# EXPERIMENTAL INVESTIGATION OF CFRP TRIMMING BY MEANS OF SHEARING

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## ABSTRACT

The usage of carbon fiber reinforced plastics (CFRP) for structural applications has been continuously growing across different industries. This trend is expected to continue in the future with the automotive industry being one of the main drivers of the CFRP market growth. The reason for this is the legislatively imposed limits on CO2 emissions from vehicles. Lightweight design and the resulting fuel efficiency is one possibility to reduce the CO2 emissions. Due to a high specific strength, CFRP is very suitable for manufacturing of lightweight structural components. Accounting for this fact, a high volume production of CFRP components may be deployed in the future. Therefore, in order to increase the adoption of the CFRP, novel efficient technologies enabling cost and cycle time reduction in high volume manufacturing of CFRP components are required. CFRP components are produced near-net shape. Due to the process related limitations, CFRP components have to be trimmed or pierced during the finish processing in order to fulfill geometric or functional requirements. Shearing can be potentially implemented for a highly productive and cost efficient piercing and trimming of CFRP components in high volume production. Up to now, there exists insufficient technological knowledge on the applicability of shearing for CFRP finish processing. In order to close this knowledge gap, CFRP trimming was experimentally investigated in this work. The effects of process parameters like cutting clearance, blank holder pressure, punch geometry and cutting edge radius on the structural integrity of the laminate, the sheared edge morphology as well as the cutting forces were analyzed based on the experimental data. By these means, a basic understanding of CFRP separation in trimming is established which enables a knowledge based process design of CFRP trimming processes.

## 1 INTRODUCTION

Carbon fiber reinforced plastic (CFRP) is a man-made composite material. The industrial CFRP usage has been continuously raising across different industries [1]. The reason for this is an unprecedented specific strength of CFRP in comparison with other constructional materials as metals [2]. This property renders CFRP particularly suitable for lightweight applications where the required strength of a structural component is to be achieved at minimum weight [3]. For mobility applications, lightweighting improves the fuel efficiency of vehicles. An increase of the fuel efficiency of vehicles with combustion engines reduces their CO2 emissions [4].

The legislatively allowable CO2 emissions from vehicles have been continuously reduced due to the environmental reasons [5]. Lightweight design realized by means of CFRP is one of the possible means to achieve the legislatively set CO2 emission targets [6]. In the automotive industry lightweighting of series manufactured cars by means of CFRP would be necessary. Therefore, the automotive industry is expected to have the highest growth rate of CFRP usage in the future [7]. However, nowadays high costs of CFRP components prevent their adoption for price sensitive and high volume automotive applications [8]. Therefore, novel manufacturing technologies enabling cost efficient manufacturing of CFRP components in series production are required.

Although CFRP components are produced near-net-shape [9], finish processing is usually required for the component to fulfil geometric or functional requirements [10]. In the finishing step, trimming or piercing operations are performed by means of machining or abrasive waterjet cutting (AWJ) technologies [11].

Shearing is a highly productive and cost efficient technology for material separation in series production [12]. Due to these reasons, shearing is used for trimming and piercing of sheet metal car body components. Therefore, shearing has a potential to be used for a highly productive and cost efficient finishing of CFRP components in series production. In order to provide a necessary background for this work, the state of the art on shearing of CFRP is outlined in the next chapter.

## 2 LITERATURE REVIEW ON TRIMMING OF CFRP

Up to now, there are only a few publications concerning trimming of CFRP by means of shearing. In the following, some relevant pieces of research on trimming of CFRP by means of shearing are summarized. Nakamura et al. investigated the influence of the workpiece temperature, and punch geometry on the maximum cutting load, delaminations, and sheared edge morphology of a CFRP laminate with an epoxy matrix [13]. The workpiece temperature was varied on the interval $T_{wp}$ = [25,110] C°. In order to specify the punch geometry, the cutting edge angles nomenclature is given Fig. 1a. The punch geometries used in the study are schematically depicted in Fig. 1b.

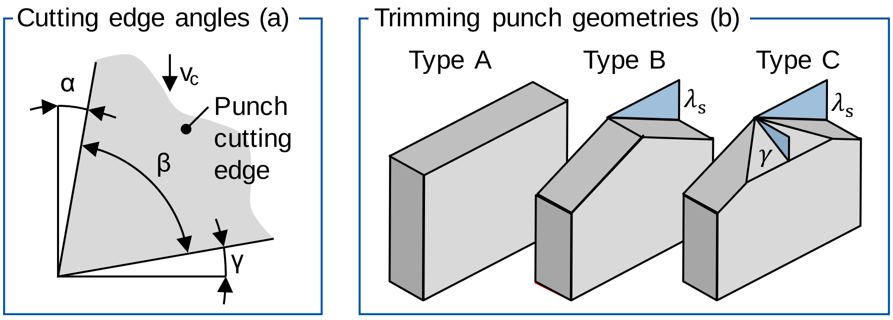


Figure 1: Cutting edge angles (a) and trimming punch geometries (b). Legend: $v_c$ - punch velocity, α - clearance angle, β - wedge angle, γ - rake angle, $\lambda_s$ - cutting edge inclination angle

The laminate thickness was s = 1.2 mm and a relatively low the blank holder pressure $p_{bh}$ = 4 MPa was set. Due to the softening of the laminate, a decrease of the maximum cutting load was observed at higher temperatures. A combination of a Type C Punch and the workpiece temperature $T_{wp}$ = 70 °C resulted in delamination free specimens. The variation of the punch geometry and the workpiece temperature on the sheared edge morphology demonstrated no particular effects.

