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Experimental investigation of the hole accuracy, delamination, and cutting force in piercing of carbon fiber reinforced plastics

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Abstract

Legislative regulations limit allowable CO2 emissions from automotive vehicles. One possibility to reduce CO2 emissions is lightweight design using carbon fiber reinforced plastics (CFRP). However, high costs of CFRP components prevent them to be adapted for price sensitive and high volume applications in the automotive industry. CFRP components are manufactured near-net-shape. In order to fulfill geometric or functional requirements, they have to be trimmed or pierced in finish processing. In high volume production, shearing can be potentially implemented for a highly productive and cost efficient piercing and trimming of CFRP components. Up to now, there exists little technological knowledge on the applicability of shearing for CFRP finish processing. In order to address this knowledge gap, an experimental investigation of CFRP piercing with round cutting line was performed in this work. The effects of the process parameters like cutting clearance, blank holder pressure and cutting edge radius on the dimensional and shape accuracy of the pierced holes as well as the cutting forces were experimentally investigated and possible explanations for the observed phenomena formulated.

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Keywords: carbon fiber reinforced plastic; piercing; dimensional and form accuracy; cutting force.

1. Introduction

Regulations require a future reduction of CO2 emissions from automotive vehicles [1]. One of the possible ways to reduce CO2 emissions of automotive vehicles is lightweighting [2]. Hybrid designs combining the carbon fiber reinforced plastics (CFRP) and metals are considered a promising approach to realize the light-weight design [3]. However, high costs of CFRP components prevent them to be adapted for price sensitive and high volume applications in the automotive industry [4]. Therefore, novel manufacturing technologies enabling cost efficient manufacturing of CFRP components in high volume production are required.

CFRP components are manufactured near-net-shape [5]. However, in order to fulfill geometric or functional requirements, they have to be trimmed or pierced in finish processing [6]. CFRP finishing is conventionally performed by means of machining or abrasive waterjet cutting (AWJ) [7].

Shearing is a highly productive material separation technology that is highly cost efficient in high volume production [8]. In the automotive industry, shearing is used for trimming and piercing of sheet metal car body components. Therefore, shearing has a potential to be effectively used for a cost efficient finishing of CFRP components for high volume automotive applications. A review of the state of the art on shearing of fibrous composites with polymeric matrix is given in the following.

Chan et al. performed piercing experiments with a dual stage punch and analyzed the achieved accuracy of the pierced holes [9]. A polymer matrix laminate with a thickness $s = 3.2\,\text{mm}$ was used. The experiments were performed without blank holder. Piercing was shown to be technically possible. However, an intensive fraying in the pierce holes was observed.

Nakamura et al. investigated the influence of shearing process parameters, workpiece temperature, and punch geometry on the maximum cutting loads, delaminations, and sheared edge morphology in trimming of a CFRP laminate with an epoxy matrix [10]. The laminate thickness was $s = 1.2\,\text{mm}$. The blank holder pressure was set to $p_{ph} = 4\,\text{MPa}$. A reduction of the cutting forces was observed at higher workpiece temperatures. A V-shaped punch with a sharp cutting edge angle and the workpiece temperature $T_{wp} = 70\,°\text{C}$ were observed to reduce delaminations. No clear influence of the workpiece temperature and the punch geometry on the sheared edge morphology was observed. Using the same experimental set-up, Ogi et al.

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investigated the influence of the cutting clearance on the cutting force, delaminations, and the sheared edge morphology [11]. The experiments were performed at the workpiece temperature T_{wp} = 70 °C according to the results of Nakamura et al. It was observed that the maximum cutting force decreases from the clearance u = 0.01 mm to u = 0.04 mm by about 19 % and then remains nearly constant up to the clearance u = 0.1 mm. No clear effects on delaminations and the sheared edge morphology were observed from the experimental data. Finally, Ueshiba et al. investigated the influence of the geometry of a cylindrical punch with a V-grooved face and the workpiece temperature on the sheared edge morphology and delaminations [12]. A low, uncontrolled blank holder pressure was used. Break-out of the material from lower plies, uncut material protruding into the hole interior, and delaminations protruding l_d = 0.3 mm inside the workpiece were observed.

