THE INFLUENCE OF MOISTURE CONTENT ON THE HEAT AFFECTED ZONE AND THE RESULTING IN-PLANE SHEAR STRENGTH OF LASER CUT THERMOPLASTIC CFRP

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Abstract
In this paper investigations on the effect of the moisture content of thermoplastic CFRP on the laser induced heat affected zone (HAZ) and the resulting in-plane shear properties are presented. For this purpose carbon fiber reinforced polyetherimide (PEI) and polyphenylene sulphide (PPS) sheets were conditioned to different moisture contents and were then used for laser machining test specimens with contour und multipass cutting strategies. The extents of the HAZ were measured and in-plane shear tests were performed, revealing that the shear properties decrease when cutting material with high moisture content. This behavior can be correlated with the type of HAZ which contains porosity caused by the vaporization of water.

1. Introduction

Carbon fibre reinforced plastics (CFRP) offer great potential for lightweight construction especially in the transportation and energy sector due to their high strength-to-weight ratio. Within this field, structures based on thermoplastic matrix materials are of growing interest. Compared to thermosets, thermoplastic matrix materials provide improved properties regarding formability, weldability, damage tolerance, reparability and recyclability. To enter mass markets such as the automotive sector, fast and cost-effective manufacturing processes are required.

The composition of two different materials which provide the outstanding mechanical properties on one hand, also result in significant challenges for the machining of these materials on the other hand. Conventional machining techniques such as milling or water jet cutting result in high tool wear or require complex water circuit handling. In addition, both techniques are not force-free. [1]

Laser machining of CFRP provides a processing method for cutting and trimming that is force-free, wear-free, fast and automatable. However, for cutting processes the heat generated can lead to heat affected zones (HAZ) in the material, which can be distinguished by areas with vaporization or decomposition of the matrix material, delamination of the laminate and the formation of porosity. As shown in previous publications, the HAZ has an influence on the mechanical properties of CFRP structures. [2, 3, 4]

From thermal joining methods of thermoplastics such as laser, hot-tool or vibration welding it is known that the quality of the joint and the mechanical properties are influenced by the moisture content of the material. It is also reported that the strength of thermoplastic welding

joints can be increased when using material with lower moisture content [5, 6]. At present publications taking both the problems moisture influence and laser-induced heat from cutting processes into account are not known.
Considering the advantages but also the challenges of laser cutting, a better understanding of the material and process conditions on the cutting results is needed to offer the growing thermoplastic CFRP market a well-engineered processing method. The objective of this paper is therefore to investigate the influence of moisture content on the laser cutting result and the effect on the in-plane shear properties of the thermoplastic CFRPs.

2. Experimental set-up

For the experiments Tencate Cetex® organic sheets consisting of either polyphenylene sulfide (CF-PPS) or polyetherimide (CF-PEI) matrix material were used, which differ in moisture absorption properties**.** The laminate was a 5-harness satin weave layup with 4 layers in the case of CF-PPS and 5 layers in the case of CF-PEI. A summary of the characteristics is given in Table 1.

material	fabric	thickness *b* [mm]	number of layers	fiber orientation
CF-PPS	5H satin weave	1.24	4	$[(0)_2,(90)_2]_T$
CF-PEI	5H satin weave	1.6	5	$[(0)_3,(90)_2]_T$

Table 1. Tencate Cetex® material characteristics

In order to produce material with different moisture content, sheets from both materials were initially dried for 48h at 120°C in an oven and were then stored in distilled water or in ambient conditions (humidity between 30-40%). For the determination of the saturation point the weight was measured every 24h. The moisture content M was calculated using equation (1), dividing the weight difference between the conditioned material m and the dry material m_{dry} by the weight of the dry material m_{dry}. In addition, dry material sheets were used for laser cutting immediately after a short cool down period.

$$M = \frac{m - m_{dry}}{m_{dry}} \times 100\% \qquad (1)$$

The cutting experiments were performed using a single mode fibre laser provided by Rofin-Sinar Laser GmbH. The laser emits continuous laser radiation at a wavelength of λ=1080nm and a maximum power of P_L=1kW. The laser beam is guided through an optical fibre to a collimator and a scan head, which deflects the laser beam within a 2D working field. For focusing an f-theta objective with a focal length of f=167mm was used, resulting in a focal diameter of D_f=40µm. For cooling purposes, cross jets were used to generate a constant nitrogen gas flow on the surface of the CFRP. The setup is shown in Figure 1.

