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Online-monitoring for abrasive waterjet cutting of CFRP via acoustic emission: Evaluation of machining parameters and work piece quality due to burst analysis

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Abstract

This paper deals with an additional option of online-monitoring for abrasive waterjet cutting processes. In the presented studies the carbon fibre reinforced polymer M21/T800S was machined under variation of different machining parameters, which are the machining pressure, the amount of abrasive and the feed speed. In a series of experiments linear cuts were monitored by measuring structure-borne sounds caused by the machining process. For the evaluation of the acoustic emission signals a burst analysis was applied using the acoustic emission sensor iMPact XS of the company iNDtact. In the investigations the count of bursts and the energy of the bursts are correlated with the machining process or rather the cutting quality. The results show that the machining parameters affect the acoustic emission signals significantly in a characteristic way. In conclusion the emitted bursts allow an evaluation of the cutting quality during the machining process.

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Keywords: waterjet cutting ; acoustic emission ; CFRP ; burst analysis ; quality evaluation ; M21/T800S

1. Introduction

The usage of lightweight materials, especially of carbon fibre reinforced polymers (CFRP), has significantly gained in importance in the past decades. Particularly the automobile and aerospace industry benefit from the advantages of these materials. Regarding the diverse industry sectors, the requested quality requirements are strongly varying leading to differing machining processes for finishing near-net-shape CFRP structures. For instance, in the automotive industry there are already production lines using waterjet cutting [1], whereas in aerospace, machining with defined cutting edge is the predominantly preferred production process. Therefore, contour milling and the preparation of rivet joints due to drilling are some of the most commonly used machining operations. By default, the quality assessment is always done after the completion of a work piece. The disadvantage of this evaluation procedure is, that the influence of machining parameters can be numbered exclusively subsequent, as well as tool wear and degradation processes like delamination.

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One method for online detection of degradations and process monitoring respectively is the acoustic emission (AE) analysis. If a work piece is mechanically stressed or receives a variation of the actually applied loads, this causes measurable solid borne sounds. These sounds may be generated for example by inter- and intralaminar cracks or by delamination at the top layers of a composite. By means of an intelligent evaluation of these transient signals, also known as burst analysis, distinctive acoustic characteristics can be correlated with machining parameters and delamination processes. For this purpose a classification of phenomenon specific burst events is carried out, establishing correlations between machining operations and resulting work piece quality.

Machining process control by acoustic emission is used in a wide field of applications, especially for online-monitoring in the manufacturing technology. In literature there are various investigations concerning this topic. Thus, this principle is used for categorization of tool wear in turning processes [2,3] or for in-situ online evaluation of grinding processes [4]. Therefore, the emitted structure-borne sounds give information about the actual conditions in the machining process. For example, the impact of a grinding plate on the workpiece can be identified exactly. Additionally, abrasive waterjet cutting is another scope of application some authors have studied, as well as the machining of CFRP. Hloch [5,6] and Momber [7] have used piezoelectric acoustic emission sensors for investigating the effects of different machining parameters at cutting metal plates with abrasive waterjet. Their researches discuss the relation between input-factors like the amount of abrasive and the cutting results or the detected acoustic emission signals. Rabani et al. [8] addressed their work at acoustic emission analyses of waterjet cutting as well, but focused more on the energy of the emitted signals. The results showed, that the amount of abrasive and the machining pressure influences strongly the energy content of the emitted acoustic waves. The performed experiments where evaluated mainly by the use of the fast fourier transformation. Alberdi [9] carried out a study about the process parameters for abrasive waterjet cutting of CFRP. He correlated the machining parameters, the type of work piece material and the machining quality. Based on his experiments he tried to establish optimal machining parameters for good cutting quality. However, Crivelli [10] used the acoustic emission technique for detection of fibre cracking and delamination in CFRP. In his studies it is evident, that various degradation phenomena in CFRP can be characterized by specific frequencies of the emitted acoustic waves.

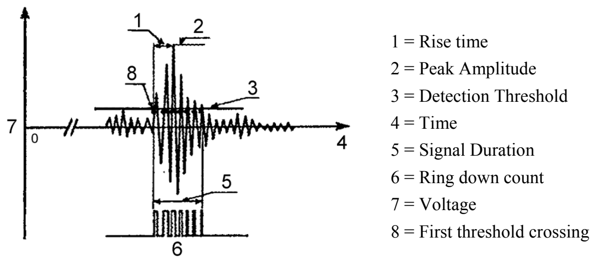


Fig. 1. Characteristics of a burst signal. [11]