Tatsuno et al. implemented a production system for manufacturing of a variant-cross-section CFRP beam with a thermoplastic matrix using a servo press [13]. The workpiece contour was trimmed at room temperature by means of shearing. V-grooved punches were used for trimming. The blank holder pressure was about p_{bh} = 10 MPa. No influence of the cutting clearance u on the cutting force F_c was observed. On the basis of a qualitative assessment, no influence of the cutting velocity and clearance on the sheared edge morphology was observed.

Zal et al. investigated experimentally the influence of process parameters in piercing of multi-layer glass fiber reinforced laminates with thermoplastic polyvinyl chloride matrix on the cutting force F_c and the fracture angle of the sheared edge [14]. The varied process parameters were the relative cutting clearance u_{rel}, cutting velocity v_c, and workpiece temperature T_{wp}. Neither the clearance u_{rel} nor the cutting velocity v_c demonstrated any significant effects on the cutting force F_c. Smaller fracture angles of the sheared edge were observed at higher cutting velocity v_c and smaller clearance u_{rel}. Piercing of the laminates above the glass transition temperature led to a deterioration of the dimensional accuracy of the holes.

Formisano et al. investigated the cutting resistance k_s of glass fiber laminates with epoxy matrix in shearing tests according to ASTM D732-10 under the variation of the fiber orientation angle to the shearing direction [15]. The experiments at the orientation angle 90 correspond to the situation observed in shearing. The observed crack formation of on the punch and die side of the laminate demonstrates the material separation mechanism in shearing.

Shirobokov et al. experimentally investigated trimming of unidirectional CFRP with a thermoset matrix under variation of the fiber orientation to the cutting line [17]. 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.

Sheared edge morphology of CFRP specimens differs significantly from that of metals. Therefore, it cannot be described by means of the conventional sheared edge parameters. In order to address this problem, Shirobokov et al. developed integral characterization parameters and showed their applicability for a quantitative and unambiguous characterization of the sheared edges of CFRP specimens [17].

From the review above a lack of basic knowledge on the correlations between the shearing process parameters and the process characteristics like form and dimensional accuracy, sheared edge morphology, delaminations as well as the cutting force are identified. Furthermore, a physical explanation of these correlations with regard to the material separation mechanisms has not yet been given. Therefore, the aim of this work is the experimental investigation of the correlations between the process parameters of piercing process (clearance, blank holder pressure, cutting velocity, cutting edge radius, punch diameter, and punch coating) and the resulting form and dimensional accuracy as well as the cutting forces. Additionally, significant process parameters are to be identified and explanations for the observed effects formulated.

2. Experimental set-up

Piercing process parameters have to be systematically varied in experiments in order to understand how they affect the shearing process. A scheme of the piercing process including the process parameters varied in this study is shown in Fig. 1. Due to the lacking understanding of the piercing process parameters effects on CFRP separation in shearing, all process parameters that could be technically controlled within given experimental facilities were varied in this study.

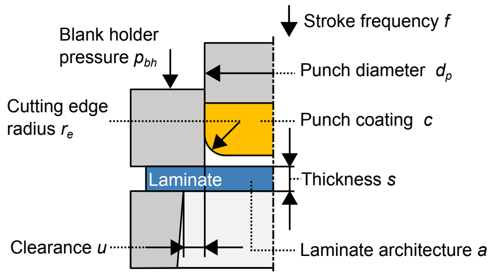

Fig. 1. Piercing tool scheme and experimental parameters.

Due to the novelty of the approach, appropriate levels of the process parameters in CFRP piercing are unknown. Therefore, the rationale for the selection of the process parameter levels was the magnification of the parameter effects. Assuming the effects linearity, larger variation magnitudes of the process parameters lead to larger parameter effects. By these means, the effects can be more reliably detected against the background of the process inherent variance. At the same time, the realizable parameter levels were limited by the experimental facilities. Therefore, the experimental set-up is to be regarded as a screening approach to delineate the process boundaries and identify the relative importance and the direction of the process parameter effects.

