Materials Research Proceedings **25** (2023) 315-322 https://doi.org/10.21741/9781644902417-39

High speed impact cutting of continuous fiber reinforced thermoset plastics

Fabian Dietrich[1,a*], Matthias Nestler[2,b], Verena Kräusel[2,c], Matthias Kolbe[1,d]

[1] Westsächsische Hochschule Zwickau, Kornmarkt 1, 08056 Zwickau, Germany

[2]Fraunhofer Institut für Werkzeugmaschinen und Umformtechnik, Reichenhainer Straße 88, 09126 Chemnitz, Germany

[a]Fabian.Dietrich@fh-zwickau.de, [b] matthias.nestler@iwu.fraunhofer.de, [c]verena.kraeusel@iwu.fraunhofer.de, [d]Matthias.Kolbe@fh-zwickau.de

Keywords: Fiber Reinforced Plastic, Quality, High-Speed Impact Cutting

Abstract. Endless fiber-reinforced plastics are being used to an increasing extent as alternative materials for highly stressed or lightweight components instead of metallic materials. In order to achieve the geometric requirements, peripheral machining of the raw parts is necessary. Instead of the currently mainly used cutting processes, which are not suitable for clocked production, high-speed impact cutting (HSIC) was examined in the presented experiments. This technology is known as adiabatic cutting from the processing of metallic materials. Due to the high process energy which is released in a very short time resulting in high punch speed, the prevailing separation mechanism changes. Instead of bending the fibers due to the shear force the high-speed cutting experiments with a punch speed of 10 m/s lead to a brittle shearing of the glass fibers and a locally very limited heating and hence softening of the matrix material resulting in a clean surface of the cut specimen. The inter fiber breakage, meaning the separation between fibers and matrix called delamination, can be avoided or at least be sealed at the surface due to heat induced smearing of the matrix material. The resulting surface quality of the cutting edge is exceptionally good. However, the technically necessary cutting clearance leads to a jump in diameter within the cut surface.

Introduction

Even today a significant proportion of the energy required by humans is obtained by the use of fossil fuels. One problem of this approach is the limited availability of oil and gas, another is the environmental impact caused by the combustion of these fuels that leads to damage of the environment and reduction in human quality of life. As a result, in addition to revolutionizing drive systems and power generation, consistent lightweight construction is necessary to achieve the environmental goals that have been set. This concerns especially the area of transport, which is responsible for around 20 % of global CO_2 emissions [1]. Lightweight design is a key driver to reduce vehicles energy consumption and is often applied in the automotive industry [2]. Fiber-reinforced plastics have been used as a substitute for the classic metallic materials to a steadily increasing extent for several decades [3]. Application fields range from aviation up to shipbuilding and vehicle construction. Endless fiber-reinforced duromers (EFRP) are of particular importance here because they are suitable for the production of components with the same function but significantly lower mass in comparison to conventional materials due to their up to five times higher specific strength compared to steel [4]. In contrast to components made of metallic materials, for components made of EFRP near netshape manufacturing and subsequent machining of holes and edges is the typical approach to comply with the required geometric dimensions. However, conventional processes such as milling are poorly suited due to the high hardness of the reinforcing fibers and the heterogeneity and anisotropy of the composite [5]. The milling tool

Materials Research Proceedings **25** (2023) 315-322 https://doi.org/10.21741/9781644902417-39

experiences a high level of wear, which manifests itself in rounding of the cutting edges and in turn leads to damage to the workpiece which is being machined [6]. Alternative processes for producing the required dimensions are currently cut-off grinding, sawing, abrasive waterjet cutting and laser cutting. In addition to the respective process-specific advantages and disadvantages of these individual production methods, they all lack suitability for a clocked production process, since the entire contour of the component to be produced always has to be traversed in order to perform the separation process. An alternative to this is peripheral machining using shear cutting, in which one or even several components can be manufactured using only one press stroke. Shear cutting is widely used in the sheet metal processing industry [7] and it offers high cost-effectiveness [8]. Aiming for an improvement of the geometric accuracy of the cut surface and good surface quality, high speed impact cutting (HSIC) is a promising process variation [9]. In contrast to conventional shear cutting, this technology is characterized by the high speed (i. e. above 3 m/s) of the cutting tool (punch). This causes high and strongly localized strain rates and temperatures, leading to a nearly rectangular cut surface, a reduction of burr and a reduced rollover height for metallic materials [10]. The presented study aims to show the general feasibility of cutting EFRP with high cutting speed.