In this study an additional analysing method is presented, to rate machining processes with acoustic emission characteristics as simple as possible. The investigations have been carried out for abrasive waterjet cutting of CFRP using the evaluation of transient signals. Transient signals can also be specified as burst events, which are superimposing a basic signal temporary. In Fig. 1 the specific characteristics of a burst signal are listed. Particularly important for the detection of burst signals is the threshold voltage (3 = Detection Threshold), which has to be determined by the standard deviation of the random noise of the basic signal. A burst event can be identified, if the threshold voltage is exceeded for the first time (8 = First threshold crossing). The burst event ends, if the voltage signals falls below the threshold voltage for a defined duration of time again (down time). To evaluate the machining process in this work, two different parameters are considered. On the one hand the total number of burst events during the machining process and on the other hand the energies of the burst events during the duration of one burst (5 = Signal duration). The energy is given in the unit V^2s to avoid the necessity of voltage rectification and the calculation of an effective value. In general burst events can be detected with common piezoelectric sensors. So, in preliminary investigations piezoelectric diaphragms with a diameter of 20 mm have been compared with the acoustic emission sensor iMPact XS of the company iNDTact.

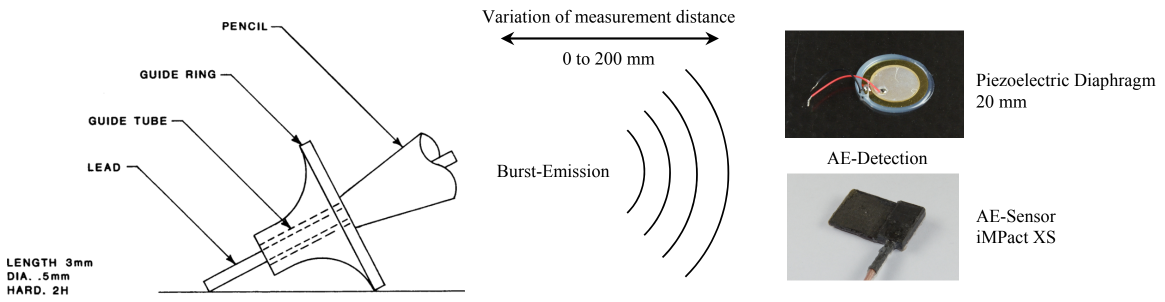


Fig. 2. The Hsu-Nielsen shoe and a pencil source [12] have been used to analyse the influence of the measurement distance between acoustic emission sensors and the acoustic source with regard to the sensor response (cumulative count of bursts, energy per burst).

To determine the reproducibility of the acoustic emission sensor response of the used sensors, the Hsu-Nielsen test has been carried out. In this test procedure the lead of a pencil source has to be broken under defined conditions using the Hsu-Nielsen shoe, which is shown on the left of Fig. 2. The mechanical vibrations are transmitted to the affixed sensors by a CFRP plate of M21/T800S. The fracture of the lead characteristically causes burst events, which were detected and evaluated. Beside the verification of the suitability of both sensors for acoustic emission detection, the influence of the measuring distance to the acoustic source has been considered as well. The results are shown in Fig. 3.

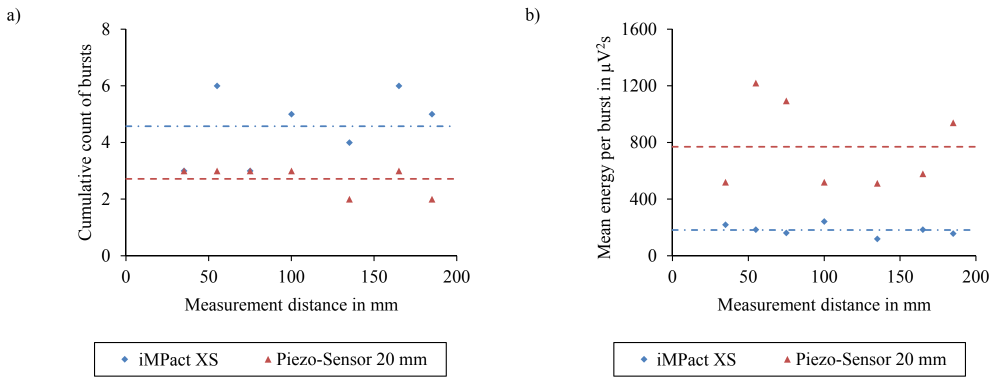


Fig. 3. Comparison of two different acoustic emission sensors with respect to different distances between the sensor and the Hsu-Nielsen source. M21/T800S autoclaved: (a) Cumulative count of bursts (b) Mean energy per burst.

In both of the diagrams the piezoelectric diaphragm is compared with the acoustic emission sensor iMPact XS with regard to the measuring distance. Whereas Fig. 3a shows the total amount of bursts of the lead break Fig. 3b demonstrates the average energy per burst in $\mu V^2 s$. There are several points in which the sensors differ from each other. The piezoelectric diaphragm generally shows a less number of burst events but at the same time a higher energy per burst is detected. Furthermore, the measuring distance has no significant influence on the measurement results in the investigated area. In addition, regarding to the energy per burst, the lower standard deviation of the sensor iMPact XS is conspicuous. The burst events detected by the piezoelectric diaphragm show a longer signal duration (cf. Fig. 1) whereby the energy per burst rises likewise. In turn the piezoelectric diaphragm has a lower resolution power in the detection respectively the separation of burst events.