A CFRP with a thermoset matrix and a fiber volume fraction V_f = 0.6 was used. In order to assess the influence of the laminate architecture a on the piercing process, laminates with biaxial (BI) and quasi-isotropic (QI) architectures were used. The laminate thicknesses were s = {1.4; 2.8} mm. The punches and dies were made of cold working steel hardened to 60 HRC. Three punch diameters d_p = {5.0; 12.5; 19.92} mm were used. Variation of the die clearance was realized by changing the die diameters D_d. In sheet metal working the clearance between the punch and the die is conventionally set in terms of relative clearance $u_{rel} = u/s$. The reason for this is that the clearance is to be adjusted according to the sheet metal thickness for optimal results [18]. In this work the relative clearances $u_{rel} = \{0; 20\}$ % were used. Punches with sharp rounded cutting edges were used. The cutting edge radii were $r_e = \{0; 0.2\}$ mm. The cutting edge radius $r_e = 0.2$ mm was produced by means of brush polishing. The cutting edge radius of sharp punches and dies was controlled to be below $r_e < 5\,\mu$m. Machining tools for CFRP are coated by diamond like coatings to reduce wear [19]. In order to assess if a coating c affects the CFRP separation in piercing a diamond like carbon coating (*DLC*) from Cemecon AG, Germany was applied to some of the punches $c = \{None; DLC\}$ [−]. In contrast to the studies reviewed in the previous paragraphs, a significantly higher maximum blank holder pressure was used $p_{bh} = \{100; 400\}$ MPa. Gas springs were used to build up the blank holder pressure. Therefore, the pressure was not constant during the shearing process. The blank holder pressure build-up due to the compression of the gas springs is below 11 % of the corresponding maximum values. The highest level of blank holder pressure $p_{bh} = 400$ MPa corresponds to about 80 % of the through-thickness compression load which the laminates endure without observable damage. The experiments were performed on a servo-electric press AMADA SDE2025SE. Due to the press kinematic, the cutting velocity is a sinusoidal function with an amplitude 125 mm and cannot be held constant during the shearing process. Nevertheless, adjusting the punch stroke frequency of the press f it is possible to vary the punch velocity v_c. The cutting velocity at the contact of the punch with the laminate was $v_c = 0.013\,\mathrm{m\,s^{-1}}$ and $v_c = 0.45\,\mathrm{m\,s^{-1}}$ for the stroke frequencies $f = 1\,\mathrm{min^{-1}}$ and $f = 35\,\mathrm{min^{-1}}$, respectively.

Eight piercing process parameters had to be systematically varied in experiments. In order to identify the effects of these process parameters with a reasonable experimental effort a Plackett-Burman design of experiments was chosen. An advantage of a Plackett-Burman design is a relatively low number of experiments required to assess the parameters effects on the response variables [20]. A disadvantage is that the interactions between the parameters might be confounded. A Plackett-Burman design with two factor levels was chosen. In order to be able to consider three punch diameter levels d_p two experimental designs (ED) with the following pairs of punch diameter values $d_p = \{5.0; 12.5\}$ mm (ED1) and $d_p = \{5.0; 19.92\}$mm (ED2) were defined. The experimental designs ED1 and ED2 are shown in Table 1. Test series 1 to 6 for $d_p = 5.0$ mm are the same in ED1 and ED2 which results in a total of 18 experimental series. 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.

The process forces were measured by means of a piezoelectric force sensor Kistler 9091B. The force transmission from the press ram to the shearing tool occurred through the force sensor. Therefore, the reaction force signal of the tool, resisting the ram motion, could be measured. Therefore, in order to obtain the cutting force signal, two reaction force signals were required. The first signal was measured during the shearing process. It included the cutting force, the blank holder force, as well as the friction forces in the tool. As for the second signal, the laminate was prepared and positioned in the tool so that only compression of the laminate but no cutting occurred during the press stroke. Executing the stroke with the prepared laminate, the reaction force signal containing the blank holder force and the friction forces in the tool was measured. Then the cutting force signal was calculated as a difference between the first and the second measured reaction force signals. After defining the cutting force signal its maximum value $F_{c,max}$ was determined. The maximum cutting force $F_{c,max}$ for each test series was determined as an average of three repetitions. A more detailed description of the measurement procedure used to determine the maximum cutting force $F_{c,max}$ can be found in previous work [17]. The geometry of the pierced holes was measured by means of a coordinate measurement machine Zeis Calypso. For every laminate thickness, the measurements were conducted in the middle of the laminate along the thickenss dimension. A stylus with the diameter $d_s = 0.3$ mm was used. The geometrical values were averaged over five specimens. The emergence of delaminations was assessed by means of computer tomography measurements using Zeiss Metronom system.

