HIGH PERFORMANCE TOOLS FOR CARBON FIBRE REINFORCED PLASTICS MACHINING

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Abstact: The aim of the research is to present several technical solutions offered by the Company Gühring oHG for machining carbon fibre reinforced plastics (CFRP) and CFRP metal sandwich materials. This work highlights new solutions for drilling CFRP. Different drill geometries like Dagger drill, 90°-head drill, “Fishtail” drill for multidirectional CFRP and for unidirectional CFRP radius grinding with "fishtail" web. New coatings which increase the durability of the drill such as Signum or Diamond coatings are also presented. Special requirements for manual drilling solutions are shown in this research. The new feed reduction unit is a universal solution which reduces the feed force and can be fitted to different types of drills. This research presents also new solutions for milling CFRP and CFRP metal sandwich materials. Different mill geometries like the compression cutter which compresses the carbon fibre so that one obtains delamination free machining.
Key words: drilling CFRP, milling CFRP, stacks, delamination, surface coating

1. INTRODUCTION

CFRP has the advantage of high strength and stiffness in relation to its reduced weight, high durability and low fatigue behaviour but there are the high material costs involved. The Company Gühring oHG is among the leading producers of high-performance tools for CFRP machining. The philosophy of the Company Gühring oHG is the holistic tool optimization. This means that Gühring oHG produces its tools from beginning to end.

The research presents the properties and the requirements needed to machine of CFRP and CFRP metal sandwich materials when machining. A categorization and classification of CFRP structures such as unidirectional CFRP, multidirectional CFRP and woven CFRP fabrics are presented and also a categorization and classification of the CFRP metal sandwich materials which are a combination of carbon fibre and different metals like aluminium, titanium or stainless steel.

Several technical solutions for the problems that appear during milling and drilling CFRP such as surface damage due to overheating, pull-outs, delamination, fraying of the carbon fibre, washouts of CFRP material by metal chip CFRP are presented.

2. THE PROCESING OF CARBON FIBRE REINFORCED PLASTICS/POLYMERS (CFRP)

The processing of advanced materials such as carbon fibre reinforced polymers/plastics (CFRP) is for the manufacturers of cutting tools a growing challenge. To machine latest generation of this high-tech material economically, effective high-tech tools are needed, especially to avoid the delamination and fibre projections at the component and thermal damage but at the same time to process with excellent efficiency. Therefore one needs to know what types of CFRP materials exist. There is no unified classification for CFRP structures. This work concentrates new solutions for drilling and milling unidirectional and woven CFRP structures or a combination of those.

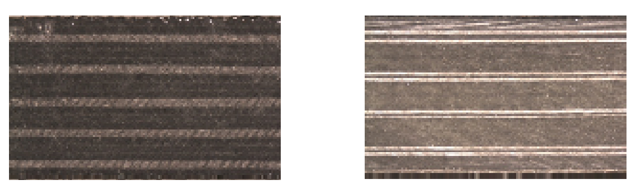


Fig. 2.1. Unidirectional CFRP

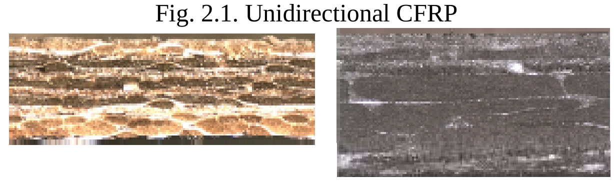


Fig. 2.2. Woven CFRP

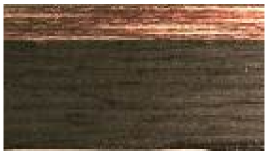


Fig. 2.3. Combination of Unidirectional and woven CFRP

This work provides also new solutions for drilling and milling CFRP stacks, which are a combination of carbon fibre and different metals like aluminium, titanium or stainless steel.

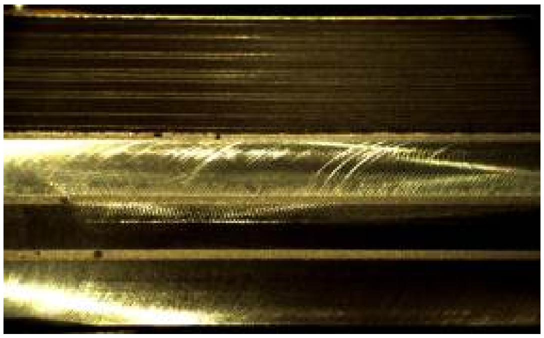


Fig. 2.4. CFRP stack CFK/Al/VA/Ti

A new trend is noticeable for the CFRP Types with less resin content and primarily unidirectional orientation of the fibres. This development affects the reliable processing of these materials significantly since the fibres can be pulled out very easily when being processed.

The problems that appear during machining CFRP are delamination, pull-out effects and surface damage due to overheating. For CFRP stacks are washouts of the CFRP material through metal chips and metal burr building which damages the CFRP structure.