Using the same experimental set-up and material, Ogi et al. investigated the influence of the cutting clearance on maximum cutting load, delaminations, and the sheared edge morphology [14]. In contrast to Nakamura et al the experiments were performed at a constant workpiece temperature $T_{wp}$ = 70 °C. The maximum cutting load decreased from the smallest clearance u = 0.01 mm to u = 0.04 mm by about 19% and then remained nearly constant up to the clearance u = 0.1 mm. No clear effects of the cutting clearance on delaminations and the sheared edge morphology could be determined from the experimental data.

Yashiro et al. investigated experimentally the cutting forces in trimming of a CFRP laminate in dependence of the cutting clearance and developed a numerical model of the trimming process using smoothed particle hydrodynamics (SPH) framework [15]. The laminate had thickness s = 1.1 mm and the punch geometry corresponds to the punch of type A shown in Fig. 1b. The cutting velocity was constant at $v_c$ = 1 mm / min. Although, a blank holder was used, no statements with regard to the blank holder pressure $p_{bh}$ were made. The investigated punch clearances were u = {0.05, 0.10, 0.20, 0.50} mm. The cutting forces were assessed as cutting resistances defined as

$$k_c = F_{c,max}/(s \cdot l), \tag{1}$$

where $F_{c,max}$ is the maximum cutting force, s the laminate thickness and l the length of the cutting line. A clear decrease of the cutting resistance from $k_c$ = 325 N/mm$^2$ at u = 0.05 mm to $k_c$ = 150 N/mm$^2$ at u = 0.50 mm was determined.

In the scope of the previous work, an experimental investigation on trimming of unidirectional CFRP laminates under variation of the fiber orientation to the cutting line Φ was performed in Shirobokov et al. [16]. A linear reduction of the maximum cutting force $F_c$ from the perpendicular to the parallel fiber orientation to the cutting line Φ was determined. Furthermore, incomplete separation of the specimens at fiber orientation to the cutting line Φ = 30° and below was observed and explained by means of the fractographical observations.

The problem of characterization of the sheared edge morphology of sheared CFRP laminates was also addressed in the previous work [17]. The sheared edge morphology of CFRP is significantly different from that of metals. Due to this fact, conventional sheared edge parameters cannot be used for a quantitative description of the sheared edge morphology. As a possible solution, integral parameters for the sheared edge morphology characterization were formulated. Their applicability for a quantitative and unambiguous characterization of the sheared edges of CFRP specimens was exemplary demonstrated.

The scientific works described above summarize the actual state of research on trimming of CFRP. Apparently, there is a knowledge gap regarding the cause and effect relationships between the extended number of shearing process parameters and the resulting process characteristics like cutting resistance, delaminations, and shearing edge morphology. Furthermore, a physical explanation of the CFRP separation mechanisms in shearing has not yet been given.

## 3 OBJECTIVE AND APPROACH

According to the knowledge gap identified in the previous section the objective of this work is formulated as a determination of the correlations between the process parameters of trimming process (clearance, blank holder pressure, cutting velocity, cutting edge radius, punch geometry, and punch coating) and the cutting resistance, delaminations, and sheared edge morphology. In the scope of this investigation, significant process parameters are identified and the observed CFRP separation phenomena explained. As a result, this work states a basis for further scientific investigations of CFRP shearing processes and their industrial dissemination.

In order to achieve the stated objective, a systematic experimental investigation according to the methodology of design of experiments (DOE) was performed. A detailed description of the experimental procedure is provided in the next chapter.

## 4 EXPERIMENTAL SETUP

The DOE enables a determination of the effects of the process factors (here trimming process parameters) on the responses (cutting resistance, delaminations, and sheared edge morphology). In order to do so, purposefully designed experiments with varying levels of the process factors are to be conducted and assessed.

For a better understanding of the chosen process parameters a process scheme of a trimming operation is shown in Fig. 2a. The trimming tool consist of a punch, a blankholder, and a die. In the first stage of the process the laminate is clamped between the blank holder and the die due to the action of the blank holder force $F_{bh}$ and the blankholder pressure $p_{bh}$ is build up. In the second stage the punch engages into the contact with the laminate causing its initial elastic deflection. At a continuing punch movement in the third stage, the laminate experiences further deflection. This leads to a formation and propagation of the cracks in the shearing zone. In the fourth stage, the laminate is completely separated. In the final fifth stage, the punch is retracted to the initial position.

Due to the lack of general understanding on the effects of process parameters on CFRP separation in trimming an extended number of the process parameters was considered in this work. A process scheme of the trimming process including the eight process parameters experimentally varied in the scope of this work are shown in Fig. 2.

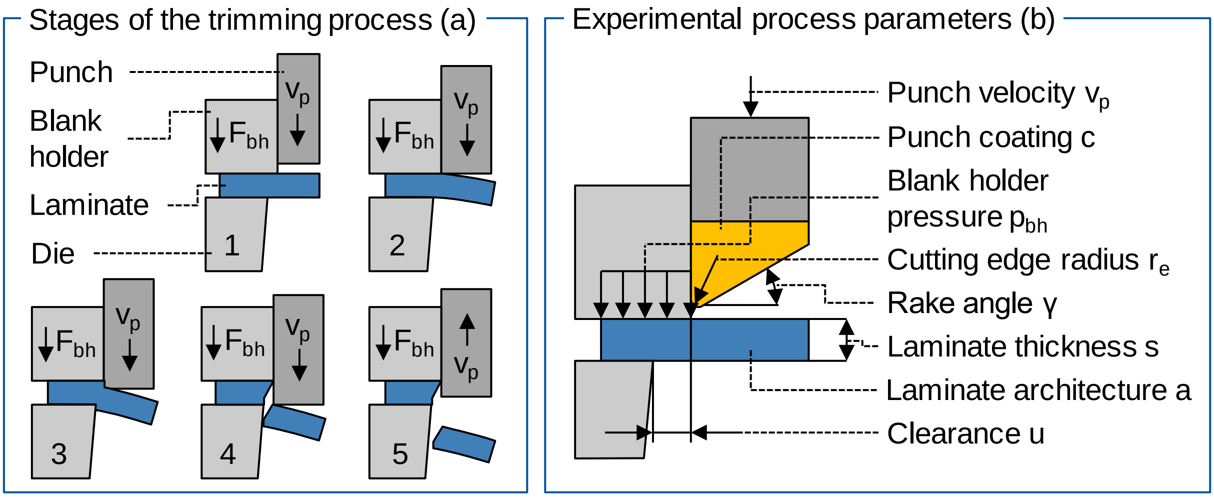


Figure 2: Stages of the trimming process (a) and experimental process parameters (b). Legend: $F_{bh}$ – blankholder force

