average area HAZ} / \text{material thickness} \quad (1)$$

The criteria used for the determination of the area of the HAZ for the CF-PPS are defined as follow (Figure 3): The HAZ can be divided in up to three regions. The region where a clear deterioration or missing of matrix material and the fibers can be observed will be named HAZ 1 within this paper. HAZ 2 defines the area with clear pore formation and matrix damages due to exceeding of the decomposition temperature. HAZ 3 is recognizable as an area with small porosities within the thermoplastic matrix but intact carbon fiber fabric [4].



a) b)

Figure 3. Micrographs of laser cut a) CF-PPS and b) CF-epoxy with definitions of the subsections of the different heat affected zones

A differentiation has to be made for the analysis of experimental series with thermoset and thermoplastic materials. While the HAZ for the thermoplastic matrices can be divided into the three described zones, for the samples with an epoxy matrix a maximum of only two zones can be identified clearly for the chosen optical analysis method. The HAZ 1 for the CF-epoxy is defined by the same criteria as for the CF-PPS. The HAZ 2 can be identified by a clear optical change in color and reflection. A detailed analysis of the process within the matrix during the cutting process has not been done, but it is assumed that the changes happen due to thermal influence.

3. Results and Discussion

The experiments concerning the best focal position for the cutting test deliver that a focal position at the bottom of the sample creates the best looking cutting edges. Due to that the focal position for all later described experiments and results is fixed to the bottom of each sample.

First of all, the experiments with the CF-epoxy will be discussed. For the cuts of CF-epoxy with a thickness of d = 3.1 mm and d = 2.1 mm both described areas of HAZ can be measured at the micrographs. For thicknesses of d = 1.1 mm only the HAZ 2 can be measured clearly.

Within Figure 4 the average widths of the HAZ 2 for all tested laser powers are visualized in dependency of the cutting velocity. It can be observed that the width of the HAZ 2 for a material thickness of d = 1.1 mm becomes smaller for a constant laser power with increasing velocity (Figure 4). Furthermore, the reachable maximum velocities increase with higher laser powers which in turn lead to a smaller HAZ 2. For the experiments with P_L =4 kW and P_L =5 kW this trend is still detectable but the maximum velocities reachable are identical and the values for the width of HAZ 2 have similar sizes for high velocities. Also, it can be seen that the decreasing of the HAZ width seems to converge asymptotically to a minimum. A further increase of the cutting velocity has no significant influence on the HAZ 2. An influence on other characteristics has to be studied within additional analysis in further investigations.

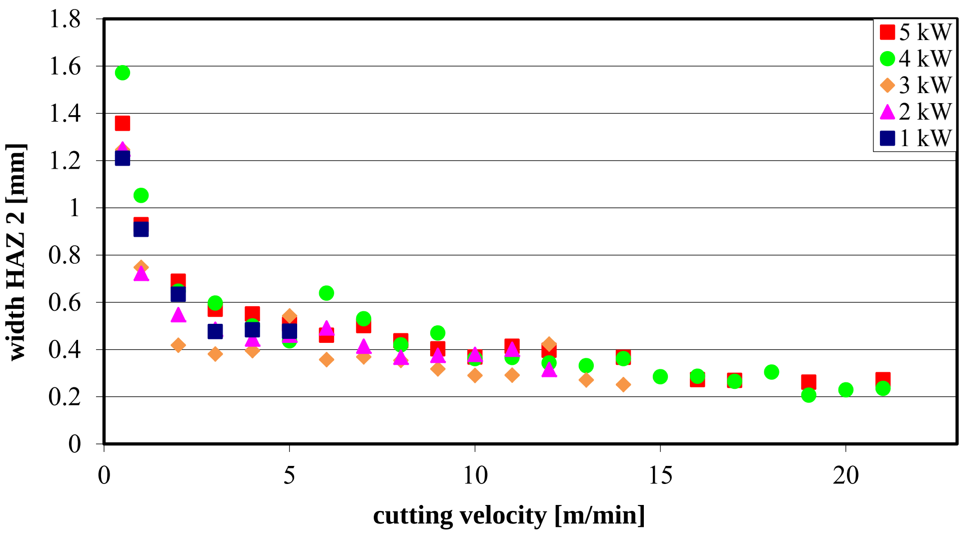


Figure 4. Width of HAZ 2 in dependency of laser power and cutting velocity for CF-epoxy with d=1.1mm