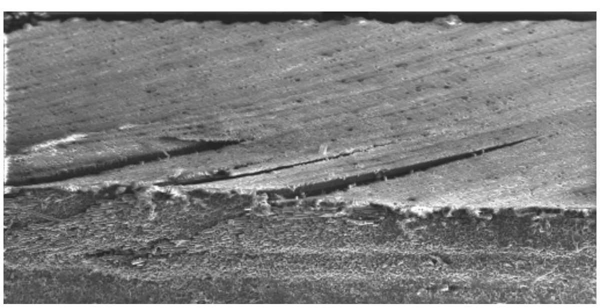


Fig. 2.5. Typical delamination of a milled unidirectional CFRP edge

While the woven fibres are stably embedded in the resin-fibre matrix, the unidirectional carbon fibres are placed side by side in the resin.

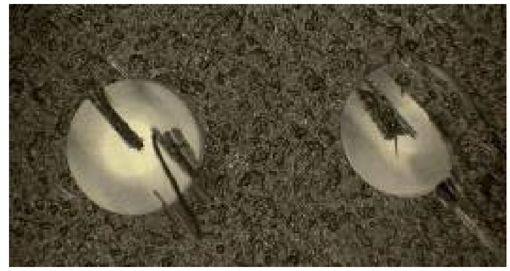


Fig. 2.6. Significant delamination: exit hole in unidirectional CFRP

The embedded form-fitting is missing. This development affects the reliable processing of these materials considerably, since the fibres as particularly in milling can be easily torn out of the compound. The higher the cutting forces, the greater are these effects.

Fig. 2.7.Typical delamination of a milled unidirectional CFRP material

Fig. 2.8. Milled unidirectional CFRP material with the new Gühring CFRP-Mill

At the Guhring Competence Centre for composite processing, are the most modern analytical and simulation methods available to study and optimized tools, materials and machining process in detail. Electron microscope and EDX analyses of processed composites or temperature analysis during the machining process using thermography camera are just some of the possibilities available at the Guhring Competence Centre for composite processing.

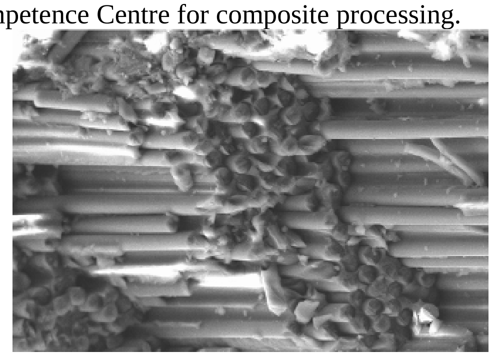


Fig.2.9. Milled unidirectional CFRP material at a magnification of 2000x

The goal is to offer for the client's own composite material a specific processing solution. Thanks to the high level of expertise in tool production and the opportunities available in Guhring competence center, the actual production situations are simulated by customers.

3. GÜHRING'S HOLISTIC TOOL DEVELOPMENT AND OPTIMISATION

The requirements for the development of innovative high-performance tools is the holistic control of all known production parameters in the design and manufacturing chain "base body Structure -surface -geometry". Starting at the base body, the foundation of the subsequent tool is created by a selection of the correct carbide and the resulting parameters for carbide production fulfilling the conditions for the potential function in the intended area of use (material, machining operation). Based on this, the selection of the suitable cutting edge geometry of the tool, based both on the experience and on the knowledge gained through simulation experiment regarding chip shape, chip removal, heat generation, etc. is crucial for the future performance potential. This selection includes both the execution variants of the macro-geometry as well as the micro-geometry (eg. cutting edge rounding) (Biermann et al, 2011). Finally the surface treatment and the hard coating are heaving further key roles that determine the functionality and durability of the tool. "Holistic optimisation" means to increase the performance of cutting tools by taking into account the interaction of these parameters and factors. Ideally, new high-performance tools are conceived like a modular design shown in Figure 3.1 and optimize to the needs of a specific application.

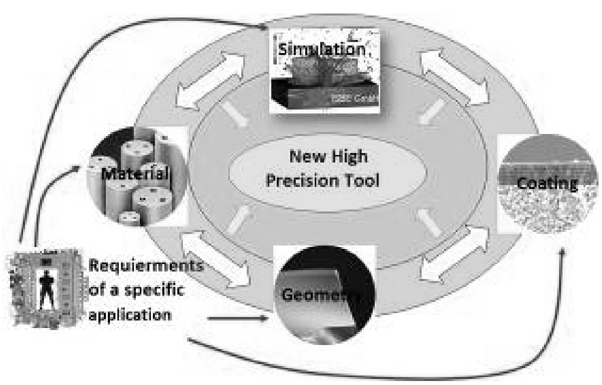


Fig. 3.1. Modular design of holistic optimisation of high-performance tools

The suitability of a cutting tool material for a specific machining process is described essentially by 5 basic properties: hardness, especially the heat hardness, fracture toughness, stiffness, edge stability and reactivity with the machined material. These basic properties are determined by the chemical and structural composition of the cutting material, and it is usually impossible, to influence only one parameter separately without influencing the others. The example of the WC-Co carbide will be briefly presented, how the carbide adapts to the load profile of a processing.