In order to determine the effect of the cutting strategy, contour and multipass cutting strategies were applied keeping the line energy E_S constant for each material. The line energy was calculated using equation (2), multiplying the laser power P_L by the number of passes n and dividing it by the scanning speed v_S. The cutting parameters are summarized in Table 2.

$$E_S = \frac{P_L n}{v_S} \qquad (2)$$

material	cutting strategy	number of passes *n*	laser power P_L [kW]	scanning speed v_S [m/s]	line energy E_S [kJ/m]
CF-PPS	contour	1	1	0.1	10
CF-PPS	multipass	6	1	0.6	10
CF-PEI	contour	1	1	0.07	14.3
CF-PEI	multipass	10	1	0.7	14.3

Table 2. Cutting parameters

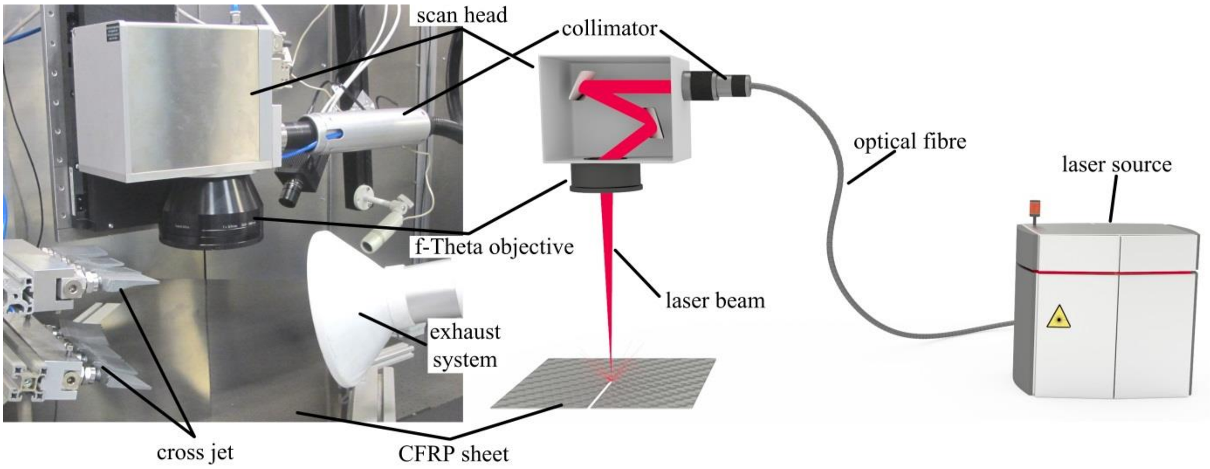

Figure 1. Experimental setup

The mechanical tests were performed according to the ASTM standard D3518M (standard test method for in-plane shear response of polymer matrix composite materials by tensile tests of a ±45 laminate) using test specimens with the length of *l*=250mm and width of *h*=25mm cut at a ±45° angle to the warp and weft yarn. The samples were end-tabbed and strain gauges were mounted at 0° and 90° to the sample axis to determine the shear strain. For statistical certainty the mechanical tests were repeated five times for each parameter set and the mean as well as standard deviation values were calculated. A sixth specimen with the same dimensions was cut for the analysis of the HAZ. After conditioning and laser cutting, all specimens were dried at 120°C for 24h in order to regulate the moisture content to an identical level. The specimens were then stored for minimum 14 days at 21°C and a humidity of 33% before performing the mechanical tests. In order to compare laser cutting to conventional cutting methods, reference samples were made by using a diamond saw for the initial cut followed by surface grinding of the cut edges.