Experimental Methodology

Samples with a reinforcement made of glass fiber fabric (fiber alignment 0/90 °, fiber volume content φ_F = 55 %) with an epoxy resin matrix in thicknesses of 1, 2, 3 and 4 mm were used for the investigations. Three slugs with the same parameters were cut out from a flat workpiece with the dimensions of 175x50 mm^2 for each material thickness. The punch had a diameter of 20 mm and the cutting clearance was varied between 0.05 to 0.3 mm by using differently sized dies. After inserting the sample into the tool, the cutting punch was accelerated by the high-speed press Adiapress ADIAflex to a speed of 10 m/s. For this purpose, an energy of 1 kJ was applied. Fig. 1 shows the press on the left and the tool on the right side.

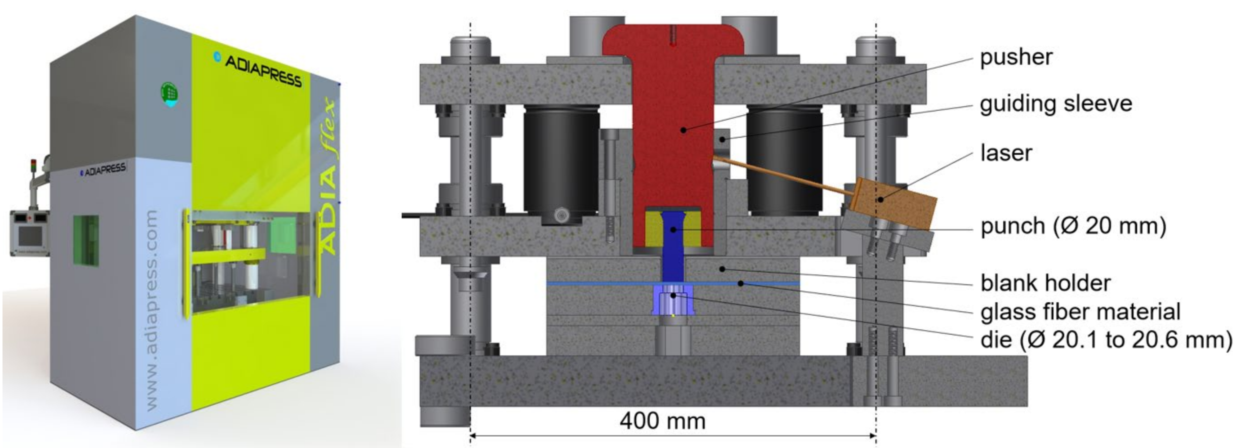

Fig. 1: Experimental setup for the HSIC tests: left) high-speed press ADIAflex; right) CAD drawing of the used tool

The cutting punch dipped into the sample for 2/3 of its thickness. The slug was then released from the workpiece by kinetic energy. After the HSIC tests the cut surfaces of the slugs and the workpiece were analyzed, as shown in Fig. 2. The percentage of breakage of the cut surface was measured manually using calipers at three positions distributed over the circumference of the slug and the perforated plate. This procedure allows fast and efficient determination of the general effects of changing parameters (DIN SPEC 25713-2017). On selected samples with typical appearance a conductive gold layer with a thickness of a few nanometers was applied using cathode sputtering (Cressington Sputter Coater 108auto). This is the only way to subsequently

Materials Research Proceedings **25** (2023) 315-322 https://doi.org/10.21741/9781644902417-39

examine the non-electrically conductive compound by using a scanning electron microscope (Karl-Zeiss EVO MA15). The used procedure is state of the art for nonconductive sample materials and a significant influence on the surface topology is not to be expected. A systematic, manually controlled scanning and exact surface measurement of typical or conspicuous separating edge areas was performed.