Table 1. Experimental design.

No.	a [-]	s [mm]	u_{rel} [%]	p_{bh} [MPa]	r_e [mm]	f [min^{-1}]	c [-]	d_p [mm]
1	*BA*	1.4	0	100	0	1	*DLC*	5
2	*BA*	2.8	20	100	0.2	1	*DLC*	5
3	*BA*	2.8	20	400	0	35	*None*	5
4	*QI*	1.4	0	100	0.2	35	*None*	5
5	*QI*	1.4	20	400	0	35	*DLC*	5
6	*QI*	2.8	0	400	0.2	1	*None*	5
7 13	*BA*	1.4	0	400	0.2	35	*DLC*	12.5 19.92
8 14	*BA*	1.4	20	400	0.2	1	*None*	12.5 19.92
9 15	*BA*	2.8	0	100	0	35	*None*	12.5 19.92
10 16	*QI*	1.4	20	100	0	1	*None*	12.5 19.92
11 17	*QI*	2.8	0	400	0	1	*DLC*	12.5 19.92
12 18	*QI*	2.8	20	100	0.2	35	*DLC*	12.5 19.92

3. Experimental results

All 18 experimental series were successfully performed. As far piercing process was concerned, only the laminate strips were analyzed, whereas the slugs were discarded. In the following the identified correlations between the analyzed factors and response variables are described.

3.1. Dimensional accuracy

The dimensional accuracy of the pierced laminates was assessed by measuring the hole diameter profile and calculating the least square hole diameter D_h. In order to assess the dimensional accuracy for different punch diameters d_p deviations of the hole diameter from the punch diameter $\Delta D = d_p - D_h$ were calculated. The corresponding effect diagrams are shown in Fig. 2.

The effects of the process parameters on the diameter difference ΔD are consistent for both experimental designs ED1 and

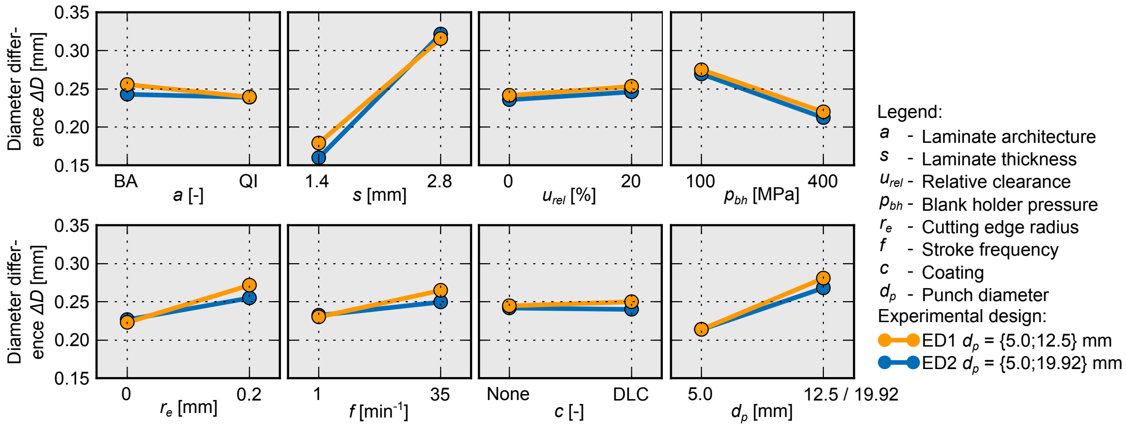

Fig. 2. Main effects of experimental parameters on diameter difference ΔD.