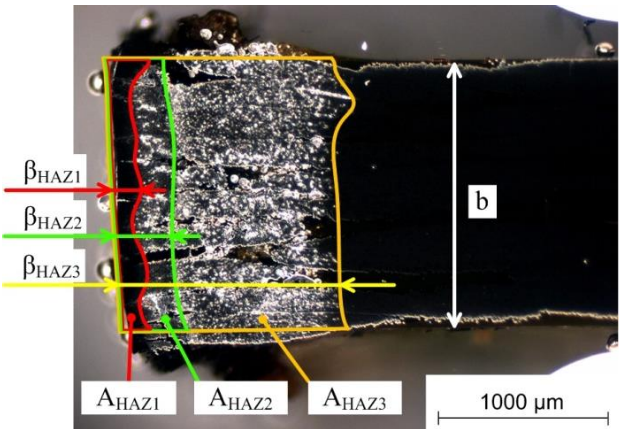

Figure 2. Micrograph of a cross section of laser cut CF-PEI showing the different heat affected zones

The quantitative analysis of the HAZ was conducted by taking micrographs of cross sections of laser cut specimens (Figure 2). Always beginning at the cutting kerf, the different HAZ areas can be differentiated as follows: A_{HAZ1} is defined as the area with charred fibre rovings and vaporized matrix material adjacent to the cutting kerf. Next to this area it is assumed that the decomposition temperature of the matrix material is exceeded and mainly the matrix material is damaged (A_{HAZ2}). The appearance of the third area A_{HAZ3} is dominated by porosity within the matrix material due to reaching the melting temperature of the thermoplastic matrix and therefore exceeding the vaporization temperature of the water within the matrix. Hence, it is assumed that the porosity is mainly formed by the vaporization of water.
The area A_{HAZ} was measured by the use of image analysis software. The mean width β_{HAZ} of each HAZ was calculated dividing the area A_{HAZ} by the material thickness b (equation (3)). For statistical certainty the measurements were repeated six times. Standard deviation values were computed for all values.

$$\beta_{HAZ} = \frac{A_{HAZ}}{b} \tag{3}$$

3. Results

As a first step, the moisture content measurements were analyzed. In Figure 3 the moisture content M is given as a function of the time t for both materials stored in distilled water (wet) and under ambient condition (rh). For all conditions and materials the highest slope of the moisture content is measured within the first 48 hours and decreases with longer duration. Saturation for CF-PEI in distilled water is reached after t=552h at a moisture content of M=0.61% and after t=384h in ambient condition at M=0.21%. For CF-PPS saturation is reached after t=408h in distilled water at M=0.16% and after t=48h in ambient condition at M=0.06%. Thus, the moisture content of CF-PEI compared to the moisture content of CF-PPS in the same condition is nearly four times higher when saturated in distilled water and more than three times higher when conditioned at ambient humidity.