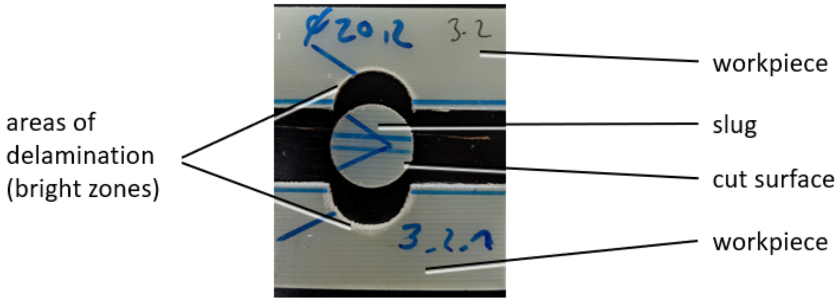

Fig. 2: Slug and divided workpiece prepared for measurements and visual inspection

Results and Discussion

Fig. 3 shows four slugs, cut by HSIC, with thicknesses of 1, 2, 3 and 4 mm (from left to right). The cutting clearance was 0.05 mm for the specimens with 1 mm and 2 mm thickness and 0.1 mm for the specimen with 3 mm and 4 mm thickness presented in the picture. With this variation of the absolute cutting clearance a relative cutting clearance between 2.5 % and 5 % was ensured, which is typically used in high-speed impact cutting of metallic materials.

Fig. 3: Cut slugs featuring thicknesses of 1, 2, 3 and 4 mm from left to right

Fig. 4 illustrates the dependency between the cutting clearance and the fraction of breakage for all examined material thicknesses comparing the workpiece (WP) and the slug (S). It is shown that the fraction of breakage increases with an increase of the cutting clearance. The slugs show a slightly higher (5-20 %) proportion of breakage, also referred as rough cut zone, than the workpiece. The minimum area of fracture occurs at a thickness of 1 mm and a cutting clearance of 0.05 mm. The relative deviation was due to the manual measuring, the heterogenous material structure and the resulting deviating cutting proportions rather high (up to 10 %). However, the influences of cutting clearance, high punch velocity and material thickness on the shear cutting process could still be identified in this study. It is clearly visible that smaller cutting clearances reduce the fraction of breakage for every tested specimen. However, the proportion of rough cut zone is not consistent through the increasing material thicknesses. Reasons for that could be different compositions of the bought EFRP material as well as the measurement inaccuracy.

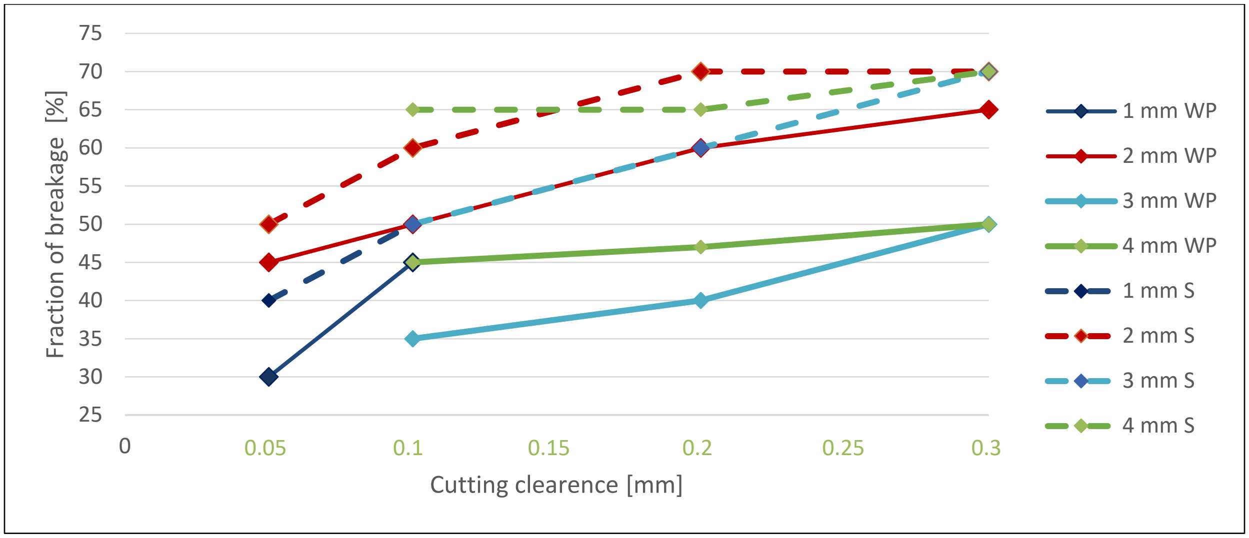

Fig. 4: Correlation between cutting clearance and fraction of breakage of workpiece (WP) and slug (S)

For one slug with a thickness of 4 mm and a cutting clearance of 0.3 mm, Fig. 5 shows the varying smooth and rough cut proportions. On the left side a photograph of the part is depicted. On the right side the result of a 3D measurement made with the scanning electron microscope is shown. Fig. 5 gives a better understanding on the resulting surface topology and shows that the proportions are irregular distributed over the perimeter which leads to a high scatter of the taken measurements. This could only be reduced by time consuming complete measurements of ever sample with the SEM for example.

