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New Measurement Processes to Define the Quality of Machined Fibre Reinforced Polymers

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Abstract

This paper deals with two possibilities, which enable the investigation of the machining quality of parts made of fibre reinforced polymers. Finishing operations like milling or drilling are necessary in actual production processes. Such operations mostly cause damages like fraying, delamination or splintering at the machining surface. The one dimensional maximum method and the three dimensional damage analysis are two tools, which allow a reliable comparison between different experiments with, for example, varied process parameters. Therefore the one dimensional maximum method (1D-MM) only needs a calliper or microscope with measuring feature and can be accomplished in nearly every environment. The three dimensional damage analysis (3D-DA) requires high end measuring equipment but provides more information. Both procedures distinguish the occurring damages in fraying, delamination and splintering, what enables the optimized enhancement of the process. Such measurement methods are the necessary basis for every development or investigation in this field and should be understood as an approach for standardization.

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1. Introduction

Fibre reinforced polymers (FRP) are more and more used in different industrial branches like the transportation, the sport or the medicine industries. The variety of different compositions consisting of fibre and bedding matrix to a composite and the following variety of characteristics is one of the biggest advantages of this material class. On

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the one hand, this variety allows the definition of an appropriate composite with partially very specific behaviour optimised for a usage. On the other hand, the grade of complexity in the production process for this material class is getting higher with every new composite.

The finishing, like the drilling of holes or the milling of grooves, is a very common process step in the production of FRP parts. Due to the construction of these materials, consisting of the matrix system and the fibre material, the cutting is very demanding. The problem is the fact that it is necessary to machine at least two different materials with different characteristics simultaneously. For example, the young's modulus of a common epoxy resin system (=matrix) is around 3 GPa [1] and the value for a common industrial fibre (toray T300) is 230 GPa [2]. That is a 76 times higher value of this material property. Complicating the matter is the fact that the young's modulus of this fibre is depending on the load direction. The maximum young's modulus is reached when the fibre is loaded longitudinal to the fibre axis. The value decreases significantly, when the fibre is loaded transversal to the axis. The resulting problem leads to the fact that the cutting conditions are constantly varying. During one tool rotation from a drilling process, there are different states of stress at the cutting edge of the tool and according to this phenomenon highly varying appearance of the different damage types at the work piece. These facts lead to generally worse machining quality in comparison to the machining of metals and to high wear effects at the tool.

The damage caused by the machining of FRP can be classified in:

- Delamination (D, d)
- Fraying (F, f)
- Splintering (S, s)

The practical problem for the industry is that there are no regulations for the definition of the mentioned damages. Furthermore, there is no measuring method defined, so that anybody who has to qualify the machining result of a finishing operation has to find a useful way to do so. This subjective way of working leads to misunderstandings and different points of view in case of business. First approaches for a measurement technology are for example presented in [4, 5, 6, 7]. In these works, the delamination factor was defined as the quotient of the maximum diameter in the damaged zone as the dividend and the bore diameter from a drilling process as divisor. Deficiencies of the delamination factor are that it was developed for the qualification of drilling operations and, that other types of damages are not assessed.

The Institute of Production Engineering and Laser Technology (IFT) of the Vienna University of Technology is dealing with this topic. Measurement technologies to define the quality of machined FRP as well as appropriate quality indices, which value the quality, were developed. The topic is to get a detailed description of the quality of the machined surface and to create processes which are on the one hand usable in small companies without the need of expensive measurement equipment, and on the other hand to get the most accurate results with the use of measurement devices of a laboratory.

2. Occurring damages

In the following chapter, the occurring damages while machining FRP parts are described. In figure 1 a schematic view of a machined hole is shown. On the left side of the figure, a drilled hole is displayed. The inner circle indicates the tool diameter. The gray annular indicates the reference area with the outer diameter as diameter of the damaged zone. The orange areas indicate delamination and the green ones fraying. Both defects principally occur at or above the reference surface. On the other hand the splintering creates a surface below the reference surface. Splintered sections are dark grey coloured.