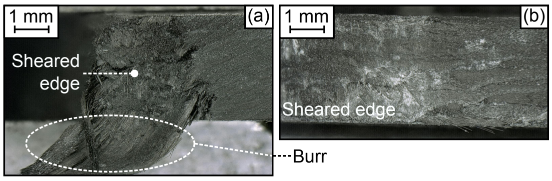

Fig. 3. Sheared edges of experimental series No. 5 (a) and No. 9 (b).

ED2. Laminate thickness s has the highest effect on the hole diameter. Thicker laminates have significantly higher diameter difference ΔD values. The punch diameter d_p has the second highest effect on the diameter difference ΔD. An increase of the punch diameter d_p results in higher absolute diameter difference ΔD values i.e. smaller holes. Conducting the significance analysis, the laminate thickness s and the punch diameter d_p were determined to have a statistically significant effect on the diameter difference ΔD. It has to be noted that there is only a small difference between the effects of the punch diameter d_p in both experimental designs ED1 and ED2. Therefore, an assumption can be made that the effect of punch diameter d_p on the diameter difference ΔD is valid up to a certain ratio between the punch diameter and the laminate thickness d_p/s. Although, not statistically significant in this study, the blank holder pressure p_{bh} and the cutting edge radius r_e have measurable effects on the diameter difference ΔD and the absolute values of the effects are close to that of the punch diameter d_p. Therefore, at higher number of experiments the effects of these parameters might turn to be statistically significant as well.

In experimental series No. 2, 3, 5, 12, and 18 the pierced holes had burrs. In order to illustrate this, a sheared edge with a burr from the experimental series No. 5 is shown in Fig. 3a. For a comparison, a sheared edge from experimental series No. 9 without burr in given in Fig. 3b. Common for all experimental series with burrs is the higher level of the relative clearance $u_{rel} = 20\,\%$. A mechanism of the burr formation can be inferred from Fig. 3a. Burrs emerge from the lower uncut plies of the laminate. Due to a high cutting clearance, there is enough space for the lower plies to be bent into the die cavity. As far as the absolute value of the cutting clearance u depends on the laminate thickness s, burr formation should be more intense at higher laminate thickness s. This is partially supported by the fact that in four out of five cases burrs occurred in laminates with thickness $s = 2.8$ mm.

3.2. Form accuracy

The form accuracy of the pierced holes was assessed by means of the roundness values ○. The effects of the process parameters on the roundness ○ demonstrate the same trends for both experimental designs ED1 and ED2, see Fig. 4. The parameter punch diameter d_p has the highest and the only statistically significant effect on the roundness ○ for both experimental designs ED1 and ED2. This explains the fact that for all other parameters the average values of the roundness ○ of the experimental design ED2 are higher than that of ED1 (all blue lines are higher than yellow lines in Fig. 4). A possible explanation of the punch diameter d_p influence on roundness ○ might be a slower change of the fiber orientation relative to the cutting line as observed along the cutting line. This leads to larger regions where the fibers are parallel to or cross the cutting line at acute angles which result in qualitatively rougher sheared edges [17]. The increasing size of the local rough regions causes an increase of the roundness ○.

3.3. Delaminations

No measurable delaminations were observed for all test series from computer tomographic analyses. This goes along with the data in literature where delaminations protruded less than 0.5 mm inside the laminate at a very low blank holder pressure $p_{bh} = 4$ MPa. In this work, the lowest level blank holder pressure was $p_{bh} = 100$ MPa which might have completely prevented the delaminations. Cross-section specimens are to be prepared in the future work in order to confirm this.