Figure 5 visualizes the width of the HAZ 2 for P_L =5 kW depending on the velocity for three different material thicknesses. Regarding the results for the samples with different thicknesses it can be seen, that due to the limited available laser power of P_L =5 kW, which leads to slower maximum cutting velocities for thicker materials, the asymptotic behavior of the HAZ 2 width cannot be seen in the corresponding graphs for CF-epoxy with d = 2.1 mm and d = 3.1 mm. While the HAZ 2 width increases significantly for the samples with d = 2.1 mm in comparison to CF-epoxy with d = 1.0 mm, the difference of values for the d = 2.1 mm and d = 3.1 mm thick samples is small for velocities higher than v = 5 m/s.

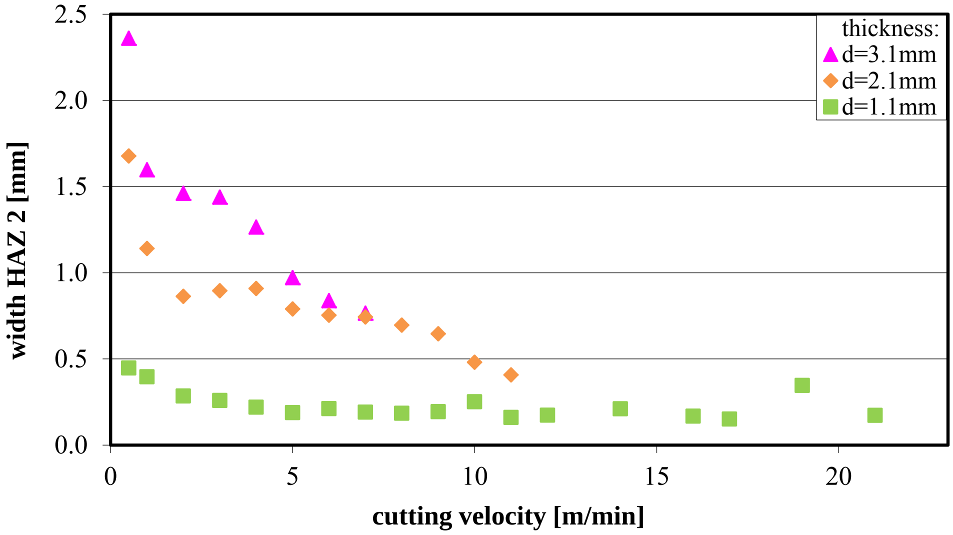


Figure 5. Width HAZ 2 of CF-epoxy depending on the velocity for different material thicknesses for P_L=5kW

The experimental series with CF-PPS show comparable results. As an example, the average width of the maximum measured HAZ 3 for CF-PPS with d = 1.0 mm are shown in Figure 6. For an increasing cutting velocity the measured width of HAZ 3 is getting smaller. A convergence of the values for the width of the HAZ 3 is recognizable. The comparison of different thicknesses of CF-PPS for a laser power of P_L=5kW (Figure 7) shows the same effects described for Figure 5.