2. Experimental setup

By reason of the characteristics of the sensors as described before, the piezoelectric diaphragm has been excluded for the following investigations. At abrasive waterjet cutting a high frequency of burst events has to be expected, for which the resolution power of the piezoelectric diaphragm will not be sufficient. Hence, in the following chapters there will be described the specifications of the material M21/T800S and the sensor iMPact XS only, as well as the measurement configuration.

2.1. Materials and acoustic emission sensors

For the manufacturing process of the CFRP plates the UD-Prepreg M21/T800S of the company Hexcel has been used. The individual plies have a weight per unit area of 268 g/m² and 196 g/m² respectively, each leading to a resin content of 35 % by weight. The CFRP specimens have a quasi-isotropic structure and a symmetrical stacking sequence with 24 plies ($[-45, 90, 45, 0]_{3s}$). The laminates were fabricated in two different ways. The prepreg with a weight unit area of 196 g/m² was cured by means of an autoclave processes, whereas the other type of prepreg was used in a heatpressing process. Thus, the two types of specimens differ mainly in porosity and the material thickness (4.6 mm and 6.0 mm). In general, the sensor iMPact XS has a frequency range from 1 mHz up to 1 MHz. However, the measurable frequency band is limited to a maximum of 500 kHz due to the used pre-amplifier. The sensors accuracy is ±5 % with a reference sensitivity of > 1200 pC/N. To fix the sensor reversibly on the CFRP specimens the hot glue technicoll 9310 is used.

2.2. Measurement configuration and machining parameters

The main goal of the investigations is to correlate the machining parameters with the burst events and the achieved cutting quality. For this purpose linear cuts have been made into CFRP plates. The experimental setup is shown in Fig. 4. The used waterjet cutting machine is a self-constructed system, which provides a maximum pressure of 4000 bar at a nozzle diameter of 0.28 mm. For abrasive waterjet cutting, garnet sand can be dosed in with 100 g/min to 700 g/min. The acoustic emission sensor has been sealed up with a plastic envelope additionally, to avoid direct water contact. The pressure generation is done in a safety distance of 25 mm to finally start the cutting process at constant conditions regarding to machining pressure and abrasive supply.

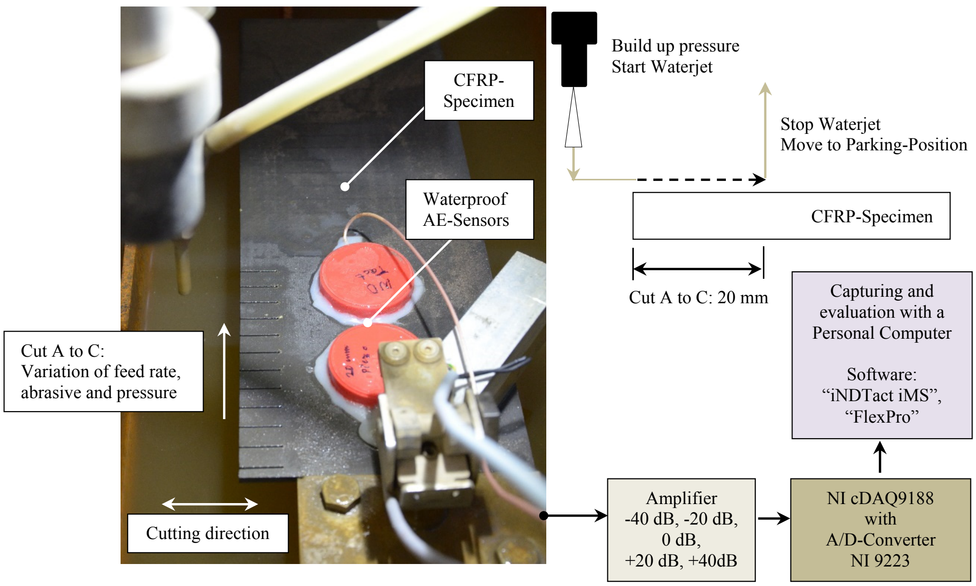


Fig. 4. Experimental setup for the AE-investigations of linear waterjet cuts in CFRP with different machining parameters.

Beginning at the edge of the work piece, the cutting distance was 20 mm. The measurement signals have been captured by a pre-amplifier and an A/D-Converter (cf. Fig. 4), whereas the evaluation was done with the software iNDTact iMS and Flexpro of the company Weisang. The machining parameters and the measurement settings are listed in Table 1. As it can be seen in the table, the adjusted frequency range of the amplifier was from 16 kHz to 2.1 MHz at an amplification of 0 dB. Within the experimental series the feed speed, the pressure and the amount of abrasive was varied in accordance with Table 1.