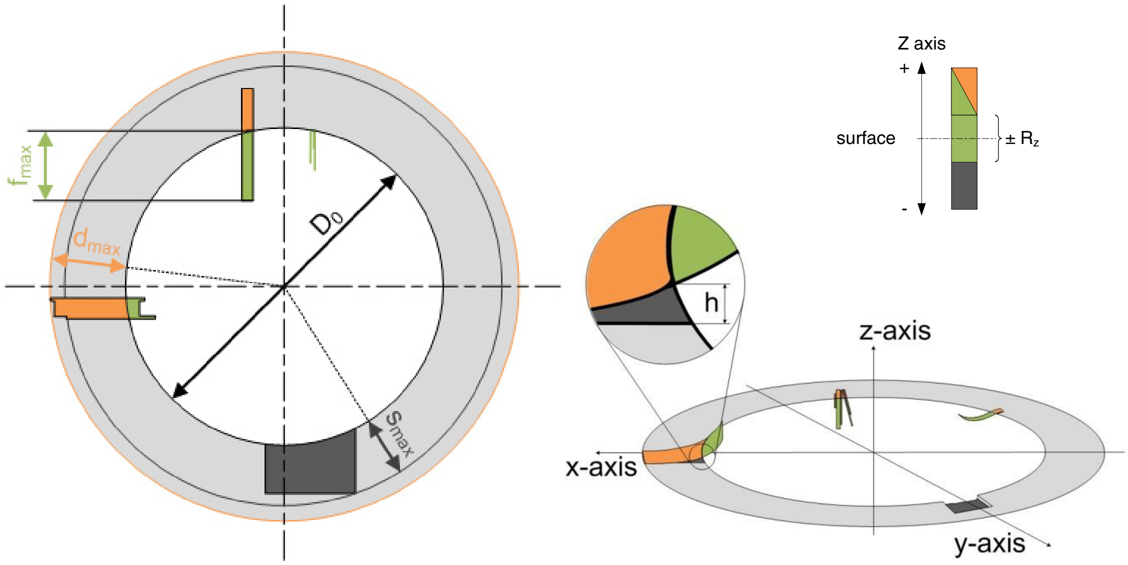

Fig. 1. Schematic views of a machined hole and the associated damages; fraying is green, delamination is orange and splintered sections are grey; upper right corner: legend of contour levels.

2.1. Fraying

Fraying of fibres mostly occurs at the top or bottom layer. The fibres move away from the cutting edge without being cut. Frayed material stays in the machined volume after the process. Whether the frayed material has to be removed or not is dependent on the individual requirement. It can happen that the fraying is so long that it would not be possible to stick a screw through the bore. Then the rework with for example a deburring process is necessary. Due to the fact that every additional process spoils the economics of the manufacturing process, it is obvious that fraying has to be reduced or completely eliminated.

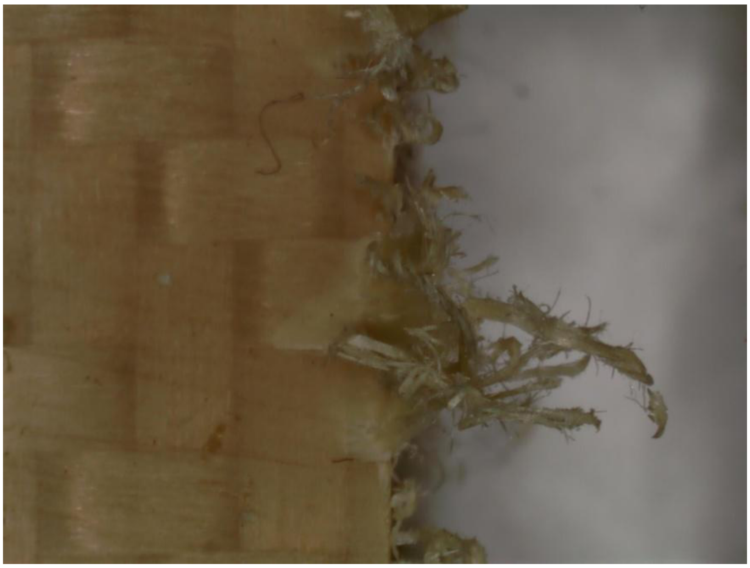

Fig. 2. Photograph of a frayed cutting edge after milling of an aramid fibre epoxy compound.