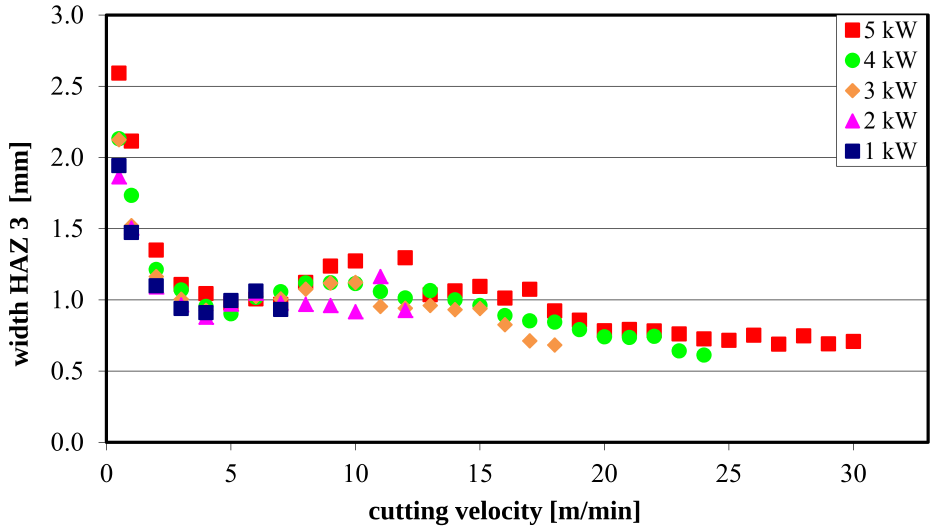


Figure 6. Width HAZ 3 in dependency of laser power and cutting velocity for CF-PPS with d=1.0 mm

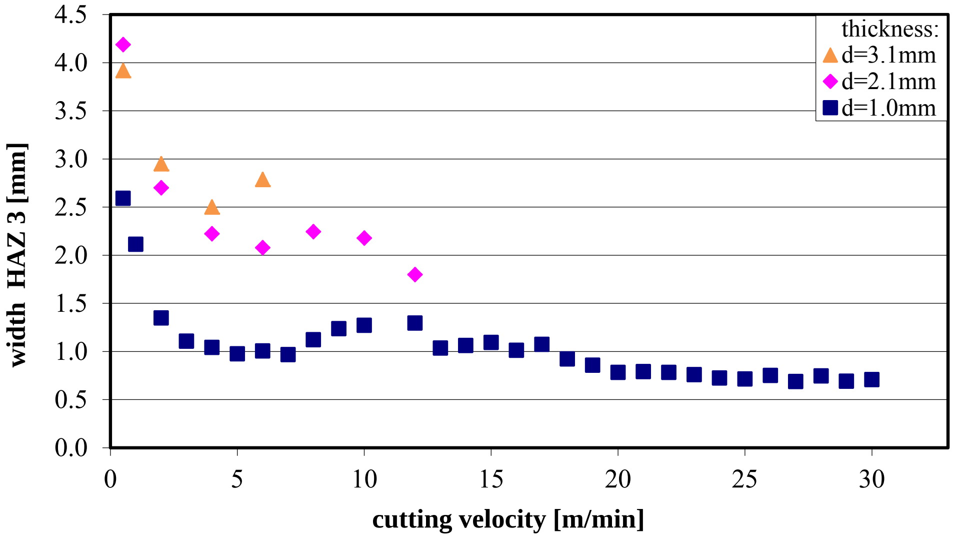


Figure 7. Width HAZ 3 of CF-PPS depending on the velocity for different material thicknesses for P_L=5kW

In order to compare the results for CF-epoxy and CF-PPS the different measured HAZ regions of the d = 1.1 mm and d = 1.0 mm thick samples are plotted within one diagram (Figure 8). These experimental series are chosen because of the identical number of layers and the high reachable velocities for a laser power of P_L=5kW. This allows a comparison of a high amount of values. Comparing the different HAZ regions for both matrices, the widths of the HAZ 2 for CF-PPS have comparable values to the measured HAZ 2 for CF-epoxy. Observing the HAZ 3 for CF-PPS, it can be seen that the values are much bigger than the HAZ 2 for CF-epoxy.