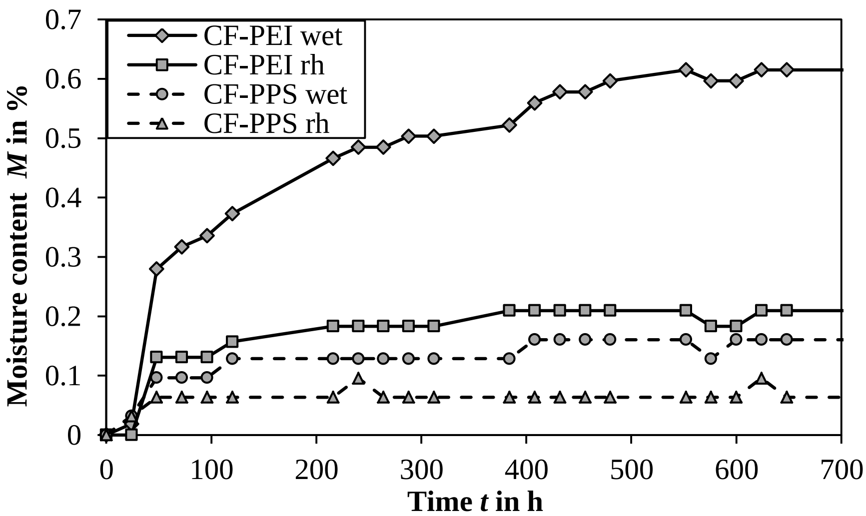

Figure 3. Moisture content curve of CFRP plates with PEI and PPS matrix in distilled water (wet) and ambient humidity (rh) condition

In the next step the HAZ has been analysed, in order to determine the influence of the moisture content on the laser-induced damage. In Figure 4 the average widths β of the HAZ are shown for contour and multipass cut CF-PEI with different moisture contents. Within the same cutting strategy the width of the HAZ1 β_{HAZ1} stays constant for all moisture contents while β_{HAZ2} increases slightly for wet material. A significant increase of more than 100% is observed for β_{HAZ3} between dry and wet material. Comparing the two cutting strategies, β_{HAZ1} and β_{HAZ2} can be reduced by more than 50% using multipass cutting. Compared to contour cutting, the width β_{HAZ3} for multipass cut dry material also decreases, but steps up to width values higher than for contour cut material when using ambient humidity or wet material. The maximum width of β_{HAZ3}=1.63mm is measured for wet multipass cut material. Furthermore, higher standard deviation values are observed for multipass cut materials, which is assumed to be an effect of the longer lasting and highly dynamic heat input arising from the cutting strategy. In summary, the moisture content affects mainly the extent of β_{HAZ3}. Advantages of contour cutting can only be found in lower values of β_{HAZ3} when cutting ambient humidity or wet material.

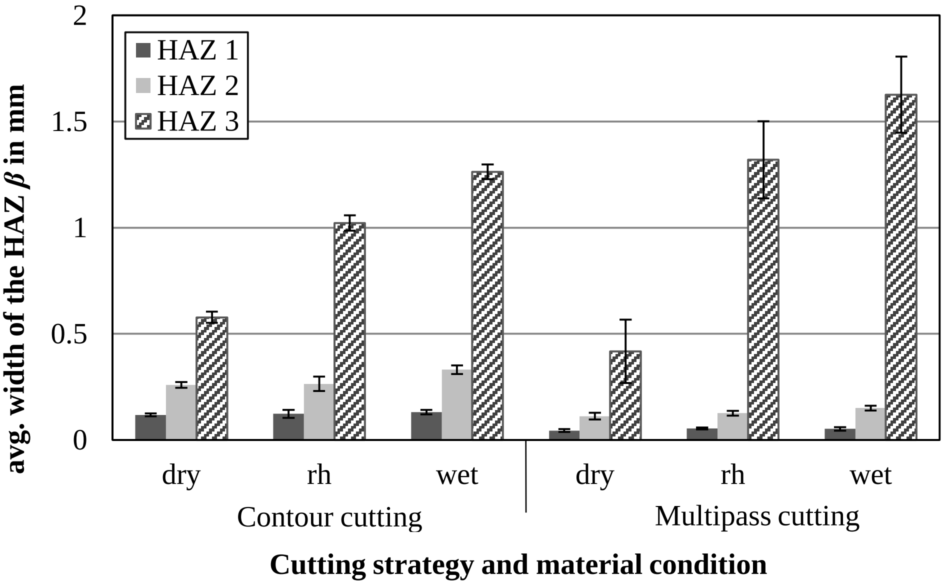

Figure 4. Average width β of the HAZ of laser cut CF-PEI using different strategies and material conditions

In Figure 5 images of the specimen surface and corresponding cross sections are shown for multipass cut CF-PEI with different moisture contents. Here the significant increase of the HAZ3 with increasing moisture content is clearly visible in the cross sections. This is also noticeable in the HAZ appearance on the specimen surface.