Table 1. Machining parameters and measurement settings for the series of experiments with the two types of material.

Measurement Settings iNDTact iMS	Measurement Settings Pre-Amplifier	Cut	Cutting Parameters Feed rate mm/min	 Pressure bar	 Abrasive g/min
Highpass 9. Order Freq. 20 kHz	Gain 0 dB Freq low 16 kHz Freq high 2,1 MHz	A1	600	2400	90
		A2	1400		
		A3	2200		
		A4	3000		
		A5	600	3600	
		B1	600	2400	283
		B2	1400		
		B3	2200		
		B4	3000		
		B5	2200	3600	
		B6	3000		
		C1	2200	2400	530

3. Results and discussion

3.1. Burst analysis for online-monitoring

In Fig. 5 the relevant parameters of an exemplary acoustic emission measurement are plotted. It can be seen, that the cutting distance of 20 mm was machined with a feed speed of 600 mm/min corresponding to an absolute machining duration of 2 s. The different plots show the separate burst events and corresponding burst energies as a function of the machining time. Fig. 5a demonstrates, that the burst events happen at frequencies up to 180 kHz taking into account that each point in the diagram is equivalent to one burst. The curve progression of the cumulative characteristics shows typical trends at different points of time in the cutting process. First of all there is a short rise of the cumulative count of bursts (cf. Fig. 5a), which marks the beginning of the waterjet cut at the edge of the work piece. For both of the cumulative plots the following part of the curve can be separated in two sections then. In the first section there are less burst events, although they are of a higher energy level. As soon as the cutting conditions become constant, a linear progression of the cumulative values is apparent, which marks the second section of the machining process.

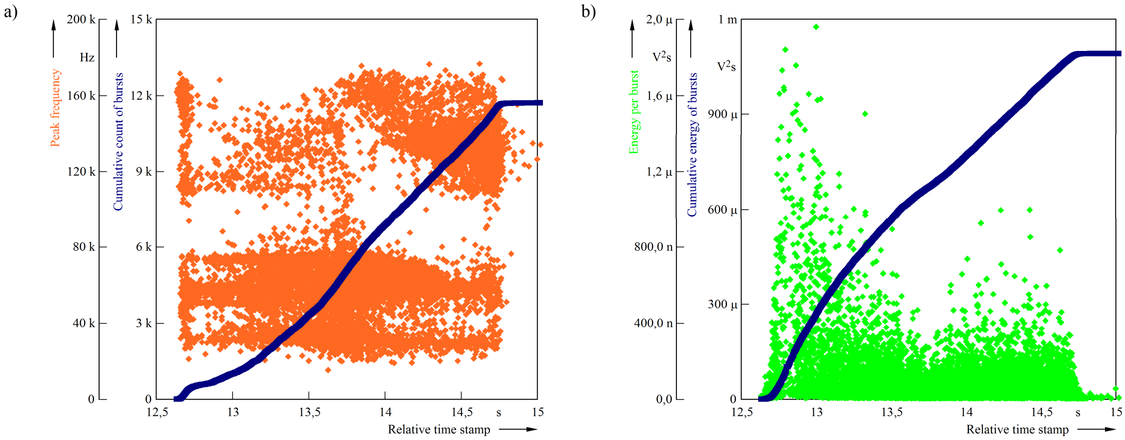


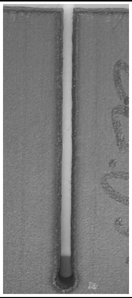
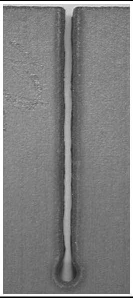
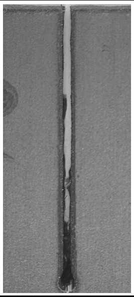
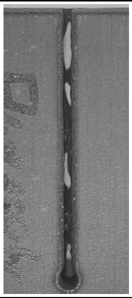
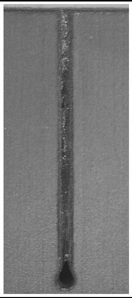
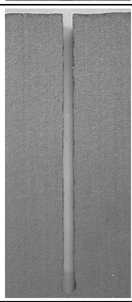
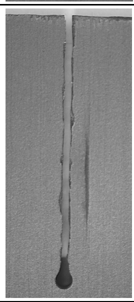
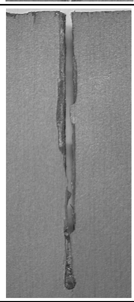
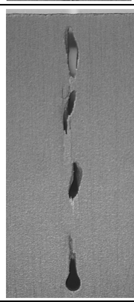
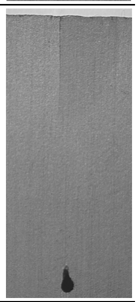
Fig. 5. AE-measurement of a linear waterjet cut in CFRP: (a) Peak frequency and cumulative count of bursts (b) Energy per burst and cumulative energy of bursts. (Machining parameters: v_f = 600 mm/min ; p = 2400 bar ; abrasive = 90 g/min ; material = M21/T800S autoclaved)

For most of the following considerations all burst events will be summed up to the cumulative count of bursts. This approach is applied for the evaluation of the energy of the bursts as well, generating the cumulative energy of bursts as a second characteristic value. Thereby, the resulting intention is to rate the cutting processes as simple as possible allowing to use this monitoring method directly in practical applications.