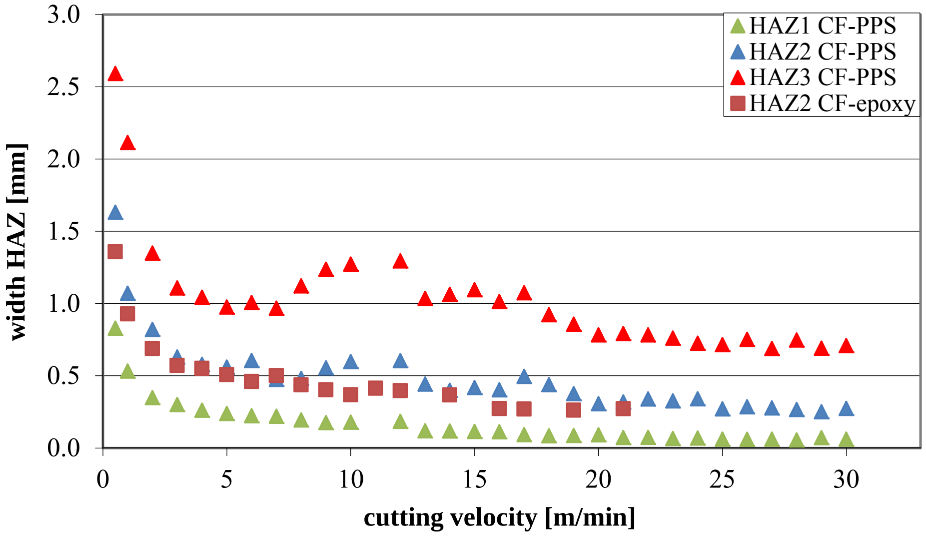


Figure 8. Comparison of HAZ for CF-epoxy with d=1.1mm and CF-PPS with d=1.0mm for P_L=5 kW

Conclusion and Outlook

The asymptotic convergence of the HAZ width for the performed experiments leads to the assumption that it is possible to reduce the HAZ by the chosen processing strategy, but not to avoid it entirely. In general, the results show that a higher laser power enables higher cutting velocities which effect a smaller HAZ. In order to investigate if this effect follows an ongoing trend, preliminary experiments were performed with a disk laser with a maximum laser power of P_L = 16 kW and CF-PPS with d = 1.0 mm. Apart from the used laser source and the cutting optic the experimental set-up is identical to the described set-up in Figure 1. The results of the disk laser experiments with P_L = 16 kW and the fiber laser experiments, with a varying laser power of P_L = 1 kW to P_L = 5 kW, described in this paper are merged in one diagram (Figure 9). The results for the HAZ 2 of the experiments with a laser power of P_L = 16 kW fit well into the results of the described fiber laser experiments. The width of the HAZ 2 is becoming smaller for the high reachable velocities and it seems to converge to a minimum as suggested. Because of these promising results further investigations with the high power disk laser are in progress. Additionally, it is investigated in which way a correlation of the HAZ 2 for CF-epoxy and CF-PPS is approvable.

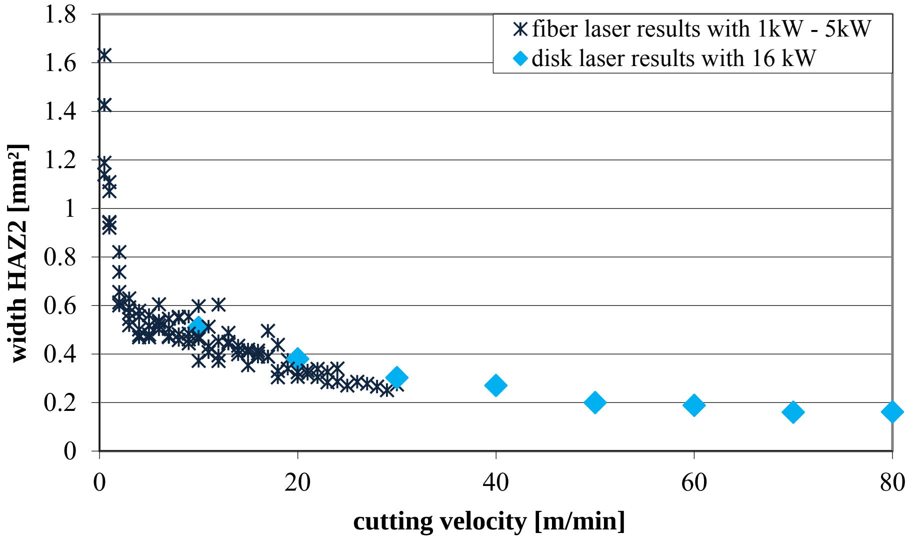


Figure 9. HAZ 2 of CF-PPS with d=1.0mm depending on velocity for varying laser power and laser source

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