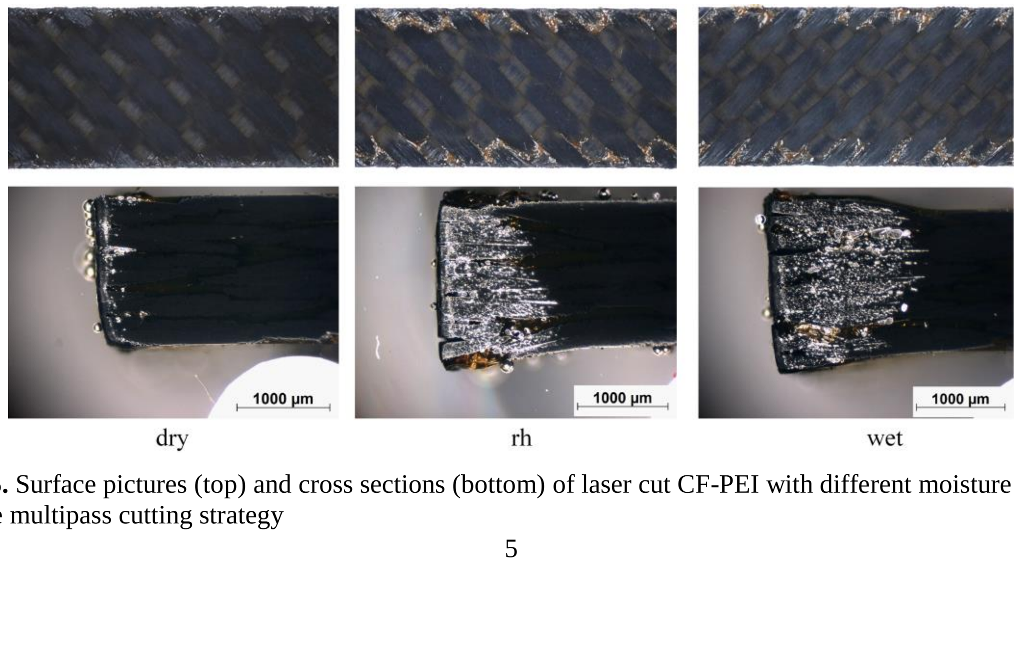

Figure 5. Surface pictures (top) and cross sections (bottom) of laser cut CF-PEI with different moisture content using the multipass cutting strategy

The changes in the HAZ follow a similar pattern when cutting CF-PPS (Figure 6). As a main difference, it is observed that the HAZ widths can be decreased for all types of HAZ when applying the multipass cutting strategy. Here the maximum width of β_{HAZ3}=0.93mm is measured for wet, contour cut material. As for CF-PEI, higher standard deviation values are observed for multipass cut materials. In summary, for CF-PPS the moisture content also affects mainly the extent of β_{HAZ3}. Advantages by using multipass cutting can be found in the reduction of all types of HAZ, regardless of the moisture content.