2.2. Delamination

The delamination occurs mostly at the top or bottom layer of a structure. It can also occur in the laminate, for example at the boundary of different materials or in the solid material, if a contamination or a defect affects the matrix system. These layers delaminate because of a transgression of the maximum interlaminar bonding force. When machining FRP, such a transgression could be initialised by the machining forces. The geometric definition of a delamination for the measurement is a local increase of the topological behaviour of a surface. During measuring, additional attention has to be given to the roughness and the global waviness of the part to avoid influences of the delamination result.

Repair of delamination is complex. If the delamination of a part is critical, the technician would ban these parts. That indicates that the occurrence of delamination can affect the economy of a production line significantly.

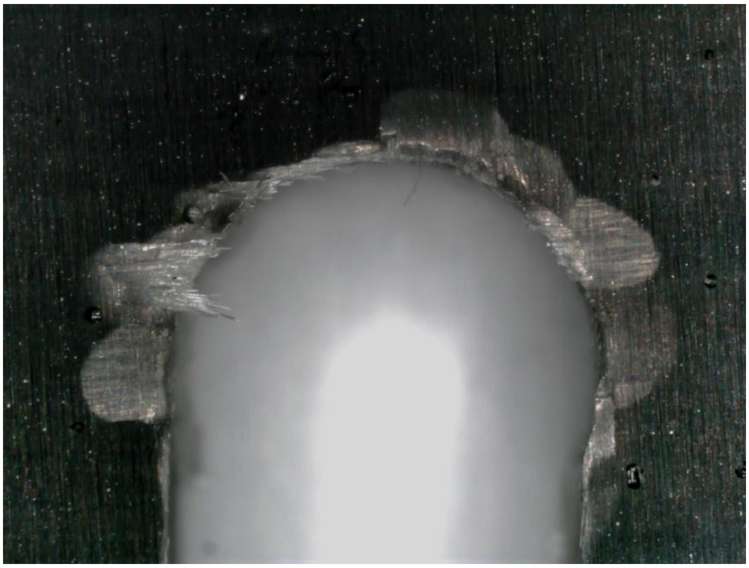

Fig. 3. Photograph of delamination at a blackened glass fibre epoxy compound.

2.3. Splintering

Splintering as a defect is also occuring in the surrounding areas of a machining operation. The damage progress starts with delamination. If the angle from the delaminated section to the part surface of the ply increases during the machining process over the angle at maximum strength, the section will splinter. Such a defect, resulting from a drilling process, is indicated in figure 4. Splintering does not require rework in the production process but it can affect the lifetime of the product. The big difference to a delamination is that a splintered section is less susceptible for a further increase of damage, compared to a delaminated section.

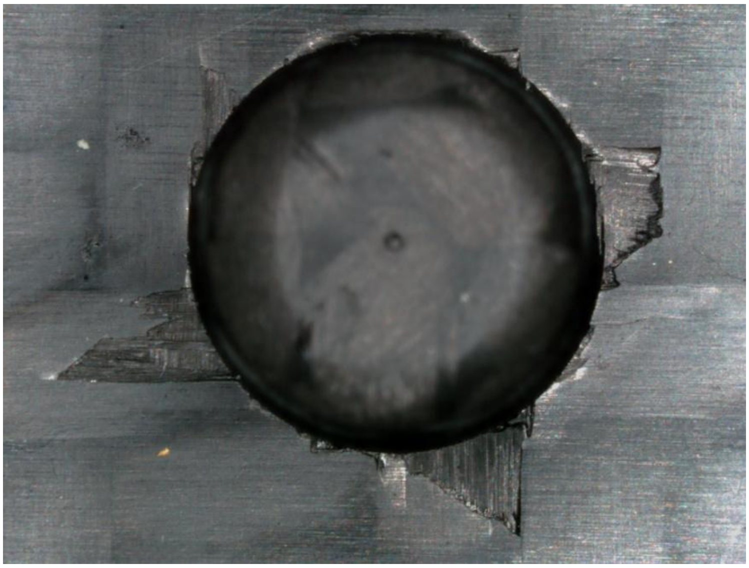

Fig. 4. Photograph of a drilled hole in a carbon fibre epoxy compound with multiple splintering.