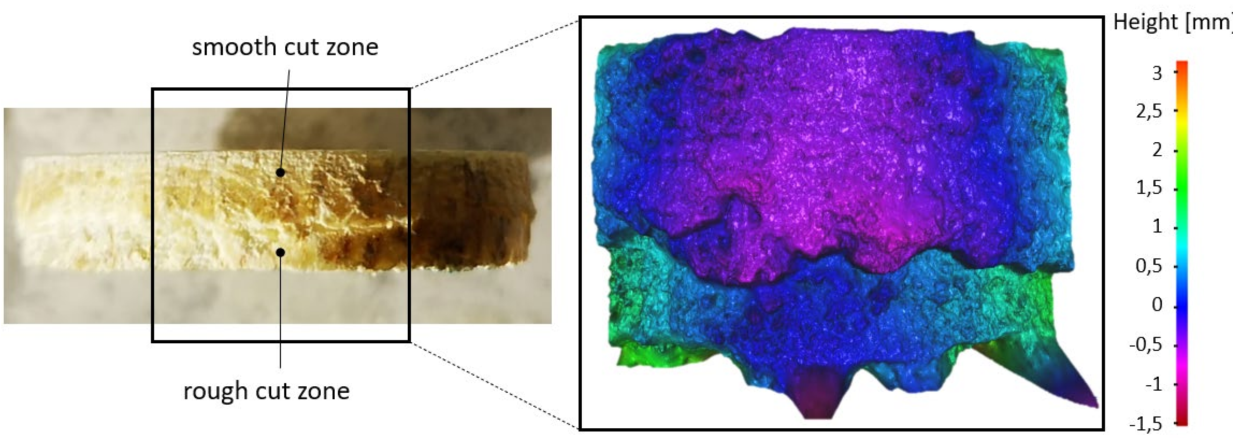

Fig. 5: Varying smooth and rough cut proportions on a slug, v_{Die} = 10 m/s, t = 4 mm, c = 0.3 mm

A more detailed analysis of the cut surface was performed by using the SEM for recording detailed images of the fracture surface, pictured in Fig. 6. In the area of the rough cut zone, numerous protruding fibers and fiber bundles can be seen in addition to an irregular surface topography, which is typical for shear cutting of EFRP (compare “punchside” in Fig. 6). The part of the workpiece facing the punch and the part of the slug facing away, both being classified as smooth cut zone, show an even and less rough surface. In this area, thermal damage to the matrix material can be recognized by a slight brown discoloration visually and by a significantly higher oxygen content measured by laser-induced plasma spectroscopy, indicating the temperature induced oxidation of the matrix material. This diffusion of oxygen into the matrix material has to be activated by heat according to [11]. The observed changes of the matrix material indicate heating above the glass transition temperature up to the temperature of thermal decomposition.

However, as it is already known from the adiabatic cutting of metallic materials, this damage is strongly localized [10]. This results in "blurring" of the matrix material in the direction of the slug ejection. As a result, the cutting edge consists exclusively of matrix material. Loose fiber ends or cracks cannot be seen in the smooth cut zone. This means that the material seals itself as a result of the heating during the shear cut, which significantly simplifies further processing of the component, such as painting. Traces resulting from the withdrawal of the stamp from the cutting zone cannot be seen, because the residual heat from the cutting process transferred into the poorly heat conductive composite material was not enough to keep the matrix material in a soft state until the punch withdrawal. This confirms the assumption of strong local limitation of the thermal influence.

The effect of matrix softening increases with increasing thickness of the workpiece. At t = 1 mm, only a very small thermal influence and unsealed surface with clearly visible fibers can be observed as shown in Fig. 7, while at t = 4 mm an extensive smooth-cut zone with closed surface can be seen (Fig. 6). This is caused by the energy necessary to cut the samples. While cutting thicker samples, a lot of kinetic energy from the punch is transformed into heat while cutting the slug. However, if thinner specimens are being processed only a small part of the provided energy is absorbed by the composite, which means that there is very little heat generated and no matrix softening takes place. Despite this, the high velocity of the punch still ensures a clean cut of the glass fibers, resulting in a good surface quality for the 1 mm specimen. It has to be noted nonetheless, that the matrix softening increases the smoothness of the cutting surface significantly.