3.2. Quality ranking

To evaluate the waterjet cutting quality in CFRP using varying machining parameters, the cuts 1 to 12 respectively A1 to C1 were sorted with regard to different aspects. Therefore, the main characteristics have been the quality of the machined edge of the work piece, the reached cutting depth during the cutting process and if necessary CFRP specific degradations like delamination and spalling. Table 2 exemplarily shows the quality assessment of some cuts of a series of linear waterjet cuts in M21/T800S (cured due to heatpressing) in which a quality ranking of Qr1 stands for a good cutting quality and Qr12 demonstrates the worst cutting result. In the next chapter the correlations between machining parameters, cutting quality and acoustic emission characteristics will be discussed in detail, whereby especially in Fig. 6 the previous described quality ranking is applied.

Table 2. Quality ranking of a waterjet cutting series in CFRP. (Material = M21/T800S heatpressed)

Quality ranking	Qr1 (B1)	Qr3 (C1)	Qr6 (B6)	Qr7(B3)	Qr12(A4)
Entry Side					
Exit Side					

3.3. Process characteristics: Count of bursts and energy per cutting volume

In Fig. 6 the detected cumulative count of bursts and the cumulative energy is plotted as a function of the Qr-level of the waterjet cuts. Following the characteristic value of the cutting volume, which is used in machining processes with defined edge, in the diagrams the energy is given as the energy per theoretical cutting volume in V^2s/mm^3. For both types of material (autoclaved: Fig. 6a ; heatpressed: Fig. 6b) the cumulative count of bursts decreases exponentially with a bad quality ranking. In contrast to that the emitted energy per cutting volume develops exactly oppositional. Comparing the absolute values of the cumulative bursts, the autoclaved material only reaches about half of the detected burst events of the heatpressed material. However, this allows no clear conclusion about the manufacturing process, as it is caused mainly by the higher material thickness of the heatpressed CFRP specimen. With respect to the energy one can observe that waterjet cuts with a bad quality ranking are of a higher energy level. The reasons for this are shown in Fig. 7, which compares the burst development for low and high feed rates.

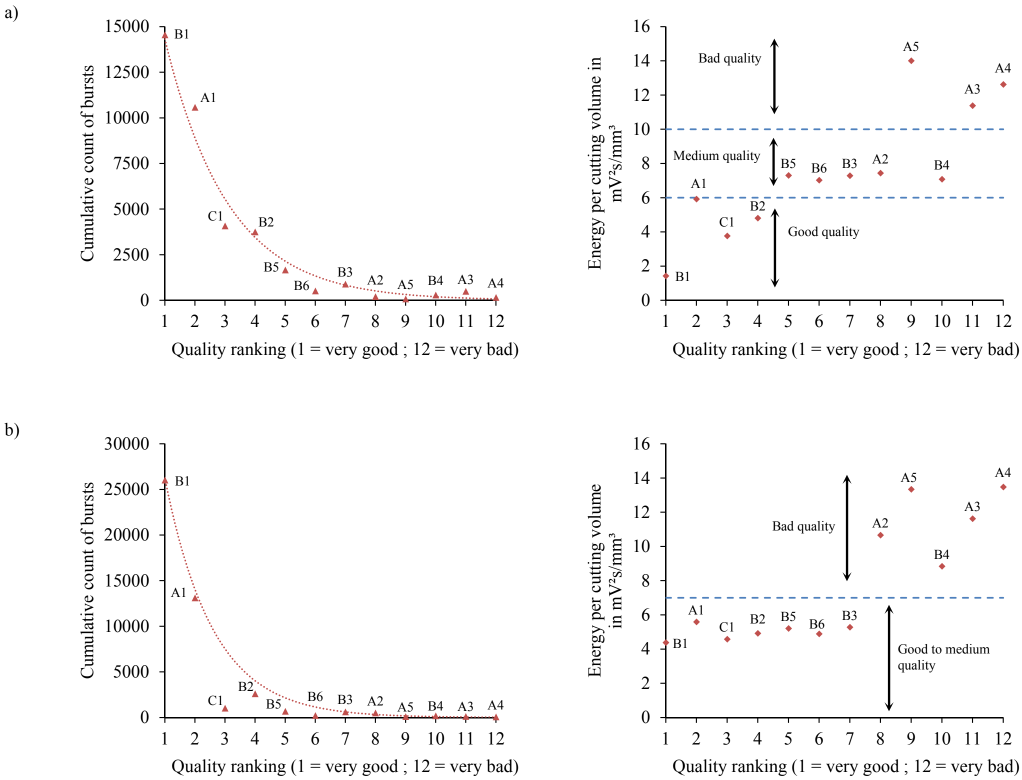


Fig. 6. Classification of the waterjet-cuts considering the quantity of bursts and the energy per cutting volume.
(a) M21/T800S autoclaved (b) M21/T800S heatpressed