CFRP laminates with a thermoset matrix and a fiber volume fraction $V_f = 0.6$ were used in this work. In order to capture the influences of the material on the trimming process laminate architecture a and laminate thickness s were varied. Laminates with biaxial (BA) and quasi-isotropic (QI) architectures a ={BA, QI} were used. Two laminate thicknesses were used s = {1.4; 2.8} mm. The laminates were prepared as strips with a width of 20 mm. The laminate strips were completely cut with a punch so that the length of the cutting line was l = 20 mm. The punches and the dies were made of cold working steel hardened to 60 HRC. The variation of the cutting clearance u was realized by adjusting the die thickness. In sheet metal working, it is an established approach to set the clearance in terms of the relative clearance which is defined as $u_{rel} = u / s$. The reason for this is that the clearance has to be adjusted according to the sheet metal thickness in order to obtain optimal results [18]. This approach was adopted in this work and the relative clearances were varied between two levels $u_{rel} = \{0; 20\}$ %. As far as the punch geometry affects the separation process [13], two different punch geometries realized through the variation of the rake angles γ = {0; 30}° were considered. Furthermore, the rounding of the cutting edge at the punch, characterized by means of the cutting edge radius $r_e$, was varied as well. Punches with sharp and rounded cutting edges were used $r_e = \{0; 0.2\}$ mm. The cutting edge radius of sharp punches $r_e = 0$ mm was controlled to be below $r_e < 5$ µm. Brush polishing process was used for the cutting edge preparation to produce the cutting edge radius $r_e = 0.2$ mm. The cutting edge radius of the die was not varied and it was controlled to be below $r_e < 20$ µm. Diamond like coatings to reduce wear are used for CFRP drilling or milling tools [19]. This approach is potentially applicable to the shearing tools as well. In order to asses, if a coating affects the CFRP separation punches with and without coatings were prepared. A diamond like carbon coating (DLC) from Cemecon AG, Germany was applied to some of the punches c = {None; DLC}. The investigations of Nakamura et al. [13], Ogi et al. [14] and Yashiro et al. [15] described in chapter 2 were performed using a bolted fixture as a blank holder. In this study, an industrial-grade shearing tool with gas springs to build up the blank holder pressure $p_{bh}$ was used. Due to the compression of the gas springs the blank holder pressure $p_{bh}$ increased during the shearing process. The maximum blank holder pressure levels used in the experiments were $p_{bh} = \{100; 400\}$ MPa. The pressure build-up due to the compression of the gas springs was below 11% of the corresponding maximum values. The highest level of the blank holder pressure $p_{bh} = 400$ MPa corresponds to about 80 % of the bearable through-thickness compression load which the laminates withstands without observable damage. The experiments were carried out using a servo-electric press AMADA SDE2025SE. Due to the press kinematics, the cutting velocity realizable by the press is not constant and follows a sinusoidal function. Adjusting the punch stroke frequency f of the press it is possible to vary the amplitude of the punch velocity $v_c$ function. Two settings of the punch stroke frequency were used f = {1, 35} $min^{-1}$. Using these settings the punch velocity at the contact of the punch with the laminate was $v_c$ = 0.013 m/s and $v_c$ = 0.45 m/s 1 for the stroke frequencies f = 1 $min^{-1}$ and f = 35 $min^{-1}$, respectively.

In order to systematically identify the effects of the selected process parameters on CFRP trimming an experimental design is to be defined. As far as a relatively big number of the process parameters has to be accounted for a Plackett-Burman design of experiments was chosen. An advantage of a Plackett-Burman design is a relatively low number of experiments, as compared with other designs, required to assess the factor effects on the response variables [20]. By these means a reasonable experimental effort could be maintained. A disadvantage of Plackett-Burman design is that the interactions between the factors are confounded. A Plackett-Burman design with two factor levels was chosen and the resulting experimental series to are shown in Table 1. Each experimental series consists of $n_{rep}$ = 5 repetitions in order to account for statistical effects. The statistical assessment of the experimental results was performed by means of Software Minitab.

| ES No. | a [-] | s [mm] | $u_{rel}$ [-] | $p_{bh}$ [MPa] | $r_e$ [mm] | $\gamma$ [°] | f [$min^{-1}$] | c [-] |
|---|---|---|---|---|---|---|---|---|
| 1 | BA | 2.8 | 0 | 400 | 0 | 0 | 1 | DLC |
| 2 | BA | 2.8 | 0 | 400 | 0.2 | 0 | 35 | None |
| 3 | QI | 1.4 | 0 | 400 | 0.2 | 30 | 1 | DLC |
| 4 | QI | 1.4 | 0 | 100 | 0 | 0 | 1 | None |
| 5 | QI | 2.8 | 0 | 100 | 0 | 30 | 35 | DLC |
| 6 | BA | 1.4 | 0 | 100 | 0.2 | 30 | 35 | None |
| 7 | QI | 2.8 | 0.2 | 100 | 0.2 | 0 | 1 | None |
| 8 | QI | 2.8 | 0.2 | 400 | 0 | 30 | 35 | None |
| 9 | BA | 2.8 | 0.2 | 100 | 0.2 | 30 | 1 | DLC |
| 10 | BA | 1.4 | 0.2 | 400 | 0 | 30 | 1 | None |
| 11 | QI | 1.4 | 0.2 | 400 | 0.2 | 0 | 35 | DLC |
| 12 | BA | 1.4 | 0.2 | 100 | 0 | 0 | 35 | DLC |

Table 1: Experimental design.