Looking at the top surfaces of the samples white discoloration occur along the cutting edges. This suggests that the applied shear forces cause delamination due to fiber bending especially at high material thicknesses. Also, the transition from smooth cut surface to fracture surface is clearly marked by a step in the separation edge for thicknesses bigger 1 mm, where the diameter of the cut hole and the slug increases/decreases. This abrupt change in diameter, determined by the 3D measurement of a sample using SEM, is shown on the embedded diagram in Fig. 6. The cutting clearance for the sample pictured is 0.3 mm, which roughly corresponds to the change in radius visible in the diagram. This shows that the cutting clearance is too large and should be significantly smaller instead according to examination results of shear cutting metallic materials [12]. Since the cut begins at the punch and at the die side of the workpiece, the two cutting fronts are running almost parallel to each other at about the same distance as the set cutting clearance. When both separation zones in the material have reached the same level of the laminate consisting of matrix material (black, horizontal line in the diagram), a crack develops in almost horizontal direction through this matrix layer, which connects both separation fronts.

Materials Research Forum LLC
https://doi.org/10.21741/9781644902417-39

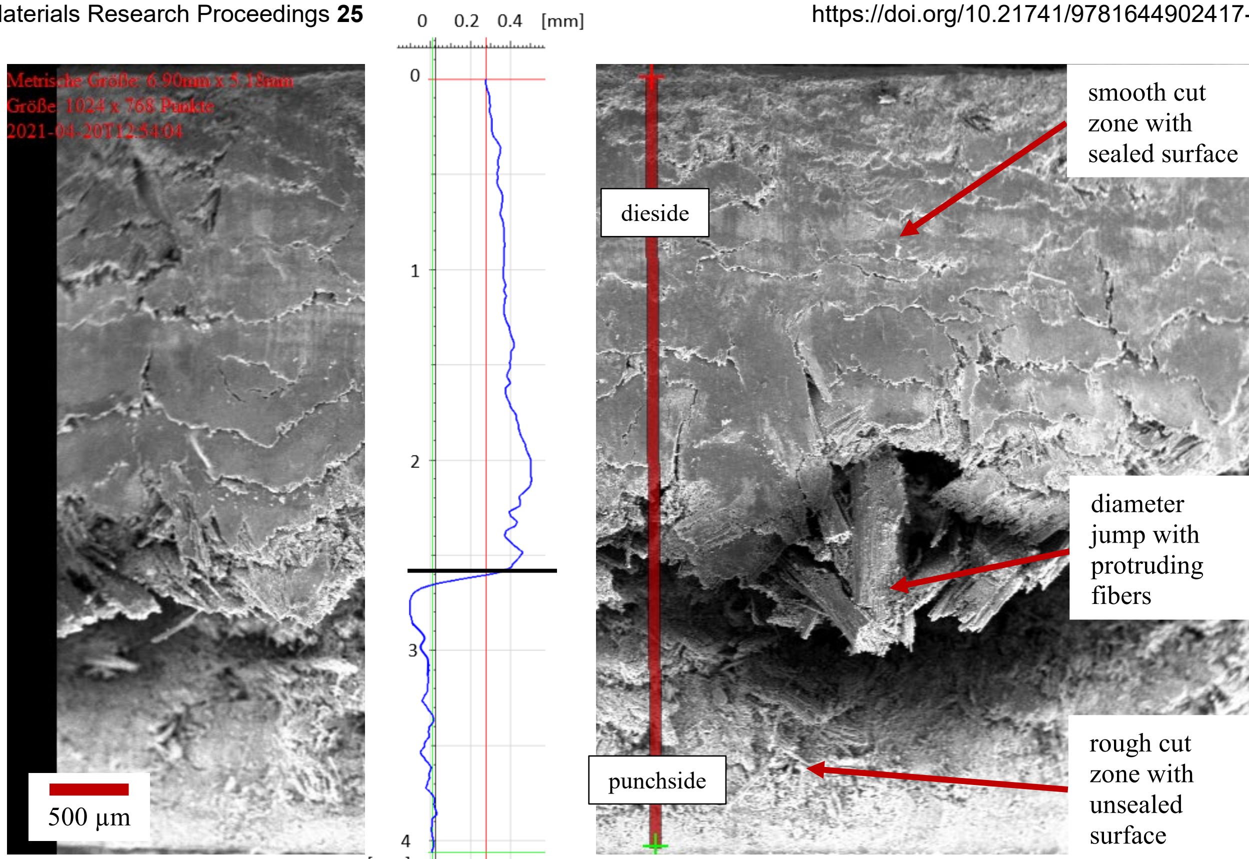

Fig. 6: Variance of the radius along the cut surface on a slug at v_{Die} = 10 m/s, t = 4 mm, c = 0.3 mm

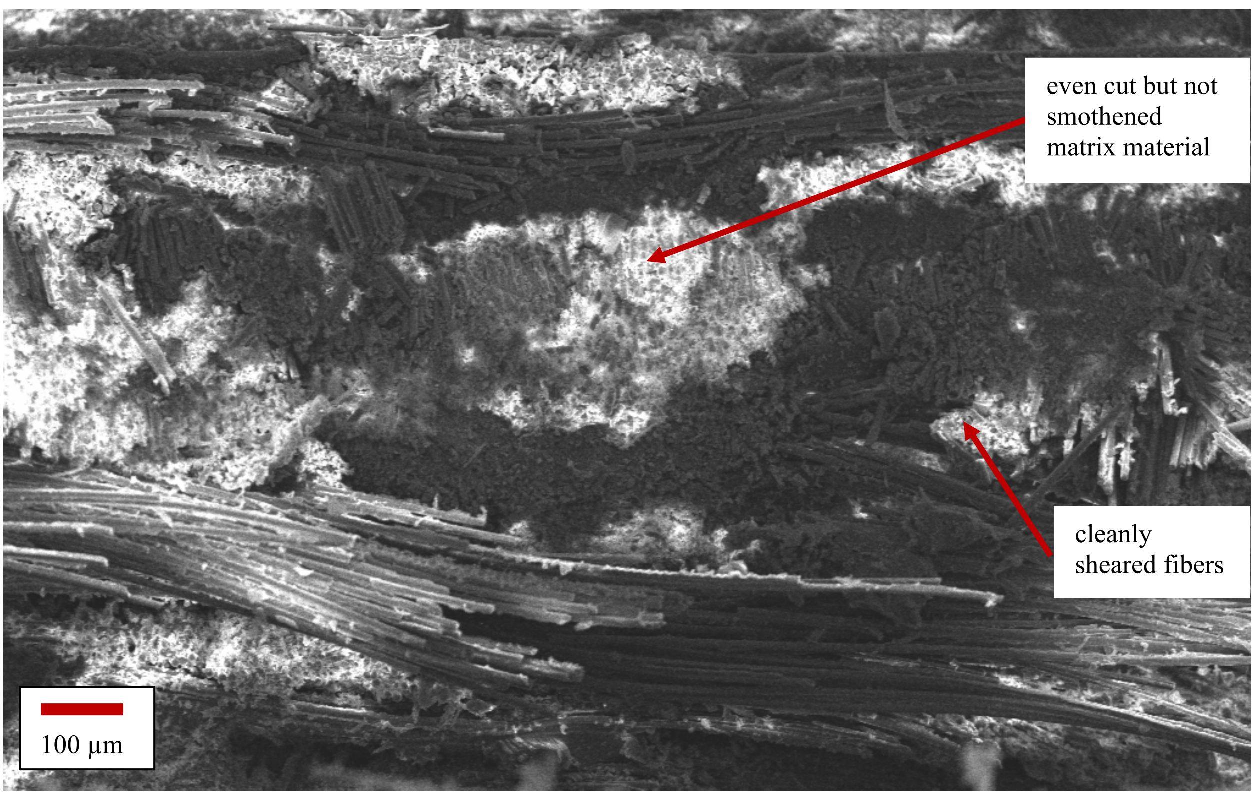

Fig. 7: Unsealed but even cut surface on the workpiece, v_{Die} = 10 m/s, t = 1 mm, c = 0.05 mm

Materials Research Proceedings **25** (2023) 315-322 https://doi.org/10.21741/9781644902417-39

The fracture surface on the die and on the punch side of the workpiece or slug respectively is characterized by fiber tear out and a rough surface, comparable to preliminary tests carried out with a conventional punch speed. Fig. 8 shows a 4 mm thick sample, analyzed in previous studies, for comparison. In contrast to the high-speed impact cutting this sample does not show any sealing effects in the smooth cut zone but pushed out, delaminated fibers at some places. Furthermore, there are loose matrix particles and a lot of protruding fibers in the rough cut zone. Also, severe delamination took place and on the resulted surface no finish could have been applied without extensive rework such as grinding.