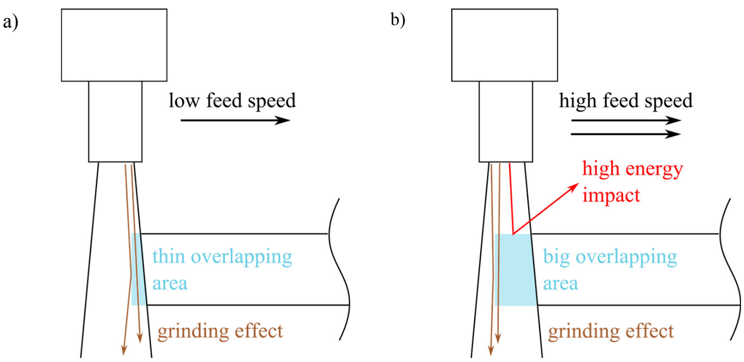


Fig. 7. Influence of the feed speed on the emitted energy of AE-signals during abrasive waterjet cutting.
(a) Low feed speed (b) High feed speed

Equivalent to the machining with defined edge (feed rate per tooth) low feed rates at waterjet cutting also cause a small overlapping area for chip removal. In this case the waterjet cutting process is similar to a grinding process making the sand grains producing a very high amount of bursts with a low energy level. In contrast, a high feed rate effects a big overlapping area. Thus, the emitted burst events consist of low energy level bursts from the grinding effect and high energy level bursts which arise from the frontal impact of the garnet sand on the specimen material. Overall it can be assumed that this effect is intensified by a higher burst duration because of the likewise higher basic level of the energy, which finally causes an increased energy per burst or rather energy per cutting volume. In Fig. 8 the relationship is shown in detail. The plots demonstrate the energy per cutting volume and the cumulative count of bursts as a function of the feed speed at constant machining pressure. For all experiments and corresponding diagrams the amount of abrasive has been varied.