Based on the experimental design the effects of the piercing process parameters on the cutting resistance, delaminations, and sheared edge morphology were determined. Carrying out the experiments the process forces were measured by means of a piezo-electric force sensor Kistler 9091B. The process force includes the blank holder force, friction in the tool, and the cutting force. In order to define the cutting force, additional process force measurement capturing only the blank holder force and friction in the tool is required. Such a measurement could be easily realized when the laminate was located between the die and the blank holder but did not protrude under the punch so that no cutting occurred. Calculating the difference between the process force signals with and without laminate cutting the cutting force signal $F_c$ was obtained. A more detailed description of the force measurement procedure can be found in the previous work [16]. After that, the maximum value of the cutting force signal was obtained $F_{c,max}$ was determined and the cutting resistance $k_c$ calculated according to Equation 1. The cutting resistances $k_c$ were averaged over three values. For the characterization of the delaminations computer tomography measurements using Zeiss Metronom system were performed.

For the assessment of the sheared edge quality, the sheared edge profiles were measured using a digital microscope Keyence VXH-2000. The measurement resolution was $\delta$ = 1.43 µm so that the measured sheared edge profiles contained about 1000 and 2000 measurement points for the laminate thicknesses s = 1.4 mm and s = 2.8 mm, respectively. According to the previous work [17] the sheared edge quality of CFRP laminates was assessed by means of quadratic average of profile heights parameter Pq calculated from the measured profile values as:

$$P_q = \sqrt{\frac{1}{s}\int_0^s h(s)ds}, \tag{2}$$

where h(s) is the height of the sheared edge profile and s is the laminate thickness.

## 5 RESULTS AND DISCUSSION

In this chapter, the results of the conducted experimental study are presented. Firstly, the effects of the process parameters on the cutting resistance are presented. Secondly, the conducted assessment of the delamination is outlined. Finally, the identified cause-and-effect relationships between the process parameters and the resulting sheared edge morphology are addressed and critically discussed.

### 5.1 Cutting resistance

The effects of the considered process parameters on the cutting resistance $k_c$ are graphically presented in Fig. 3.

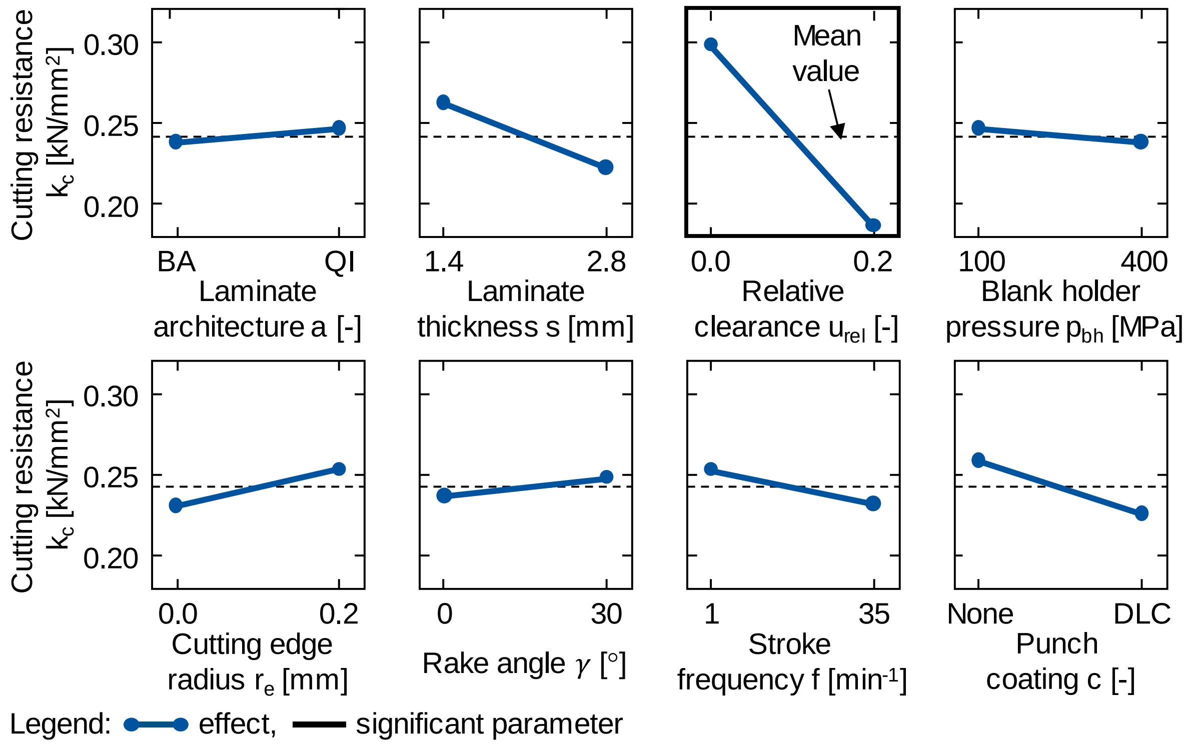


Figure 3: Effects of the process parameters on the cutting resistance $k_c$

The mean value of the cutting resistance from all experiments was $k_{c,m} = 0.24$ kN/mm$^2$. The magnitude of the cutting resistance is consistent with the findings of Yashiro et al. [15]. The parameter relative clearance $u_{rel}$ has the biggest effect magnitude on the cutting resistance $k_c$. An increase of the relative clearance $u_{rel}$ leads to a reduction of the cutting resistance $k_c$. From statistical point of view, only the parameter relative clearance $u_{rel}$ was determined to have a statistically significant influence on the cutting resistance $k_c$ at 5 % significance level. The second biggest effect magnitude has the parameter laminate thickness s. Laminates with a higher thickness s demonstrate a lower cutting resistance $k_c$. The directions of the effects for the relative clearance $u_{rel}$ and the laminate thickness s can be explained from mechanical point of view. If the relative clearance is concerned, Yashiro et al. proposed that the reduction of the cutting resistance occurs due to an increase of the bending stresses in the laminate, which are caused by a bigger distance between the cutting edges of the punch and the die [15]. This explanation approach can be extended to the effect of the laminate thickness. Again, due to a higher distance between the cutting edges of the die and the punch in thicker laminates, higher bending stresses are induced, which promotes the crack initiation in the laminate.