The most influential factors for determining the properties of the carbide are the proportion and the chemistry of the binder metal and the particle size distribution of the WC (Luyckx, 2000). The influence on the mechanical basic properties results basically from the modification of the width of the webs between the binder and the WC grains and also through the strength of the bond between the WC grains and binder metal. With increasing WC grain size the hardness and the edge strength decreases, while the toughness is increased. An increasing Co content lowers the hardness and rigidity, however, increases the toughness, the edge strength and the reactivity. Additionally the relation between the reaction depth of the machined material with the binder metal and the WC grain size affects the wear rate through adhesive wear.

For economic machining optimized tools and cutting parameters are necessary. To minimize in this context the number of expensive prototypes and field trials, the process simulation using "Finite Element Method" FEM is an appropriate tool for the development of an application specific optimal tool. The following objectives are in this approach of particular relevance (Denkena et al, 2009):

-The numerical calculation of the machining process with a predetermined geometry, tool and workpiece and associated cutting parameters

-Determining the influence of the cutting parameters regarding the stress applied to the tool.

-The simulation and evaluation of chip formation and resulting chip shape.

-The geometry optimization of the tool by comparing the mechanical and thermal loads

For the layout of coatings is a wide range of parameters to be covered. The selection of the chemical layers determines parameters such as hardness, toughness and stiffness, the crystal structures, the quality of the connection to the substrate and the tribochemical interactions with the work piece material. By changing the crystal structures and bond types are not only the hardness will be modified but also the residual stresses, the electrical conductivity and thermal conductivity. The choice of coating determines the exact properties within the specified property sheet and determines the residual stress on the possible formation of a given geometry or layer thickness. Through the development of multi-layer coatings, these properties can be local bound depending on the case of application. Multilayer structures also modify the

residual stress state of the entire layer by the combination of layers of different stress conditions.
The approach to the holistic optimization in tool development enables the production of cutting tools, taking into account the interaction of the performance determining parameters such as hardness and elasticity of the cutting material and the coating, microgeometry of the cutting edge or coefficient of friction and heat transfer properties on the surface. By using a modular building block approach for tool development, very efficiently specific tools can be produced. The modular principle of development "base - geometry - surface - simulation" allows systemizing and thus rationalizing for developing of new tools. An economically diversification of standard tools is made possible, allowing to generate new high performance tools in a very short time.

4. CFRP DRILLING

CFRP drilling is one of the supreme disciplines of complex materials machining. Since CFRP materials are usually drilled in material stacks with aluminium and titanium, in this operation, the chip removal is a particular challenge. Consequence of insufficient chip removal are CFRP washouts, the carbon fibres embedded in resin peel off during the entry and exit of the drill and create delamination. Delamination during drilling CFRP has been reconised as one of the major problems by almost all the researchers (Babu and Pradhan, 2007). Another focus in the processing of CFRP is the avoidance of excessively high processing temperatures.

4.1. Analysis of the drilling process

Due to the complex analysis of the drilling process, Gühring succeeds to develop precise tools regarding their application. These improvements go far beyond common improvements such as depositing a diamond layer: Through surface investigations with the scanning electron microscope (SEM and EDX) processing damage may be almost entirely excluded.

4.2. Carbide or PCD

In general, these studies relate both the group of cemented carbide tools as well as the one with the PCD tools. PKD has advantages of absolute sharpened edges that ensure a clean separation of carbon fibres through. Carbide tools allow tool designs allow with far more diverse and complex geometries.

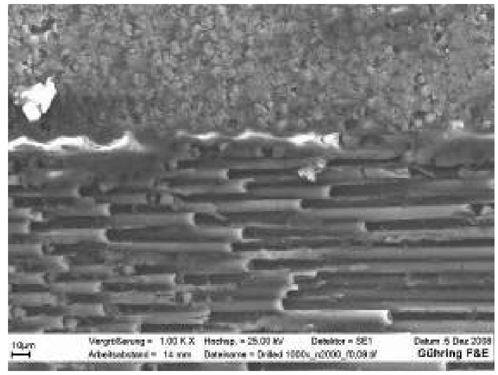


Fig. 4.1. SEM analysis of the surface of a hole with clean-cut carbon fiber (2 layers a with different fibre orientation)

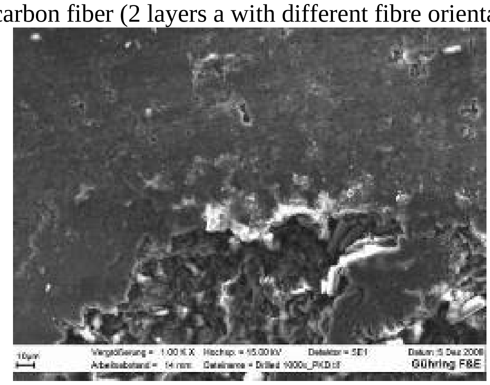


Fig. 4.2. CFRP surface from damage due to excessive heat, smeared, melted resin as well as outbreaks of the fiber composite

4.3. Cooling factor

Another significant factor is the cooling of the cutting process itself. Particularly the use of a suited CFRP machining cooling shows enormous advantages over the dry machining.