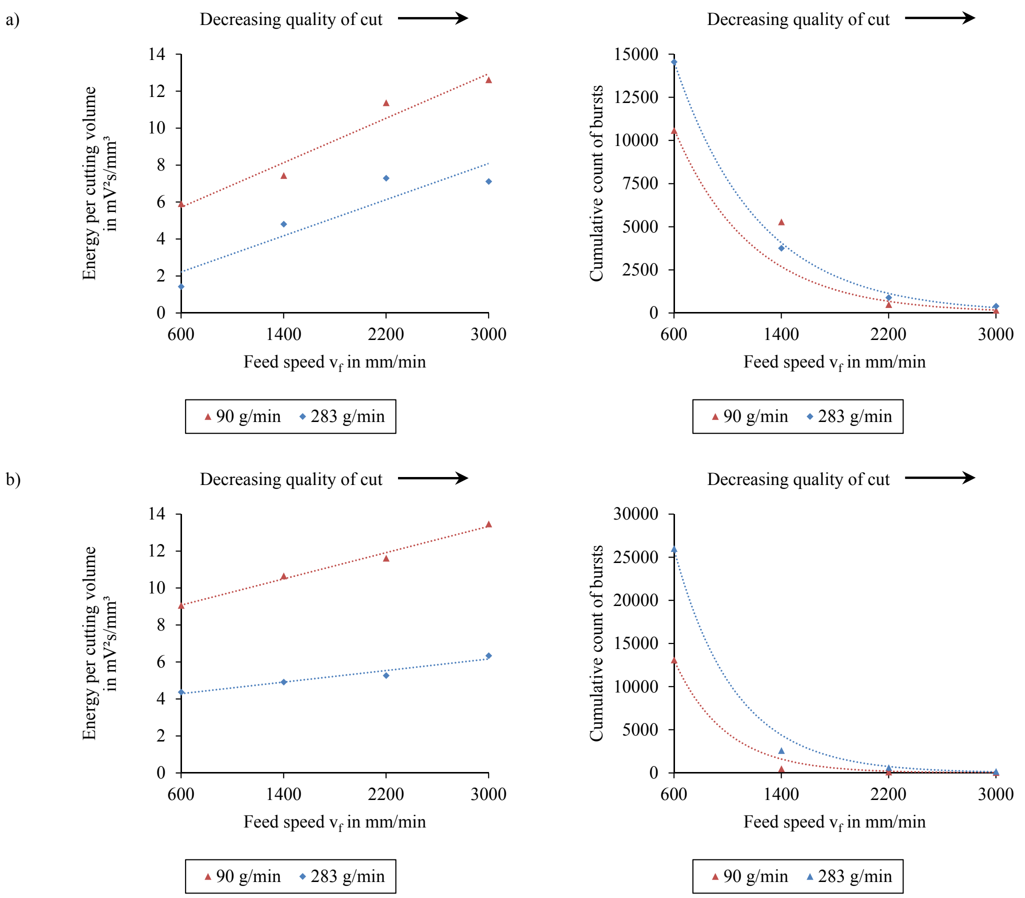


Fig. 8. Influence of the amount of abrasive on AE-signals during abrasive waterjet cutting of CFRP (p = 2400 bar).
(a) M21/T800S autoclaved (b) M21/T800S heatpressed

Regarding the energy, there is a linear proportional increase of the energy per cutting volume with enhancing feed speed. In contrast, the cumulative count of bursts is exponentially decreasing. As well as shown in Fig. 7, the cutting quality decreases with higher feed rates, and as expected, at 283 g/min of abrasive there is a higher amount of burst events. However, although there are more sand grains grinding at the machined edge per time, the absolute values of the energy are lower. So the higher quantity of abrasive is counteracting the negative effects of an increasing feed rate. Comparing the autoclaved material and the heatpressed material in Fig. 8, it is evident that the heatpressed material causes higher energy values at low feed rates. It has to be assumed, that the higher porosity additionally leads to interlaminar damages, which are emitting high energetic burst signals. Furthermore, a higher material thickness rises the burst duration, increasing the energy per burst as well. In Fig. 9 the linear waterjet cuts are compared at constant pressure (2400 bar) and constant feed rate (2200 m/min) but varying quantity of abrasive. Overall, the tendency in Fig. 8 could be confirmed by an additional increase of the amount of abrasive from 283 g/min to 530 g/min. It can be concluded that higher amounts of abrasive improve the cutting quality as long as the remaining machining parameters are constant. With regard to the acoustic emission characteristics the cumulative count of bursts is rising repeatedly whereas the energy per cutting volume is decreasing. In consequence the cuts B1, A1 and C1 (cf. Fig. 6) are of the best possible Qr-level.

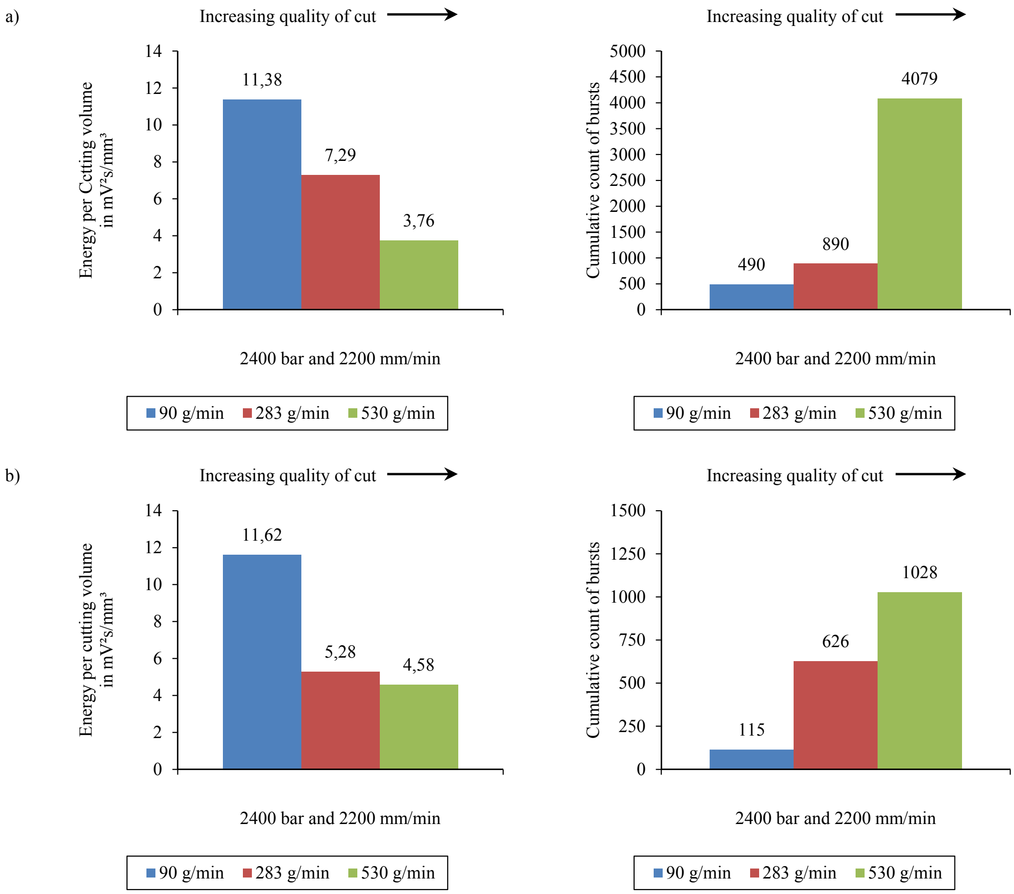


Fig. 9. Influence of the amount of abrasive on AE-signals during abrasive waterjet cutting of CFRP (p = 2400 bar ; v_f = 2200 mm/min).
(a) M21/T800S autoclaved (b) M21/T800S heatpressed