An increase of the cutting edge radius $r_e$ appears to increase the cutting resistance $k_c$. The reason for this is that a punch with a rounded cutting edge has a higher contact area with the laminate. Therefore, a higher cutting force is required to induce the stresses in the laminate leading to the crack initiation.

The effect magnitude of the punch coating c and the stroke frequency f on the cutting resistance $k_c$

is comparable with that of the cutting edge radius $r_e$. This effect of the coating c might be explained by a change of the tribological conditions leading to the friction reduction between the punch and the laminate. An increase of the stroke frequency leads to a reduction of the cutting resistance indicating a strain rate dependent material behavior.

The amplitudes of the effect of the laminate architecture a, the blank holder pressure $p_{bh}$, and the rake angle $\gamma$ on the cutting resistance $k_c$ are minimal and might be overlap with a natural process variance. This result can be contrasted with the findings of Nakamura et al. [13] who demonstrated that the usage of a v-shaped punch with a rake angle greater than $\gamma > 0°$ leads to a reduction of the cutting resistance $k_c$. Further investigations on this matter are required.

## 5.2 Delaminations

Figure 4 shows CT cross-sections of a trimmed specimen from experimental series (ES) 2. Based on the conducted CT measurements, no delaminations in the sheared zone were detected for all tested specimens. A possible explanation for this is a relatively high blank holder pressure used in the experiments which induced a through thickness compression in the laminae and thus prevented the emergence of the delaminations. This corresponds to the observations made by Ogi et al. [14] and Nakamura et. al [13]. Using a significantly lower blank holder pressure of about p =4 MPa they reported delaminations protruding into the laminate below $l_d$ < 0.4 mm. The absence of delaminations is to be confirmed in the future work by means of microscopic observations of the sheared zone from cross-section specimens.

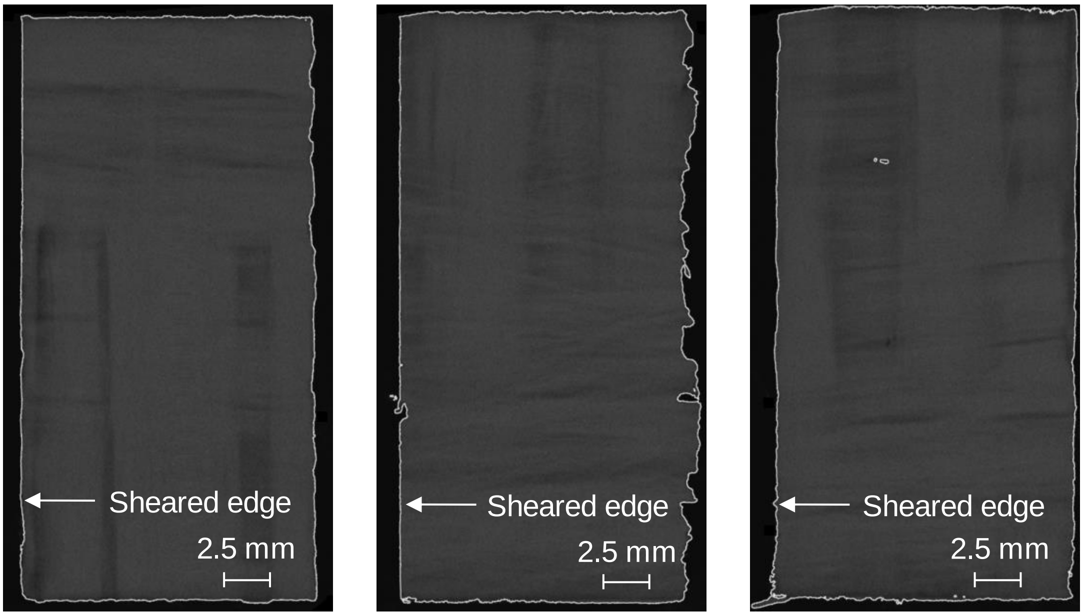


Figure 4: CT cross-sections of a trimmed CFRP laminate.

## 5.3 Sheared edge morphology

The primary assessment of the influence of the trimming process parameters on the sheared edge morphology of the trimmed CFRP specimens was conducted using the quadratic average of profile heights parameter Pq (see Equation 1). The corresponding main effect diagrams are shown in Fig. 5.

The mean value of the quadratic average of profile heights from all experiments was $Pq_m$ = 0.24 mm. The parameter relative clearance $u_{rel}$ has the biggest effect magnitude on the on the quadratic average of profile heights Pq. An increase of the relative clearance $u_{rel}$ is associated with a reduction of the parameter Pq and therefore an increase of the sheared edge quality [17]. From statistical point of view, only the effect of the parameter relative clearance $u_{rel}$ was determined as statistically significant at 5 % significance level. The parameters laminate architecture a, laminate thickness s, blank holder pressure $p_{bh}$ and cutting edge radius $r_e$ have relatively big effect magnitudes and are close to the significance borderline. The parameters rake angle $\gamma$, stroke frequency f, and punch coating appear to have marginally small effects on the sheared edge morphology.