Practical experiments show that the height of damage and the amount of damage after a machining process occur in strong dependence of the machined work piece material (fibre, resin system, resin content ...), as well as the tool characteristics (geometry and cutting edge behaviour). Further dependence consists between process parameters (cutting speed and feed velocity). In [8] is shown that the position of a bore on the work piece surface is also responsible for the occurrence of damage. The reason for this matter is the varying fibre cutting angle during the tool rotation.

For the investigation of the influence parameter, a robust and precise measurement technology is necessary. The constantly increasing demand in the composite industry also reveals the necessity of such a measurement technology. It has to be possible to detect small changes in the machining quality to enhance the process steps of the part manufacturing.

For this reason two different measurement technologies were developed at the Vienna University of Technology. The first one is called the “one dimensional maximum method” and the second one “three dimensional damage analysis”.

3. One dimensional maximum method (1D-MM)

If a fast measurement of machining results during manufacturing or in a shop floor necessary, the one dimensional maximum method (1D-MM) can be used. The 1D-MM does not demand any complex hard- or software, so everyone can do the measurement at nearly every surrounding condition. Such a procedure to define the quality after machining FRP could be used to generate an international standard. The advantages of this analysis, like the good precision and the reproducibility, enable the optimization of machining processes and the definition of a product quality standard for business transactions.

The fundamental basis for the 1D-MM is the delamination factor Fd, probably first presented in [4]. This factor is calculated with the diameter of the maximal delamination D_{max} and the diameter D of the drilled hole like shown in formula 1.

$$F_d = \frac{D_{\max}}{D} \tag{1}$$

In figure 5, a schematic result of a drilling operation with different kinds of damage is shown. On the left side, a common measurement result is displayed, as an example for the assessment with the delamination factor. The orange coloured damage (=delamination) will be valued, but the red coloured damages (=fraying and splintering) will not be investigated in any way by the procedure of [4]. The situation that fraying and splintering occur at least as often as delamination, leads to a development need. Another disadvantage of the delamination factor is that it was developed to qualify a drilling operation. Broadening the principle to milling and trimming operations is necessary for industrial usage.

In experiments it was possible to determine that the 1D-MM gives a more realistic portrayal of the machining quality, compared to the simple delamination factor. The maximum length of the delamination, fraying and splintering will be measured and saved for the quality description like shown in figure 5 on the right side. This additional information is used within the 1D-MM. The measurement of the second and third longest damage would offer further information about the quality and is also possible with the 1D-MM. However, under experimental conditions it could be determined that this additional information gives no significant advantage. Also the fact that a fast and simple measurement is a main goal of this method indicates that the extension of the method is not target-oriented.