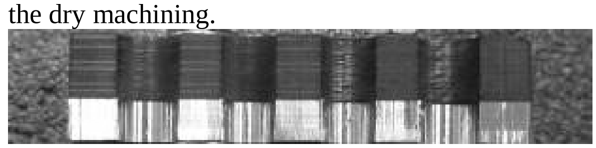


Fig. 4.3. Test-Drilling 1-4 in a CFK/Ti-Stack

After overlapping the SEM images with the titanium and carbon-mapping it can be seen that the white particles of the SEM image are titanium micro-chips which adhere to the carbon fibre surface area. The SEM image of the hole 1 with EDX spectrum and EDX mapping is presented in the next figures.

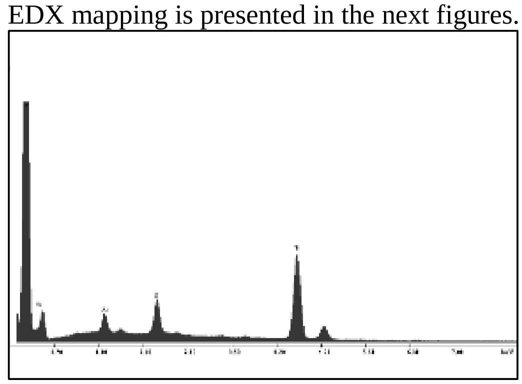


Fig. 4.4. EDX-Spectrum

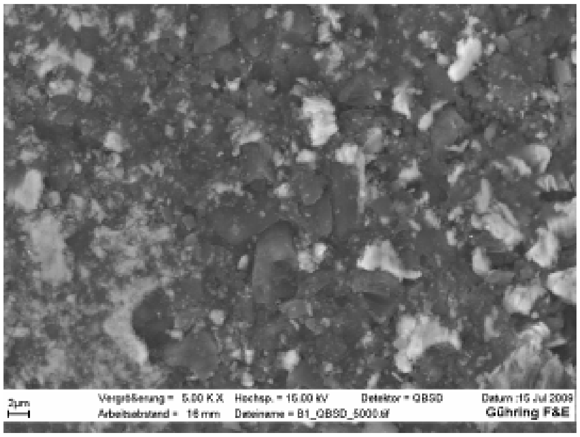


Fig. 4.5. SEM-Image, 5000x magnification

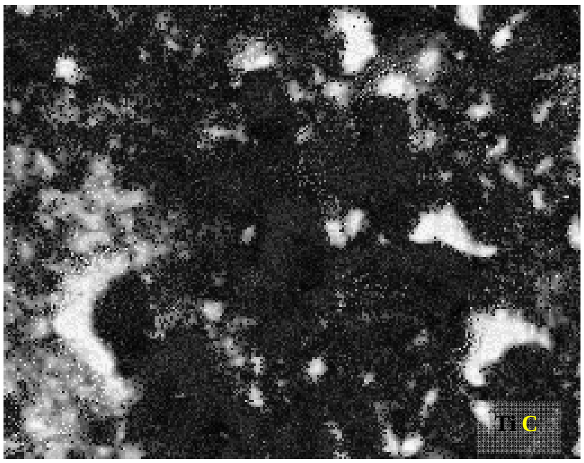


Fig. 4.6. Overlay REM 5000x, Ti-/C- distribution

When using a specific CFK cooling a clean cut is generated while in dry machining a significant thermal damage was detected.

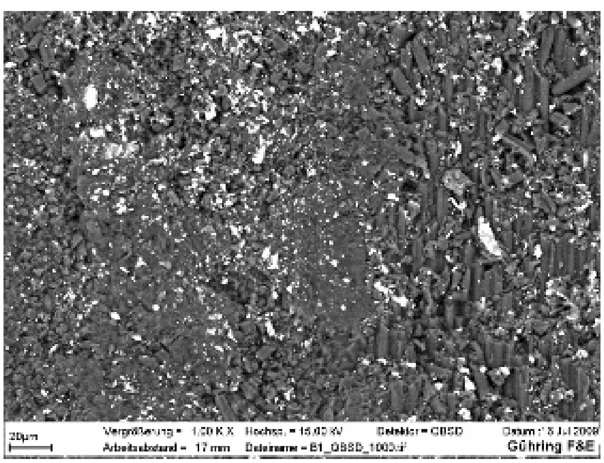


Fig. 4.7. SEM image of the hole 1, produced in Standard procedures without cooling

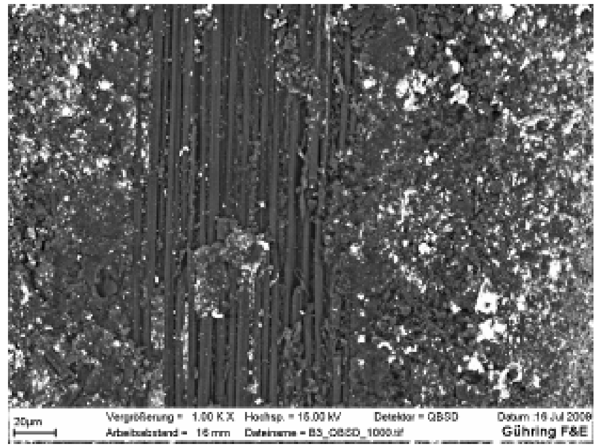


Fig. 4.8. SEM image of the hole 1, produced in Standard procedures with cooling

4.4. Improved tool geometry for the drill process

The most important requirements for drilling CFRP Stacks are no delamination during hole entry, no burrs at hole exit and no CFRP washout due to metal chips. That is why at the Guhring Competence Centre for composite processing a new chip breaker geometry was developed. This geometry has the drill point adapted to the requirements of the composite material and a new flute design.