3.4. Cutting force

Due to geometrical reasons the maximum cutting force $F_{c,max}$ required to conduct a shearing process raises with the increasing length of the cutting line l_c and the workpiece thickness s. In order to rule out the geometrical effects on the max-

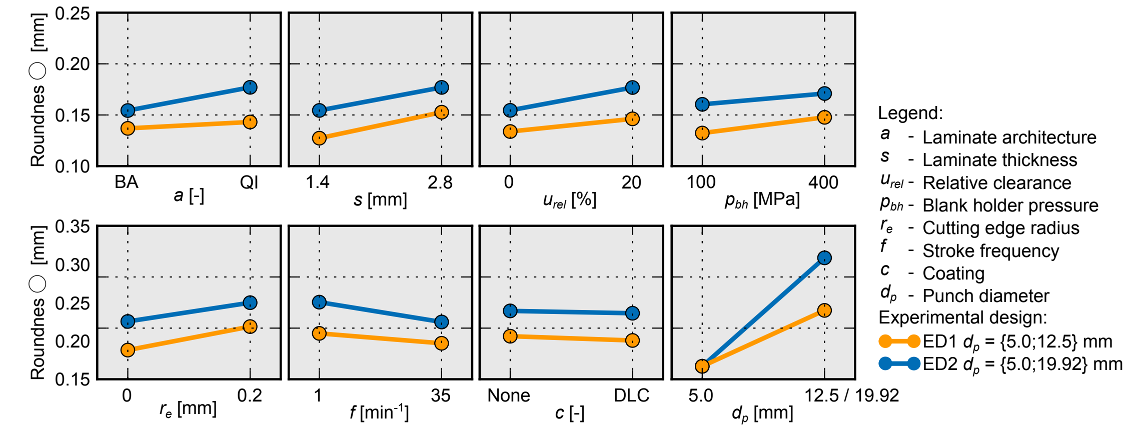

Fig. 4. Main effects of experimental parameters on roundness ◯.

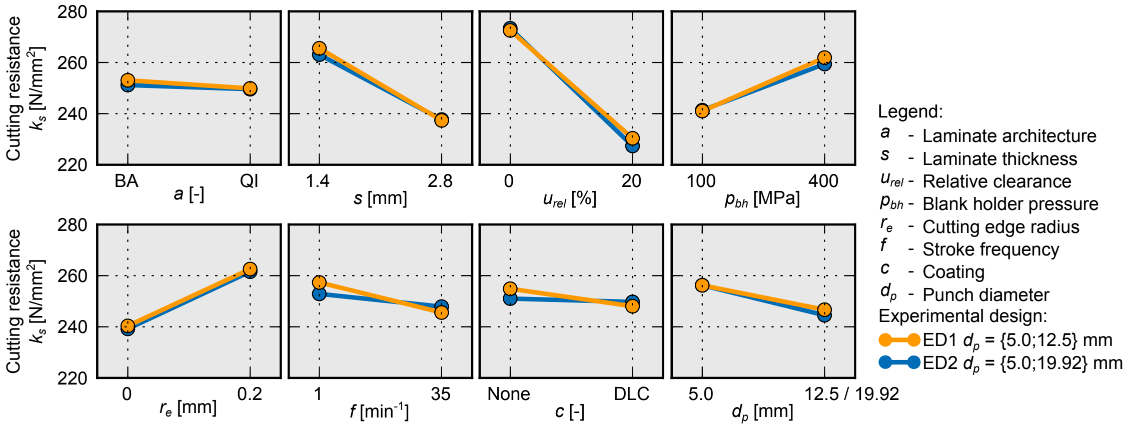

Fig. 5. Main effects of experimental parameters on cutting resistance k_s.

imum cutting force F_c, cutting resistance $k_s = F_{c,max}/(s \cdot l_c)$ is analyzed.

The effects of the process parameters on the cutting resistance k_s are presented in Fig. 5. The calculated effects of the process parameters on the cutting resistance k_s are consistent for both experimental designs ED1 and ED2. The parameters relative clearance u_{rel} and laminate thickness s have statistically significant effects on the cutting resistance k_s in both experimental designs ED1 and ED2. Furthermore, in the experimental design ED1 the effect of the cutting edge rounding r_e was determined as statistically significant as well.

The cutting resistance k_s decreases at higher relative clearance u_{rel}. This effect can be explained by a change of the stress state in the shearing zone. At higher clearance there is a bigger lever between the cutting force application point at the punch and the cutting edge of the die. As a result, higher bending stresses are induced. A stress increase due to bending promotes damage initiation in the laminate and leads to a lower cutting resistance k_s.