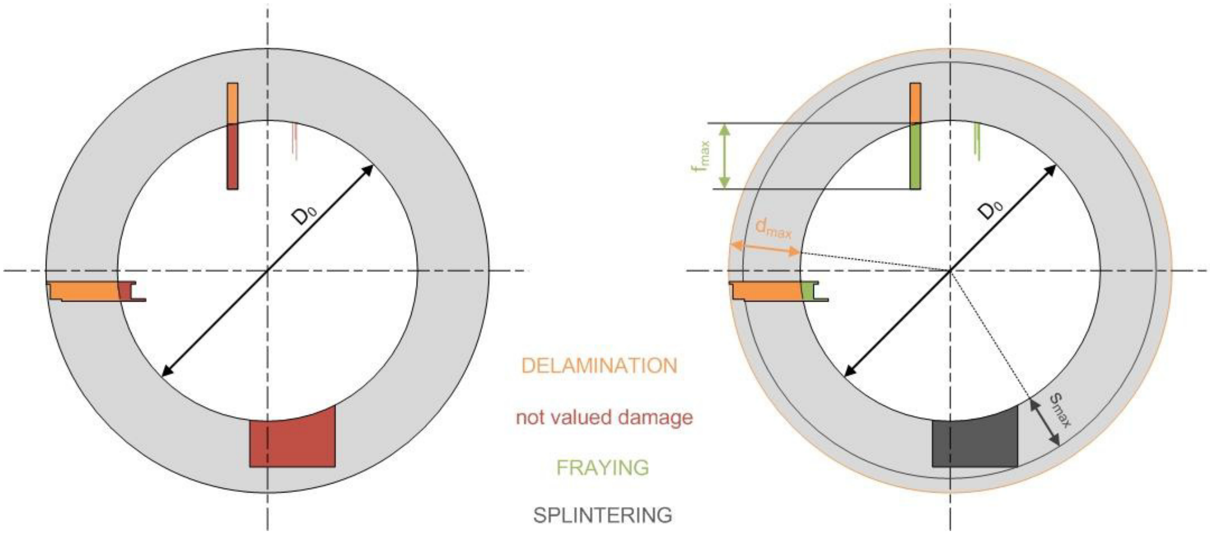

Fig. 5. Schematic illustrations of the delamination factor and the 1D-MM.

The procedure for the 1D-MM starts with the measurement of the maximum length of every damage type (f_{max}, d_{max}, s_{max}) by calliper or via microscope like illustrated on the right in figure 5. These values can be rounded for example to 0.2 mm to optimise the reproducibility. The values have to be listed in the developed excel form of the method. The excel form uses the maximum damage length and a critical damage length to calculate the index values i from formula 2. These indices go from 0 to 100%.

$$i_{n,i} = \frac{L_{\max,n,i}}{L_{crit,n,i}} \cdot 100 \; in\ \% \tag{2}$$

The critical damage length can vary in dependence of the later function of the machined surface. If there are no critical boundaries defined, the following suggestions could be used.

- Drilling: a_p (cutting width) [3]
- Trimming: a_e (cutting width) [3] for $a_e \leq D/2$ (D = tool diameter)
  D/2 for $a_e > D/2$
- Milling: $a_e/2$

When additional damage lengths are to be measured in order to enhance the process, the amount of indices will increase in correspondence. For the following process these indices will be averaged.

For a part with multiple machined geometries, the three indices (fraying, delamination and splintering index) should be measured at each machined result. In this situation the indices will be numbered with the addition n. The second addition i stands for the position of the geometry (i = [bs = back side / fs = front side]). In case of a machining process through the material thickness, it is necessary to measure the three damage lengths not only on the front but also on the back side. The so generated indices describe the damage grade of every geometry of the part.

Another aspect is that the maximum damage length can be limited to an adequate value. Theoretically the length of a fraying can be longer than for example the tool diameter. In such case the limitation simplifies the measurement. The excel form immediately analyses the quality results of one or more, same or different, machining processes. The so provided information allows an operator the immediate enhancement of the process. The received information can also be used for further improvements of the process, for example by a tool engineer for a redesign of the tools geometry.

It is important for the measurement, that the fraying is measured longitudinal to the fibre axis as it is practically the longest expanse of the fraying. This longest expanse is also the part which would interfere with later process steps like screwing parts together or pollute the assembled product. Delamination and splintering are measured normal to the cutting edge, in order to rate the penetration of the damage into the part.

For the analysis in the excel sheet, the classification in front and back side and in for example drilling, milling or trimming operations is necessary. Corresponding indices could be named $fi_{drill,\ fs}$, $si_{mill,\ fs}$ or $di_{trim,\ bs}$. The program now calculates averaged index values and displays them in tables and diagrams. Some of the calculated indices for the analysis of the machining quality are displayed in formula 3 to 5.

$$fi_{total,fs} = \frac{fi_{drill,fs} + fi_{mill,fs} + fi_{trim,fs}}{3} \tag{3}$$

$$si_{total,bs} = \frac{si_{drill,bs} + si_{mill,bs} + si_{trim,bs}}{3} \tag{4}$$

$$di_{total} = \frac{di_{total,fs} + di_{total,bs}}{2} \tag{5}$$

The value in formula 3 defines the grade of fraying at the front side of a product. Formula 4 gives information about the splintering on the back side and formula 5 elucidates the grade of delamination at all machined geometries. Other indices are calculated analogue.