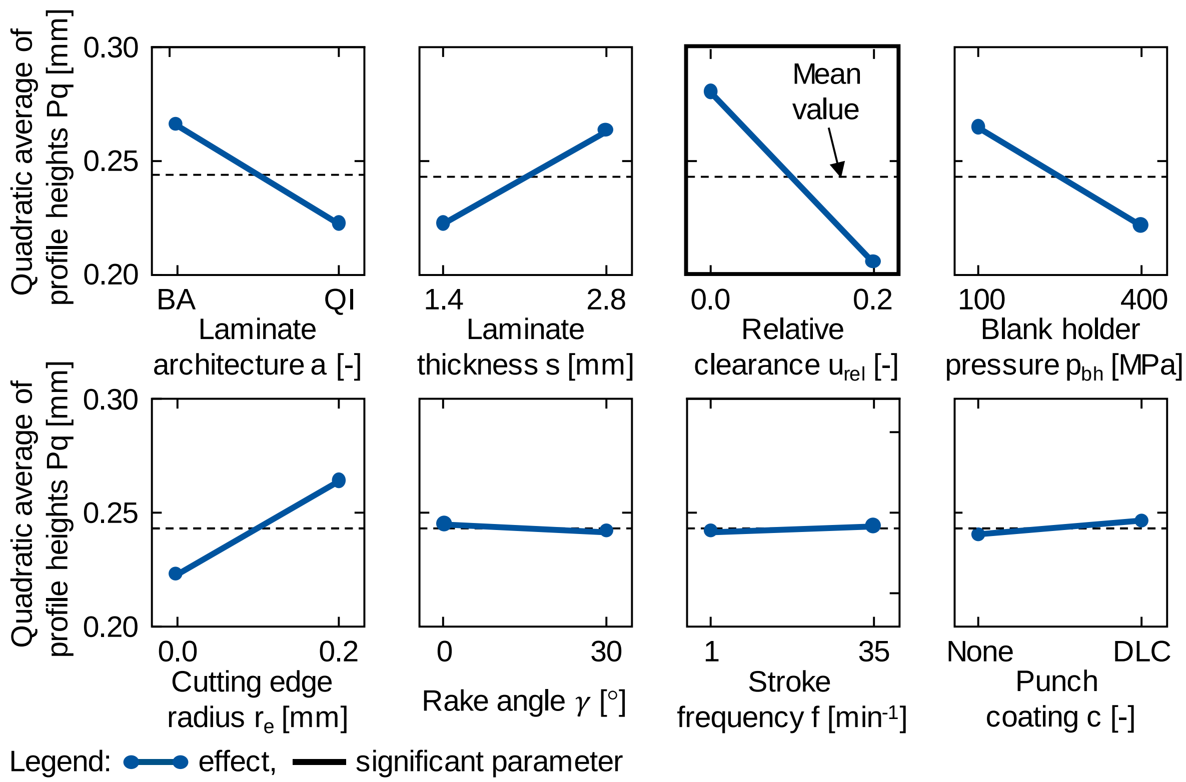


Figure 5: Effects of the process parameters on the cutting quadratic average of profile heights Pq.

In order to give a more in depth analysis of the experimental results a plot of Pq values for all experimental runs and repetitions is given in Fig. 6. Observing all experimental results it becomes clear that the mean values of Pq for five out of six experimental series with the relative clearance $u_{rel}$ = 0.2 (ER 7, 8, 10, 11, 12) are lower than the mean values of all experimental series with the relative clearance $u_{rel}$ = 0. This fact explains the effect of the relative clearance on the parameter Pq (see Fig. 5).

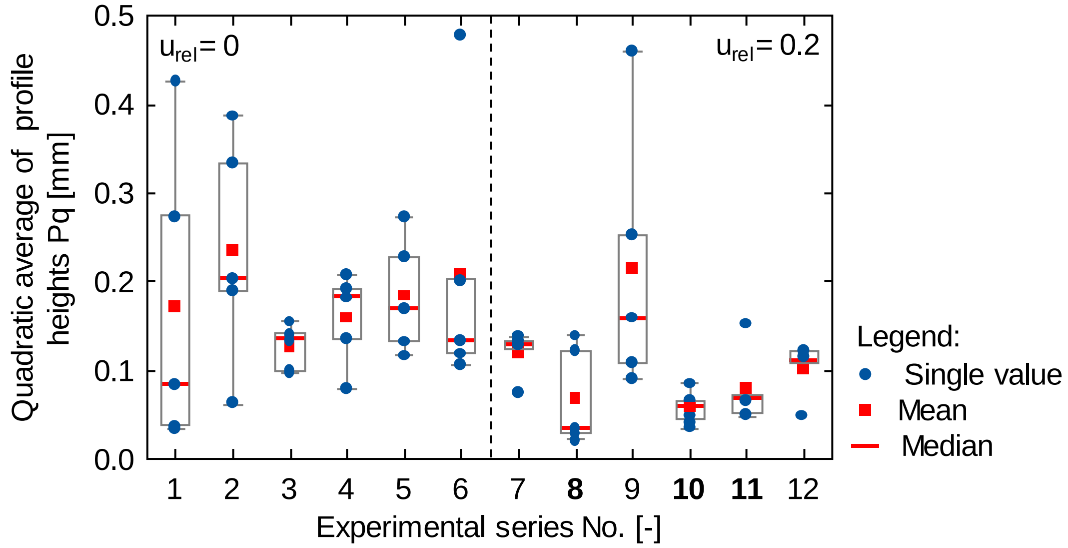


Figure 6: Quadratic average of profile heights Pq parameters for all experimental runs.