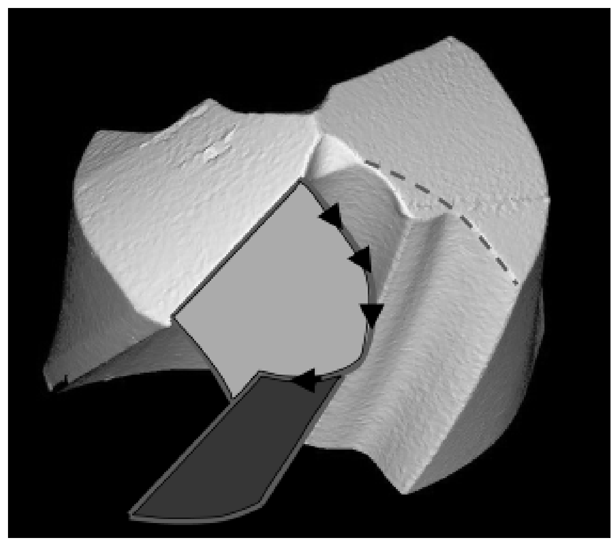


Fig. 4.9. New Chip breaker geometry

Due to the new flute design the chip rolls immediately inwards after detach from material and is broken into small fragments. The flute extends to the shaft end out allowing quick and easy chip evacuation from the hole.

Fig. 4.10 Chips without chip breaker geometry (left) and chips with chip breaker geometry (right*)*

The internal cooling canals prevent overheating the drills cutting edges and thus the thermal damage to the material. Holes of IT8 quality in a „One-Shot“ drill process can be obtained. This tool geometry assures slight delamination at the hole entry, a clean through hole and no damage on the stack by chips during the drilling process.

Additionally with thermographic images is the most appropriate tool geometry in conjunction with the drilling process determined. In particular, the patented internal Guhring cooling system combined with an exhaust device shows its immense benefits.

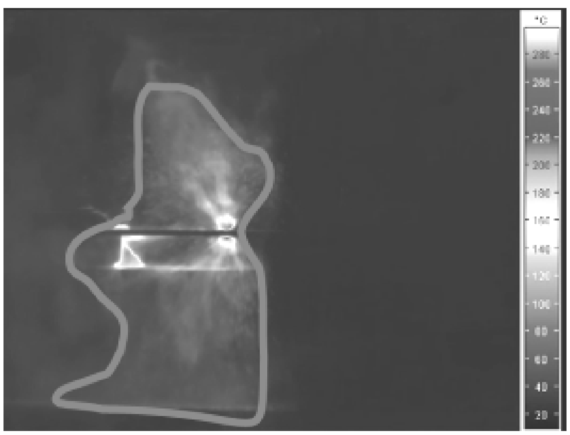


Fig 4.11.Thermography without cooling: high temperature development

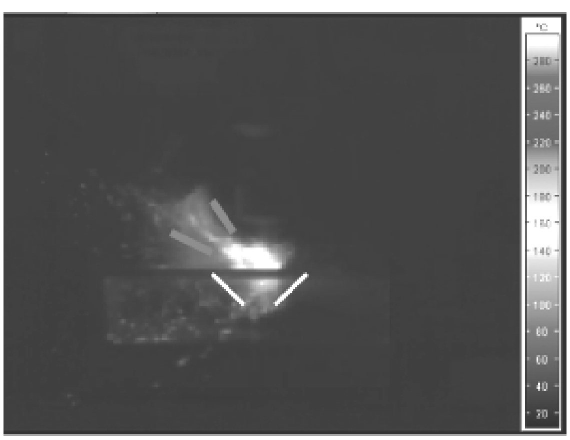


Fig 4.12. Thermography with cooling and exhaust: low temperature development

A very important step for creating optimised tools is the simulation of machining CFRP fibres. Through the simulation one can optimize the geometry for a clean cut of CFRP fibres and for preventing delamination and fibre pull outs.

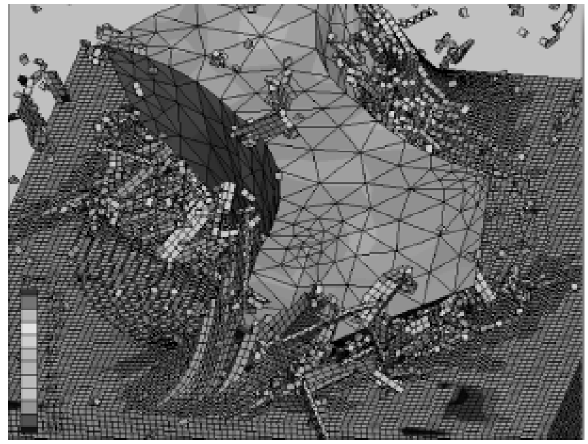


Fig 4.13. Simulation of machining CFRP (ISBE GmbH, 2012)

Due to the simulation of different geometries the Guhring Competence Centre for composite processing manufactured different types of drills for multidirectional CFRP and unidirectional CFRP shown in the following images.