Another service of the excel analysis is the definition of the primary damage type to get fast information about the major problem during machining.

To characterise the machining quality with one single value, the quality index (qi) is introduced. The qi is the averaging of the single damage indices like shown in formula 6.

$$qi_{n,i} = \frac{fi_{n,i} + di_{n,i} + si_{n,i}}{3} \tag{6}$$

Furthermore, it is possible to generate a qi_{total} for all different machining operations. Therewith it is possible to define the machining quality of a complex part. Another possibility is to compare the results between front and back side. In formula 7 to 9 some qi equations are presented.

$$qi_{total} = \frac{fi_{total} + di_{total} + si_{total}}{3} = \frac{qi_{total,fs} + qi_{total,bs}}{2} \tag{7}$$

$$qi_{total,fs} = \frac{fi_{total,fs} + di_{total,fs} + si_{total,fs}}{3} \tag{8}$$

$$qi_{total,bs} = \frac{fi_{total,bs} + di_{total,bs} + si_{total,bs}}{3} \tag{9}$$

Through this analytical procedure, the user gets different possibilities for investigation and enhancement. The following opportunities are available among others

- Determination of the cutting quality
- Analyses of the three different damage types (delamination, fraying and splintering)
- Distinction between quality at the front and back side of a specimen
- Studying of the different machining processes (e.g. drilling, milling and trimming)
- Comparison of different tools and cutting parameters
- Definition of the primary damage type and following process optimisation
- Comparison of different work piece materials (fibre and resin system) and work piece production processes

4. Three dimensional damage analysis (3D-DA)

The three dimensional damage analysis (3D-DA) is used to measure damages occurring after finishing operations of composite parts, when detailed information about the size of a damaged area and about the specific type of the damage at this area, are required [9]. The representation of this principle is based on the work of [4]. At the IFT, an Alicona Infinite Focus 4G and a Nikon Nexiv VMR 2520 are used for the investigations. The machine supported measurement increases the objectivity and the precision of the process. Very important is the fact that the measuring parameters are defined and stay constant for every measuring operation; otherwise it can happen that the results vary.

To qualify a machining result and to compare different results, a criterion has to be defined. For that reason three indices – referring to the indices in the chapter 1D-MM – were developed. The indices of the 3D-DA are contrary to the indices of the 1D-MM written in capital letters.

In table 1 the fraying index (FI) is shown. This index is generated with two digits. The first digit indicates the longest fraying (f_{max} in figure 1) in comparison to the critical length of the machined structure. The amount of fraying at the circumference of the structure is represented by the second digit. The length of the other fraying at the circumference is irrelevant. The measurement of the area of the fraying is in practise difficult. The problem is that frayed material can have different orientations, what influences the measured area. The presented process avoids such situations.

The percentile ranges in the rows and in the columns of table 1 are based on the standard line R8. The index goes from 99, for the worst result, to 11 for the best possible result. The fraying quality of a machined structure can therewith be determined more clearly in comparison to the 1D-MM. For the measurement of the frayed FRP, a light microscope like the Nikon Nexiv VMR 2520 can be used.

If the result of a drilling operation shows a fraying length of 7% of the tool diameter, the corresponding row in table 1 is $6\% \leq x < 10\%$. This row equals the first digit of the index to 5. If fraying occurs at 5% of the circumference of the drilled hole, the second digit would be 4, which represents the column 3% ≤ y < 6%. The FI for the bore is 54.

Table 1. FI matrix with the exemplary result of 54.