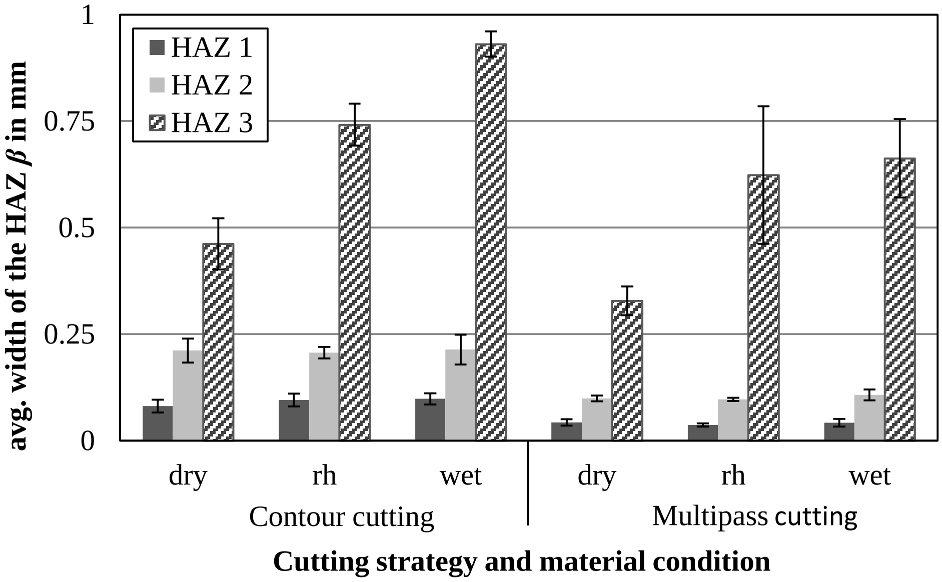

Figure 6. Average width β of the HAZ of laser cut CF-PPS using different strategies and material conditions

The following mechanical test results are focused on CF-PEI due to its higher moisture content and distinct influence on the measured HAZ values. In Figure 7 the shear strength τ (defined as the stress at 5% shear strain) is given for different material conditions and cutting strategies. The highest stress values are observed for material conditioned in ambient humidity in the case of contour cutting and for dry material in the case of multipass cutting ($\tau_{contour,rh}$=76MPa and $\tau_{multipass,dry}$=78MPa), whereas the lowest values are obtained by wet material ($\tau_{contour,wet}$=72MPa and $\tau_{multipass,wet}$=70MPa). Comparing the extent of the HAZ with the shear strength measurements, a definite tendency can only be found for multipass cut specimens, for which the strength values decrease with increasing moisture content and increasing extent of the HAZ3. For the reference specimens, a shear strength of $\tau_{reference}$=79MPa was measured.

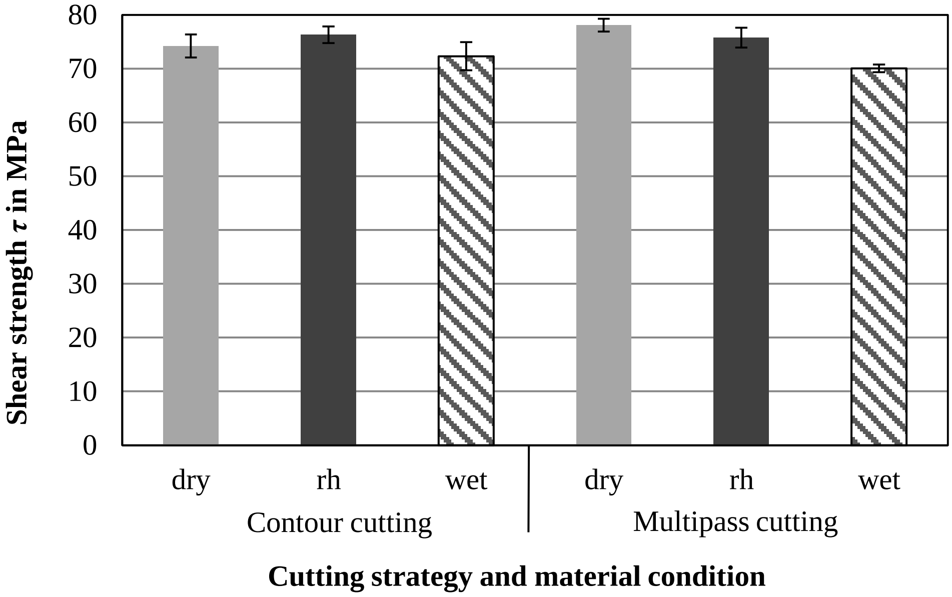

Figure 7. Shear strength of CF-PEI using different cutting strategies and material conditions