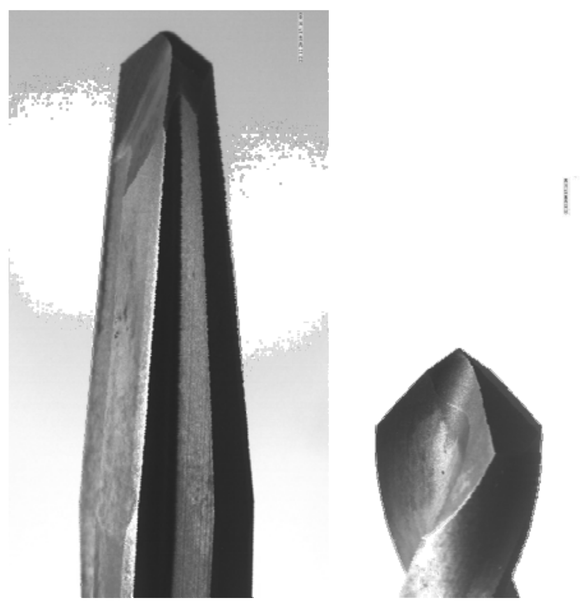


Fig 4.14. Dagger drill (left) and 90° Drill (right) for multidirectional CFRP

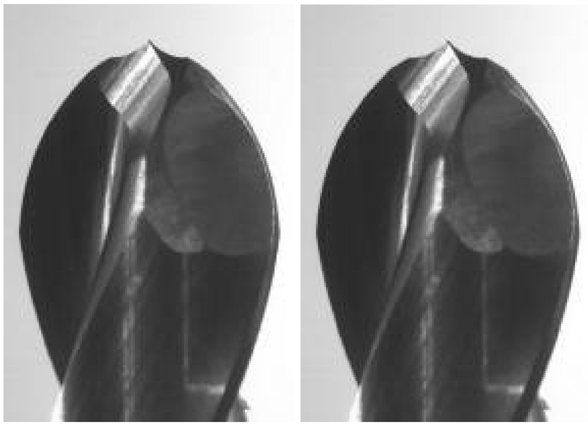


Fig 4.15. Radius grinding with "fishtail"-thinning for unidirectional CFRP

4.5. New coatings for drilling CFRP

Another important parameter for obtaining optimised CFRP drills is the coating. That is why the new superhard coating system SIGNUM was developed. It is a nanolayer and nanostructured coating system based on (Ti Al Si)N and (Ti Al X)N with a coating hardness of ca. 5500 HV, oxidation resistance up to 800°C and coating thickness of 3,5µm. This coating has a very big advantage because it can be recoated and regrinded.

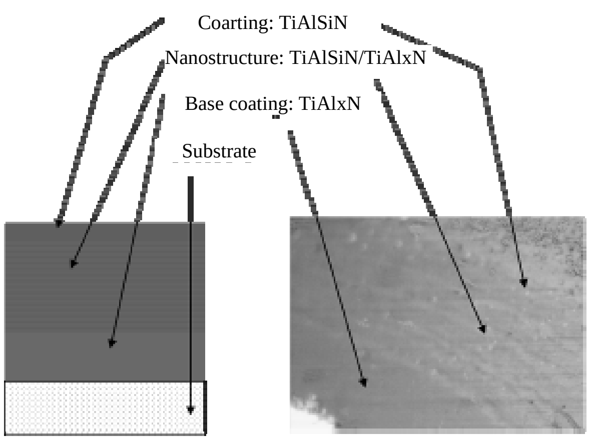


Fig. 4.16. Representation of the Signum coating

This coating was tested against two different diamond coatings at the customer Premium Aerotec. The wear criteria were the delamination due to blunt cutting edges.

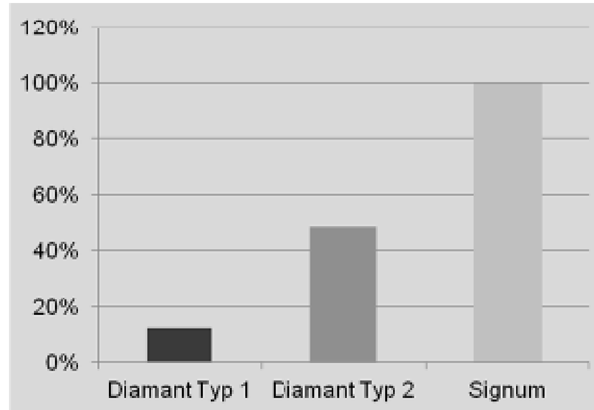


Fig. 4.17. Tool life of the 3 different coatings

The diagram up above shows that the drill with the diamond coating type 1 reached only 10% of the tool lives drill with the signum coating and the tool with the diamond coating type 2 has made only 50%. This result is not to be generalised. In other experiments the diamond coating has a greater tool life than the signum coating.