FI - Fraying Index									
longest fraying in comparison to the critical length	amount of the circumference, where fraying occurs								
	0% ≤ y < 1%	1% ≤ y < 2%	2% ≤ y < 3%	**3% ≤ y < 6%**	6% ≤ y < 10%	10% ≤ y < 18%	18% ≤ y < 32%	32% ≤ y < 56%	56% ≤ y < 100%
0% ≤ x < 1%	11	12	13	14	15	16	17	18	19
1% ≤ x < 2%	21	22	23	24	25	26	27	28	29
2% ≤ x < 3%	31	32	33	34	35	36	37	38	39
3% ≤ x < 6%	41	42	43	44	45	46	47	48	49
6% ≤ x < 10%	51	52	53	**54**	55	56	57	58	59
10% ≤ x < 18%	61	62	63	64	65	66	67	68	69
18% ≤ x < 32%	71	72	73	74	75	76	77	78	79
32% ≤ x < 56%	81	82	83	84	85	86	87	88	89
56% ≤ x < 100%	91	92	93	94	95	96	97	98	99

The classification for the delamination (DI) and splintering indices (SI) uses the same two digit principle as the one described for the fraying. The first digit of the delamination index is the maximum height of the delamination. In figure 1 this height is shown as height h. The second digit of the delamination index represents the damaged area (orange area in figure 1) dependent on the delamination reference area in percent. The reference area is the area of the annulus with the drill diameter as inner diameter and the concentric diameter $D_{max,D}$ defined thru the most distant delamination. Rephrased $D_{max,D}$ is the drill diameter plus two times the length d_{max} (figure 1) of the maximum delamination radial measured.

The third quality describing index is the splintering index. The first digit for this index is contrary to the delamination index, the maximum height of the splintered section measured downwards from the top layer surface. The second digit is again the damaged area compared to the reference area, which is bound through the maximum diameter of the splintered zone.

The measurement for the delamination index and the splintering index is done parallel by the Alicona Infinite Focus. This device uses optical focus variation to generate a three dimensional model of the part. This model can be analysed and the necessary information for the quality examination can be generated.

With the information provided by the three indices, the quality of the part surface of a machining process can be qualified with a high level of details. The summation of the results in a global quality index, like it is done for the one dimensional maximum method, is not recommended. This analysis ends with the information of every index for the three damage types. With this presentation of the results, every analyst and technician gets a fast overview of the damage distribution. It is possible to detect the primary damage type and to enhance the process in a way that this damage decreases.

Conclusion

With the possibility to use a regulation to define the quality of a machined structure, companies can produce parts with defined characteristics and avoid conflicts with business partners. The R&D society gets the necessary basis to compare results as well. The possibility to compare objectively and to measure reproducibly is most fundamental for any serious improvement in the process, like for example the development of new tools or machining strategies.

In table 2 there are some measurement procedures and quality indices compared. The first four procedures are state of the art, but none of these approaches became a standard. The last two procedures are the 1D-MM and the 3D-DA, which were developed at the IFT and should be understood as an additional approach for standardisation. The 1D-MM is practically usable for anybody. The 3D-DA is a very precise and detailed procedure which requires highly sophisticated measurement equipment. Table 2 shows that the 1D-MM is the favourable process for fast and simple measurements of machining results. On the opposite side, the 3D-DA provides the most information about a machining quality, which is needed for very detailed research and development tasks.

Table 2. Comparison of the characteristics of different damage analysis procedures; c = calliper, ips = image processing system; [4, 5, 6, 7].

characteristic	damage analysis procedure					
	Chen	Mohan	Tsao	Davim	1D-MM	3D-DA
precision	+/-	+/-	+/-	+	+/-	+
repeatability	+/-	+	+	+	+	+
measurement device	c	ips	ips	ips	c	ips
time exposure	+	+/-	+/-	-	+	-
dimensions of damage analysis	1	2	2	2	1	3

Future tasks for the development of such quality tools are for example to increase the grade of automation for the damage analysis. Especially the 1D-MM would benefit for example of an image evaluation software, which automatically measures the maximum damage length after machining. Another task is to measure delamination in the FRP-solid or between material boundaries, for example between steel and CFRP. Cracks between the phase boundaries after mechanical operations in such multi-material parts are actual problems in the industry. Another quality criterion, which will be immediately implemented in the measurement tools of the IFT, is the roughness of machined surfaces. Additional field experiments in companies should reveal the last optimization potential of the damage analysis.

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