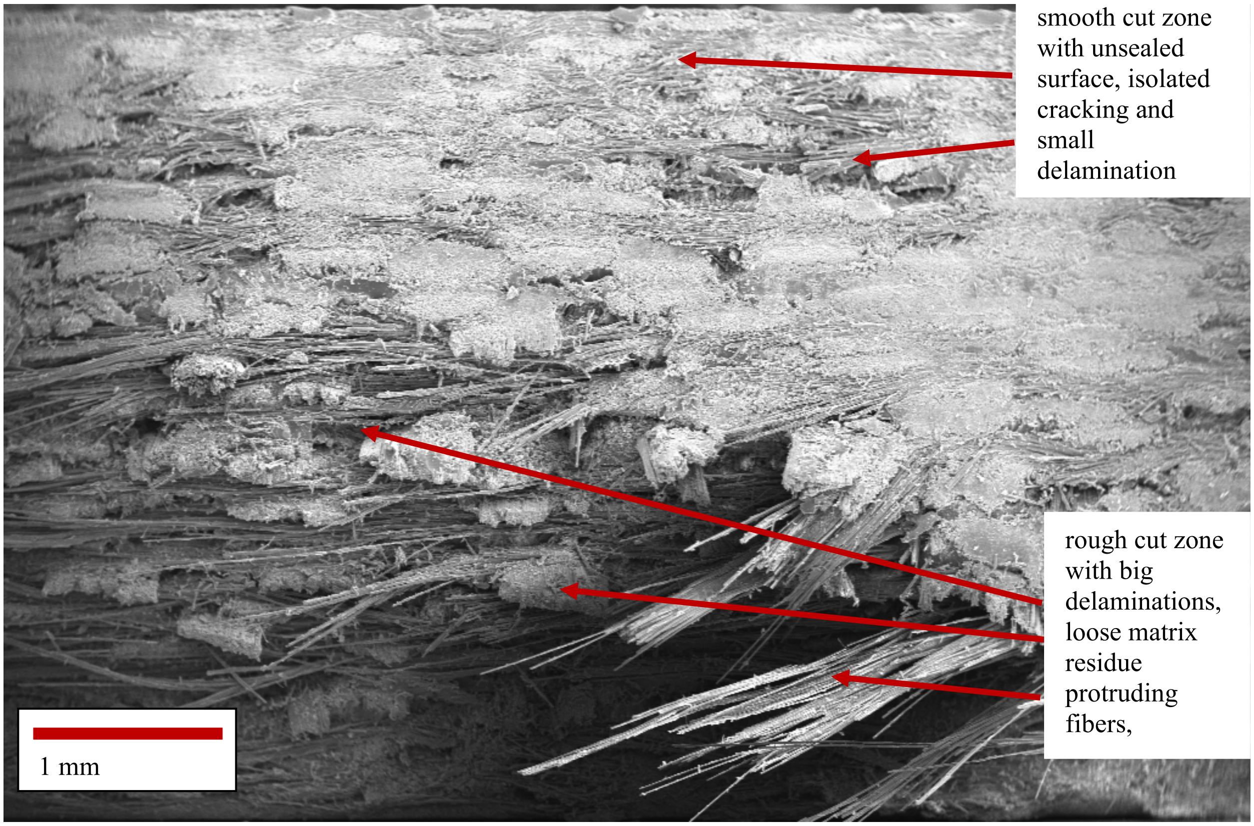

Fig. 8: Surface of a preliminary test specimen cut with low punch speed

Summary and outlook

The presented study shows that the high-speed impact cutting process, which is currently mainly used for cutting metallic materials, is fundamentally suitable for cutting components consisting of endless fiber-reinforced duromers (EFRP) even if the heterogenic material composition and the resulting crack formation properties are vastly different. The resulting cut surfaces show very little delamination in comparison to cutting tests at conventional punch speeds. The resulting finish of the edge is clean and uniform in the smooth cut areas, free of fibers and sealed by the matrix heated in the process. Moreover, thermal damage that is strongly localized takes place. However, depending on the thickness and the cutting clearance there is a jump in diameter and the fracture area shows numerous protruding fiber bundles and fiber tears. The resulting surface is still of better quality in regards of evenness, fiber protrusion and delamination than samples cut with a low velocity punch. Nonetheless further study is necessary in order to achieve a uniform, sealed cut surface over the whole thickness for all workpiece dimensions. This should include investigations of crack formation and propagation, the influence of different compositions of fibers and matrices as well as the relevance of every cutting parameter and their optimal value. The aimed goal should be a uniform temperature increase along the cutting surface to seal all fibers and voids which appear due to the occurring mechanical separation mechanism and the avoidance of the observed step formation for samples with higher thicknesses. The result would be a cut surface that requires no post-processing, is dimensionally accurate (± 0.1 mm) and can be painted immediately. Beneficial would also be the possibility to implement this process into clocked production for mass producing parts.

References

[1] Statista, Anteil der Verkehrsträger an den weltweiten CO2-Emissionen aus der Verbrennung fossiler Brennstoffe in den Jahren 2018 und 2019, BDL (2022). [https://de.statista.com/statistik/daten/studie/317683/umfrage/verkehrsttraeger-anteil-co2-emissionen-fossile-brennstoffe/] (accessed October 11, 2022).