Through analysis of the elastic modulus behavior of the specimens, a different trend can be observed (Figure 8). Here the shear modulus G is decreasing for both cutting strategies with increasing moisture content. The lowest values are measured for multipass cut wet material ($G_{\mathrm{multipass,wet}}$=3580MPa), which also represents the condition and strategy with the highest measured width of the HAZ β_{HAZ3}. The highest values are measured for multipass cut dry material ($G_{\mathrm{multipass,dry}}$=3975MPa), which was described as the condition and strategy with the lowest measured width of the HAZ β_{HAZ3}. For the reference specimens a shear modulus of $G_{\mathrm{reference}}$=3772MPa was measured.

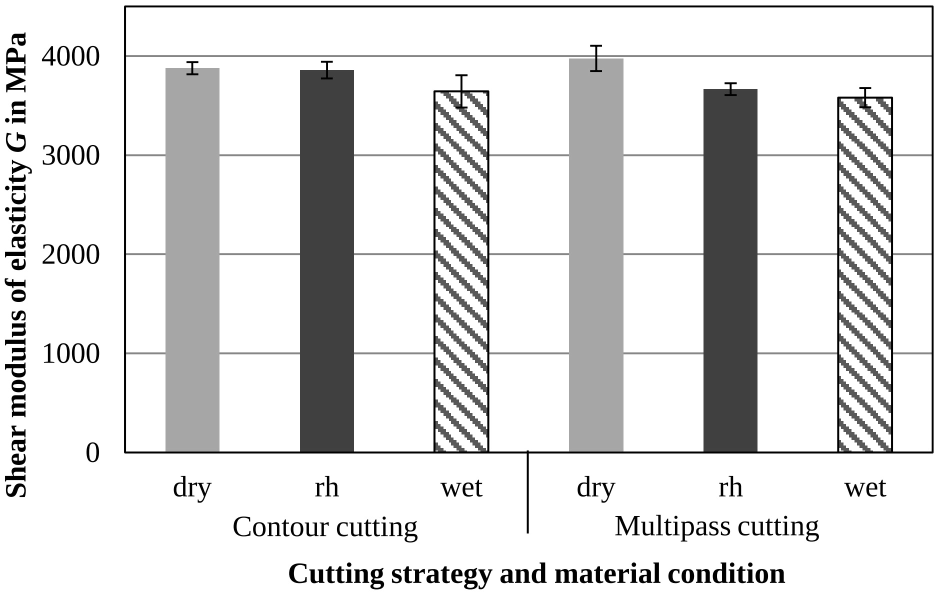

Figure 8. Shear modulus of CF-PEI using different cutting strategies and material conditions

4. Conclusion and Outlook

In this paper it was shown that the moisture content of thermoplastic CFRP has an influence on the extent of the heat affected zone as well as on the resulting in-plane shear properties. Increasing moisture content leads to distinctly increasing HAZ3, independent of the cutting strategy used or the moisture uptake properties of the material. This type of heat affected zone is likely to be caused mainly by the vaporization of water. An influence on HAZ1 cannot be observed or is negligible in the case of the HAZ2.

The cutting strategy has an impact on all types of HAZ. Using multipass cutting, HAZ1 and HAZ2 can be reduced, whereas the HAZ3 can be reduced only for dry material in the case of high moisture capability (CF-PEI) or even for all moisture contents in the case of low moisture uptake capabilities (CF-PPS).

Despite the large variations in the extent of the HAZ3, a clear trend does not become apparent for shear strength measurements of contour cut material, whereas for multipass cut material rising strength values are observed for decreasing moisture content. A definite tendency can be found for the shear moduli. Here, higher values are measured with decreasing moisture content and thus decreasing HAZ3. Considering these promising results, further investigations are in progress using other cutting strategies and analyses of the temperature distribution in the material during the laser cutting process.

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