4.6. Hand drilling of CFRP

The processing of unidirectional composite materials with hand drills had been until now practically impossible. Through the development of an new drill geometry and patented feed damping system made at the Guhring Competence Centre for composite processing it is possible to drill manually even sensitive composite materials. Particularly in the aviation and aerospace industries, the use of hand drills for machining composite materials is standard practice, in spite of all its disadvantages. This includes in particular the lack of definition of the feed forces and cutting speeds. While composites with woven fibres react relatively docile, for the unidirectional materials the drilling process tears the fibres from the composite apart which results in the destruction of the structure. At this moment the causes are abruptly dropping cutting force and the sudden extreme acceleration of the manual drill due to the drill feed while exiting the hole.

The solution is a drill with a new geometry, which avoids the extreme acceleration of the drill tool during the exit and cuts the unidirectional fibres controlled and clean.

Gühring also focuses its attention not only on the tool, but also on the drilling process. The result is a patented feed damping system that controls and guides the exit cutting force of the drill. This provides users now a practical and effective solution for simple, reliable and economical processing of particularly sensitive unidirectional composite materials and costly reworks are eliminated.

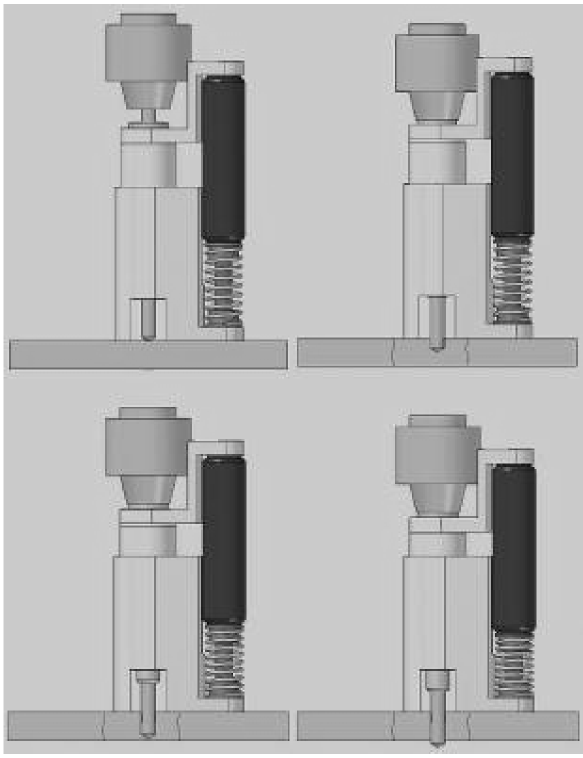
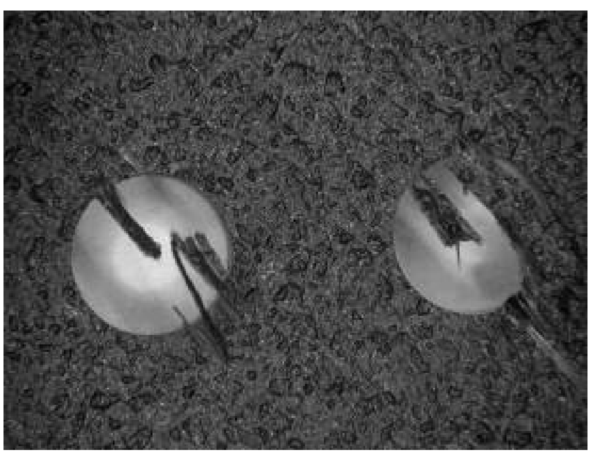
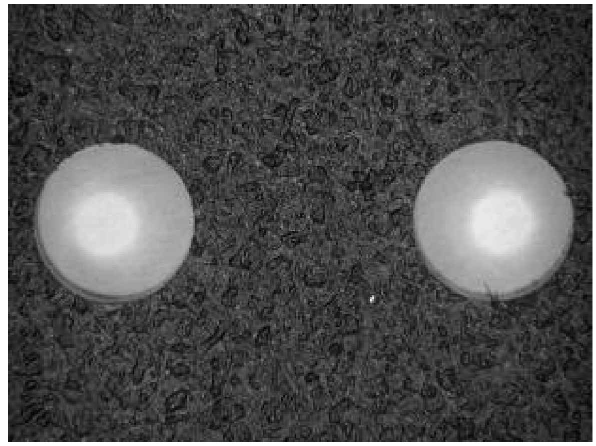


Fig. 4.18. Image of the steps during drilling in composite materials with a hand drill and patented Gühring adaptive feed damping

As part of the tool and process development Gühring leads the necessary cutting tests in its own test field. With this equipment, Guhring offers its customers analysis capabilities around the machining of composite materials, which no other tool manufacturer can and often which are not even available at the high-tech composite manufacturing companies of the aerospace and automotive industry.