The experimental runs with the relative clearance $u_{rel}$ = 0 tend to have higher variance of of the Pq values. This indicates an inhomogeneous formation of the sheared edges under the same experimental conditions. The reason for a big variance of Pq values are the torn out fiber bundles. Fig. 7 illustrates this by showing the qualitatively best (lowest Pq) and worst (highest Pq) sheared edges from ES 1.

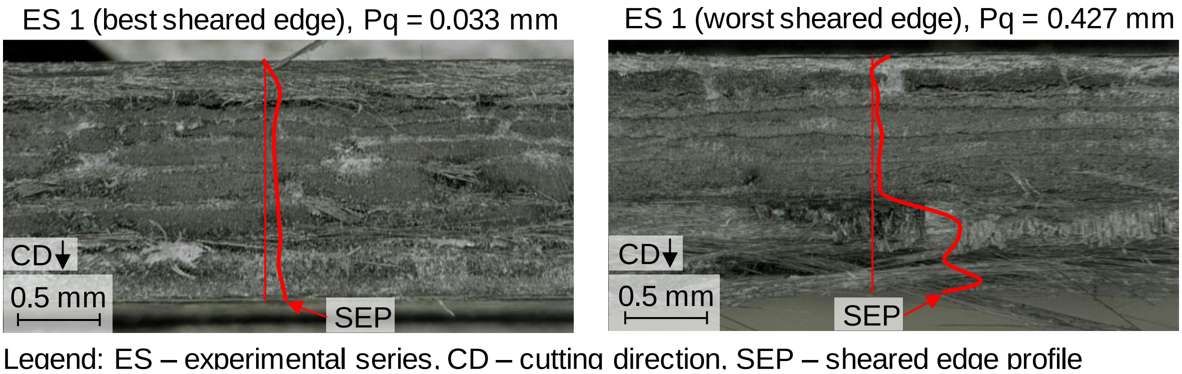


Figure 7: Variance of average of profile heights Pq parameters due to torn out fiber bundles.

The upper two thirds of the sheared edges are relatively smooth without any torn out, free fibers. In the lower part of the worst specimen, fraying fiber bundles are present. The fraying fiber bundles are measured as the sheared edge profile. The resulting shape of the contour leads to high Pq values. A possible explanation for the presence or absence of fraying at the same experimental conditions may the spacing between the single tows of the lowest ply. If a shearing crack runs through the region with a few fibers oriented in parallel to the cutting line, no or little fraying occurs. If a shearing crack passes through the fiber tow, which has a parallel orientation to the cutting line, fraying fiber bundles remain at the sheared edge. A similar fraying phenomenon in shearing of unidirectional CFRP laminates at parallel fiber orientation to the cutting line was observed and explained in the previous work [16]. As far as higher variance of Pq values occurs at lower cutting clearance, the fraying phenomenon may be associated with the smaller relative clearance.

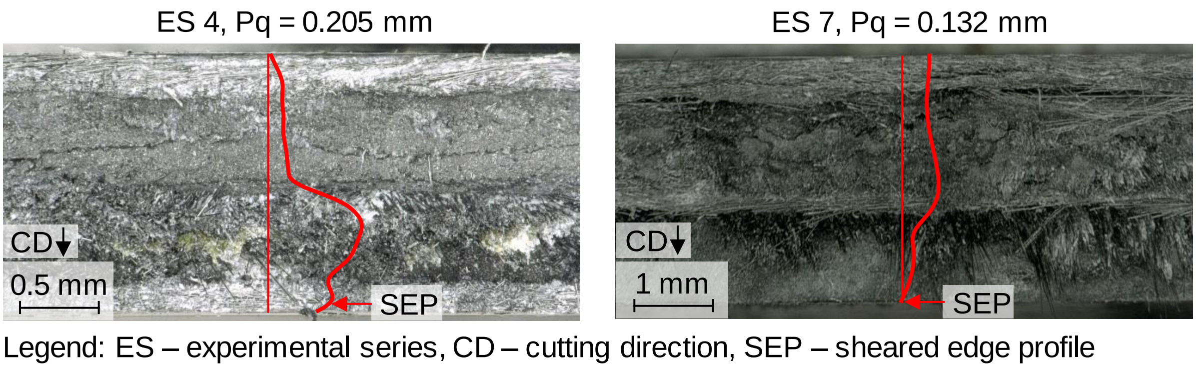


Figure 8: Variation of the sheared edge profile morphology due to different process parameter combinations.

Fraying is not a single mechanism affecting the sheared edge morphology. Depending on the parameter combination, the sheared edges may demonstrate different morphological features as exemplary demonstrated in Fig. 8. Both illustrated profiles have a vertical region in the upper half of the sheared edge. The straight area is followed by a convex region in specimens from the ES 4 where as the specimens from ES 7 demonstrate a concave region. The differences between these experimental series are laminate the architecture a, laminate thickness s, and stroke frequency f. Therefore, the morphological differences are caused by the laminate properties. Due to an integrative character of the parameter Pq, the quality of morphologically different sheared edge profiles can be compared. However, knowing only Pq values it is not possible to define whether the sheared edges have the same or different morphological features.

Finally, the sheared edges with the lowest mean Pq values (ER 8, 10, 11) are presented in Fig. 9. For each experimental run, three sheared edges with the lowest highest and median Pq values are shown.