4. Conclusions

The presented investigation about the online monitoring of CFRP waterjet cutting via acoustic emission leads to several conclusions. In general it can be said, that the simple consideration of the cumulative count of bursts and the energy per cutting volume is suitable to detect changes of machining parameters in the machining process. Since the machining parameters have a systematical influence on the machining quality of CFRP, the cumulative characteristic values allow a quality evaluation for linear water jet cuts in CFRP as well. However, by the use of the presented method it is not possible to identify the effects of single burst events and to connect them with CFRP specific degradations like delamination. To achieve this, the signals have to be analysed specifically with regard to the frequency domain. The characteristic connections between the machining parameters and the machining quality or the burst characteristics found in this work are summed up in Table 3.

Table 3. Summary of correlations between machining parameters, AE-characteristics and quality ranking for waterjet cutting of CFRP.

Cutting Parameters			Results		
Pressure	Feed rate	Abrasive	∑ Bursts	Energy per cutting volume	Quality ranking
↑	const.	const.	-	-	↑
const.	↑	const.	↓	↑	↓
const.	const.	↑	↑	↓	↑

The influence of the machining parameters on the machining process is pronounced in varying degrees. At constant pressure and feed speed, in particular a higher amount of abrasive has a positive effect on the quality of the machined edge. A higher feed speed impairs the cutting quality, whereas it is possible to counteract this effect with an increase of the machining pressure (cf. B5 und B6 in Fig. 6). Although the correlation between machining pressure and cutting quality is clearly identifiable, an explicit relation to the burst characteristics was not apparent in the course of the experimental series. In contrast, the feed speed and the amount of abrasive correlates significantly with the emitted structural born sounds. The next step will be to transfer the measurement principle to machining processes with defined edge and to identify single damage mechanisms in CFRP online using clustering algorithms.

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References

[1] Steve Rommel, Raphael Geiger, Ralph Schneider, Michael Baumann, Peter Brandstetter, Michael Held, Stefan Albrecht, Otto Creutzenberg, Clemens Dasenbrock. Leichtbau in Mobilität und Fertigung. *e-mobil*, 2012.
[2] Schehl D, *Werkzeugüberwachung mit Acoustic-Emission beim Drehen, Fräsen und Bohren*.
[3] Barry J, Byrne G, Lennon D. Observations on chip formation and acoustic emission in machining Ti–6Al–4V alloy. *International Journal of Machine Tools and Manufacture*, 2001, 41, 1055–1070.
[4] Webster J, Dong W, Lindsay R. Raw Acoustic Emission Signal Analysis of Grinding Process. *CIRP Annals - Manufacturing Technology*, 1996, 45, 335–340.
[5] Hreha P, Hloch S. Potential use of vibration for metrology and detection of surface topography created by abrasive waterjet. *IJSURFSE*, 2013, 7, 135.
[6] Peržel V, Hreha P, Hloch S, Tozan H, Valíček J. Vibration emission as a potential source of information for abrasive waterjet quality process control. *Int J Adv Manuf Technol*, 2012, 61, 285–294.
[7] Momber A, Mohan R, Kovacevic R. On-line analysis of hydro-abrasive erosion of pre-cracked materials by acoustic emission. *Theoretical and Applied Fracture Mechanics*, 1999, 31, 1–17.
[8] Rabani A, Marinescu I, Axinte D. Acoustic emission energy transfer rate. *International Journal of Machine Tools and Manufacture*, 2012, 61, 80–89.
[9] Alberdi A, Suárez A, Artaza T, Escobar-Palafox G, Ridgway K. Composite Cutting with Abrasive Water Jet. *Procedia Engineering*, 2013, 63, 421–429.
[10] Crivelli D, Guagliano M, Eaton M, Pearson M, Al-Jumaili S, Holford K, Pullin R. Localisation and identification of fatigue matrix cracking and delamination in a carbon fibre panel by acoustic emission. *Composites Part B: Engineering*, 2015, 74, 1–12.
[11] Zerstörungsfreie Prüfung – Terminologie – Teil 9: Begriffe der Schallemissionsprüfung, DIN EN 1330-9.
[12] American National Standard. Standard Guide for Determining the Reproducibility of Acoustic Emission Sensor Response, E 976 - 99.