[2] S. Rosenthal, F. Maaß, M. Kamaliev, H. Marlon, S. Gies, A. Erman Tekkaya, Lightweight, Automotive Components by Forming Technology, Automotive Innovation 3 (2020) 195-199. https://doi.org/10.1007/s42154-020-00103-3

[3] Carbon Fibers Technology – 9 Dimensional Assessment, Frost & Sullivan, (2014) 24

[4] F. Henning, E. Moeller, Handbuch Leichtbau, Methoden, Werkstoffe, Fertigung., 1. Aufl., Carl Hanser Verlag München, 2011. https://doi.org/10.3139/9783446428911.001

[5] M. Kreutzbruck, P. Fey, W. Essig, M. Rahammer, S. Joas, T. Erb, I. Solodov, Faserkunststoffverbunde – Hochleistungswerkstoffe in Leichtbausystemen als eine neue Herausforderung für die ZfP, ZfP-Zeitung 151 (2016) 31-39.

[6] Y. He, H. Qing, S. Zhang, D. Wang, S. Zhu, The cutting force and defect analysis in milling of carbon fiber-reinforced polymer (CFRP) composite, The International Journal of Advanced Manufacturing Technology 93 (2017) 1829-1842. https://doi.org/10.1007/s00170-017-0613-6

[7] F. Sergey. Golovashchenko, N. Wang, Q. Le, Trimming and sheared edge stretchability of automotive 6xxx aluminum alloys, Journal of Materials Processing Technology 264 (2019) 64–75. https://doi.org/10.1016/j.jmatprotec.2018.09.001

[8] I. Paetzold, F. Dittmann, M. Feistle, R. Golle, P. Haefele, H. Hoffmann, W. Volk, Influence of shear cutting parameters on the fatigue behavior of a dual-phase steel. IOP Conf. Series: Journal of Physics: Conf. Series 896 (2017) 012107. https://doi.org/10.1088/1742-6596/896/1/012107

[9] S. Winter, M. Nestler, E. Galiev, F. Hartmann, V. Psyk, V. Kräusel, M. Dix, Adiabatic Blanking: Influence of Clearance, Impact Energy, and Velocity on the Blanked Surface, Journal of Manufacturing and Materials Processing 5 Nr. 2 (2021) 35. https://doi.org/10.3390/jmmp5020035

[10] F. Schmitz, S. Winter, T. Clausmeyer, M.F.-X. Wagner, A. Erman Tekkaya, Adiabatic blanking of advanced high-strength steels, CIRP Annals 69 Nr. 1 (2020) 269–272. https://doi.org/10.1016/j.cirp.2020.03.007

[11] S. Moll, Untersuchung der Auswirkungen einer thermisch-oxidativen Beanspruchung auf das Emissionsverhalten von ABS und PP und der Korrelation mit dem Alterungsgrad, Friedrich-Alexander-Universität Erlangen-Nürnberg (2017) 18.

[12] P. Sachnik, Methodik für gratfreie Schnittflächen beim Scherschneiden, TU München (2016) 16.