The cutting resistance k_s decreases at higher laminate thickness s. The effect of the laminate thickness s on the cutting resistance k_s can be also explained by an increase of the bending stresses induced in the laminate. However, it has to be considered that the absolute value of the clearance u was varied according to the laminate thickness s. This might have affected the magnitude of the laminate thickness s effect. Therefore, additional experiments with a constant clearance u under variation of the laminate thickness s are to be additionally conducted.

A higher cutting edge radius r_e leads to an increase of the cutting resistance k_s. Although, the absolute magnitudes of the corresponding effects in both experimental designs ED1 and ED2 are approximately the same only in ED1 the effect of the cutting edge radius r_e on the cutting resistance k_s was determined as statistically significant. The reason for this is a higher variance of the measured force signals in ED2. An increase of the cutting edge rounding leads to an increase of the contact area between the punch and the laminate. Process related shearing stresses in the laminate are induced through the contact area. Therefore, a higher cutting force is to be developed at a larger contact area in order to reach the stress level required for the material separation.

The effects of blank holder pressure p_{bh} and the punch diameter d_p on the cutting resistance k_s were not identified as statistically significant. However, the observed effects demonstrate the same trends and the magnitude in both experimental designs and appear to be plausible. A higher blank holder pressure p_{bh} leads to an increase of the cutting resistance k_s. As described before, the experimental method used for the determination of the cutting force compensated for the friction between the punch and the laminate. Therefore, a possible explanation of the effect of the blank holder pressure p_{bh} on the cutting resistance k_s is that the through thickness compression alters the stress state in the shearing zone and delays the damage initiation.

Finally, a reduction of the punch diameter d_p raises the cutting resistance k_s. The effect magnitude in both experimental designs is virtually the same. Therefore, a reduction of the punch diameter below some limiting value causes an increase of the cutting resistance k_s.

4. Discussion of the results

The laminate architecture a and punch coating c did not demonstrate any significant effects on the analyzed response variables. Consequently, piercing process parameters can be set independent of the laminate architecture a. Coating of the punch c does not have any significant influence on the analyzed output variables. Therefore, this parameter can be omitted in the analyses of CFRP separation mechanisms in shearing. In practice, this knowledge enables a wear protection of the tools without the need to account for the material separation mechanisms.

Only the punch diameter demonstrated a statistically significant effect on the roundness $\bigcirc$. A better form and dimensional accuracy of the pierced holes can be achieved using smaller die clearance u (to avoid burrs), higher blank holder pressure p_{bh}, and punches with sharp cutting edges $r_e = 0\,\text{mm}$. Furthermore, the higher blank holder pressure suppresses the delamination of the laminate.

The determined effects of the relative clearance u_{rel}, laminate thickness s, punch diameter d_p, and the cutting edge radius r_e on the cutting resistance k_s tally with the dependencies for metals (for a reference see e.g. [8]). Therefore, the general dependencies of the piercing process hold true independent on the highly anisotropic material properties of CFRP.

5. Conclusions

In this work the effects of piercing process parameters on the dimensional and form accuracy of the pierced holes, delaminations as well as the cutting resistance were experimentally investigated. The findings can be briefly summarized as:

- The diameter of pierced holes was always smaller than the punch diameter. Higher dimension deviations were observed for thicker laminates and bigger punch diameters. Higher blank holder pressure and sharp cutting edge improve the dimensional accuracy.
- Punch diameter had the highest influence on the form accuracy. Smaller punches resulted in higher form accuracy of the pierced holes. Other parameters demonstrated significantly lower effects.
- No delaminations in the pierced laminates were observed.
- Bigger clearance, larger laminate thickness, and lower cutting edge radius result in lower cutting resistance. The observed effects of the process parameters on the cutting resistance of CFRP laminates tally with that of metals.

In the future work, an assessment of the sheared edge quality of the pierced laminates according to the assessment scheme developed in the previous work [17] is to be performed. Additionally, CFRP trimming by means of shearing is to be investigated and compared with the results of this work. Accomplishing these tasks, it will be possible to fully characterize the technical capabilities of shearing for CFRP finish processing.

Acknowledgements

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