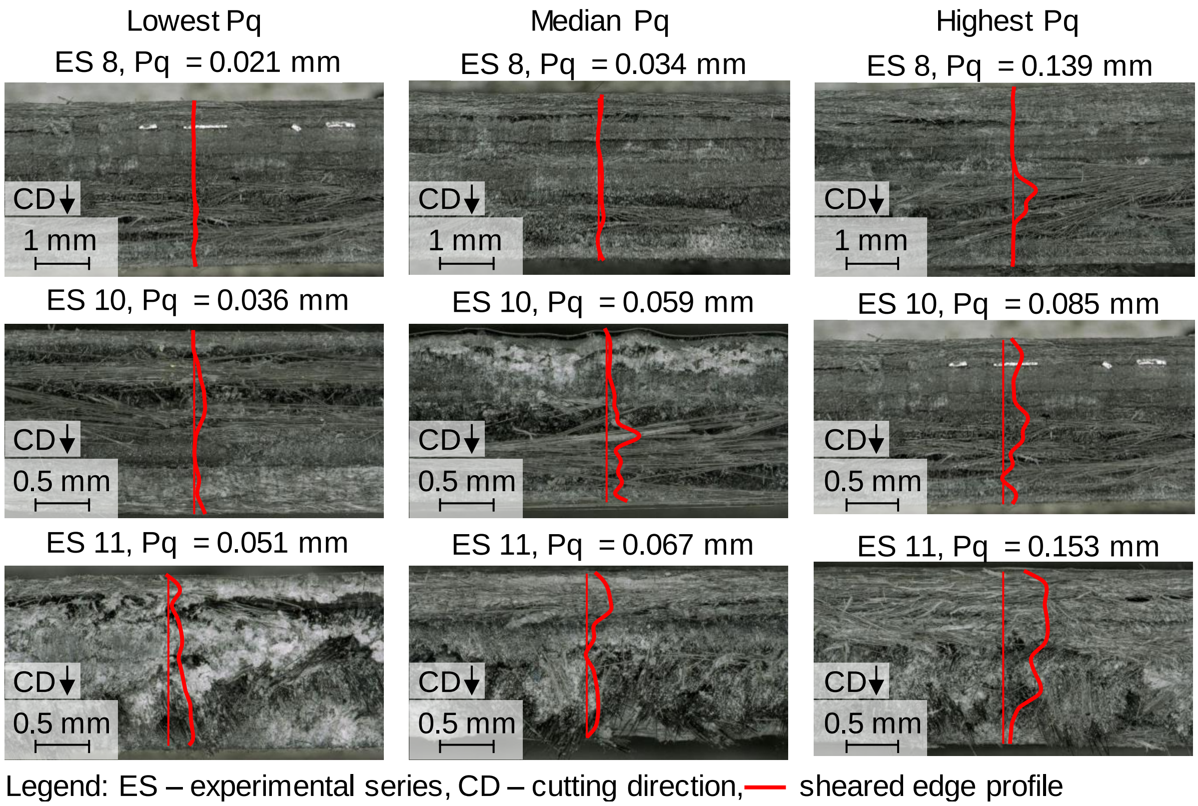


Figure 9: Sheared edges for the experimental runs with the lowest mean Pq values.

The lowest mean Pq values were achieved in ES 8. The sheared edges from ES 8 have straight profiles. Minor fraying of cutting line parallel fiber bundles may occur which increases Pq values. No signs of the matrix damage were observed. The second lowest mean Pq values were determined in ES 10. In comparison with ES 8, more fraying fibers with the parallel orientation to the cutting line are present. With regard to the process parameters only the laminate architecture a, laminate thickens s and stroke frequency f were different between the ES 8 and ES 10. A possible explanation for a more ruptured surface of the sheared edges from ES 10 is the biaxial laminate architecture a = BA. In biaxial laminates more plies had a parallel orientation to the cutting line, which resulted in more fraying. This goes along with the identified effect of the laminate architecture a, see Fig. 5. The specimens from ES 10 did not demonstrate any visible matrix damage in the sheared edge. The specimens from ES 11 had the third lowest mean Pq value. In contrast with the sheared edges from ES 8 and ES 10, the specimens from ES 11 had a matrix damage and some free fibers pointing in the direction of the punch movement. According to the identified parameter effects (see Fig. 5), an increase of the Pq values in ES11 can be associated with an increase of the punch cutting edge radius $r_e$ as compared with the ES 8 and ES 10. Rounded punch cutting edge reduces the stress concentrations during the trimming process, which would cause more deformation and consequently more matrix damage in the laminate. Qualitatively, this claim is supported by the pictures of the sheared edges from ES 11 with matrix damage in Fig. 9.

## 6 CONCLUSIONS

In this work an experimental investigation of CFRP trimming by means of shearing was performed. The effects of the trimming process parameters (clearance, blank holder pressure, cutting velocity, cutting edge radius, punch geometry, and punch coating) on the cutting resistance, delaminations, and sheared edge morphology were established and possible explanations of these effects were proposed. The findings of this study can be summarized as follows:

- **Cutting resistance $k_c$.** The parameter relative clearance $u_{rel}$ has the biggest effect magnitude followed by the parameter laminate thickness s. An increase of the relative clearance $u_{rel}$ and the laminate thickness s leads to a reduction of the cutting resistance $k_c$. Explanations for possible mechanisms of action with regard to the cutting resistance for all relevant process parameters was proposed.

- **Delamination**. No delaminations were determined by means of the conducted CT-analyses
- **Sheared edge morphology**. The quantitative characterization of the sheared edge morphology was realized by means of the parameter quadratic average of profile heights Pq. High variance of Pq values caused by fraying was observed for some experimental runs. The parameter relative clearance $u_{rel}$ has the highest influence on the mean Pq values. The parameters laminate architecture a, laminate thickness s, blank holder pressure $p_{bh}$ and cutting edge radius $r_e$ had slightly lower effect magnitudes as relative clearance $u_{rel}$. Lower mean Pq values were observed for thinner laminates with quasi-isotropic architecture trimmed at higher clearance with high blank holder pressure using punches with sharp cutting edge

The conducted analysis of the process parameter influences provides a basis for the understanding of the underlying material separation mechanisms in CFRP trimming. Based on the obtained knowledge with regard to the relative importance of the investigated process parameters further investigations are to be conducted. Therefore, in the future work a detailed validation of the identified correlations between the process parameters and the sheared edge quality will be performed.

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