4.19. Significant delamination: hole exit without Gühring drill geometry and patented adaptive feed damping



4.20. No delamination: hole exit with Gühring drill geometry and patented adaptive feed damping

5. CFRP MILLING

Composite materials, especially carbon fibre reinforced plastics (CFRP), conquer more and more applications. They were a few years ago exotics that due to the high production and processing costs were almost used just in aviation and space technology, today they are also increasingly being used in the automotive, energy engineering, shipbuilding or in the leisure industry. For manufacturers of cutting tools is the processing of composite materials a real challenge and also a growing market.

The development of machining CFRP is a real challenge, since the fibres as particularly in milling can be easily torn out of the compound. The higher the cutting forces, the greater are these effects.

Fig. 5.1. Typical delamination of a milled edge of unidirectional CFRP

Fig. 5.2. Machined edge of unidirectional CFRP with the new Guhring CFRP mill

Gühring offers intelligent solutions for milling CFRP, which is why it is important, therefore, to minimize the cutting forces that cause the tearing of the fibres. There are various approaches.

It is importance to have a sharp cutting edge with a very hard surface, which withstands the abrasive behaviour of the CFRP material and the extreme wear effect while cutting of the fibres. Diamond is ideal with its high hardness for this application. The properties of diamond allow very high cutting speeds. By exploiting the mass inertia, the fibres are cut without being torn out of the composite. However, the maximum speed is limited by the machine, and the temperature development. A good example is the compression cutter (Fig. 5.3).

Fig. 5.3. Guhring CFRP compression mill

The advantages of this tool are that it cuts the fibres on the top and the bottom by means of compression section. The compression cutter is especially suitable for milling of CFRP with strong delamination tendency.

Ideal is the use of tools with soldered PCD blanks as cutting edges. But also a protection of the cutting edges by a crystalline diamond film is possible. Disadvantage of the diamond layer, however, is the edge rounding, the layer thickness and the necessary pretreatment, which reduces the sharpness of the cutting edge. Depending on CFRP property, it is decided which version is used. Example of special solutions is the state of the art mill with 2 PCD cutting edeges.

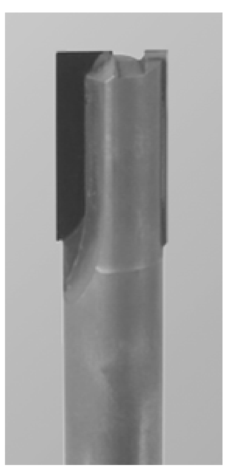


Fig. 5.4. Guhring CFRP 2 edge PCD mill

As new solution for the mill with 2 PCD cutting edges is the mill with 8 PCD cutting edges (D 6,35mm). This PCD milling cutter clearly reduced cutting forces, the tool is ideal for component machining with vacuum fixtures.

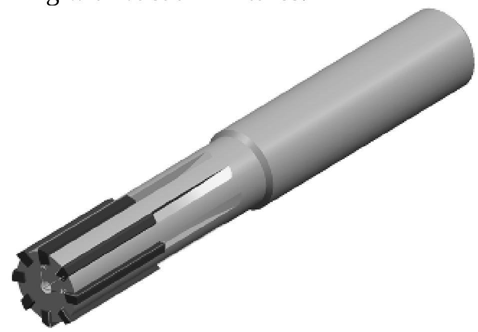


Fig. 5.5. Guhring CFRP 8 edge PCD mill

The new PCD mill with eight cutting edges which replaces the standard PCD mill with two cutting edges because it has 6 time longer tool life (133m) than the 2 edge PCD mill by double the feed rate and improved surface quality.

To improve the performance further, Guhring has been specifically looking for a new cutting geometry. The aim was also to avoid delamination with previously used cutting geometries. Since the fibres can be easily torn out of the compound, the loading direction when cutting must be adapted to the fibres. Pure shearing toward the material, can be realized only by a stroke of the blade, but with a rotary tool which is normally impossible. The solution is to align a component of the cutting force perpendicular to the material. This can be done via a helix angle. Previously it was only possible for structural reasons, to execute only PCD tipped tools with small spiral angles of 4 to 6 degrees.

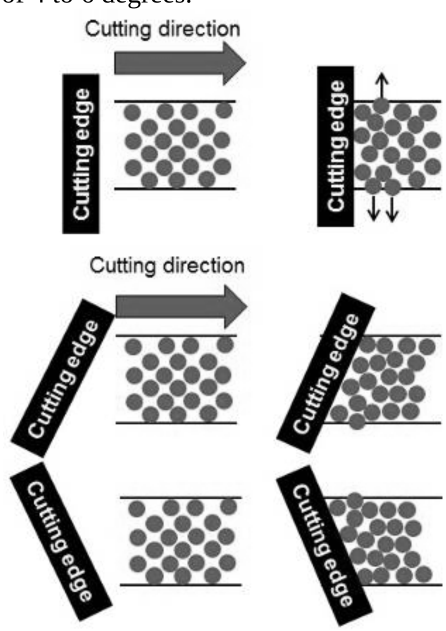


Fig. 5.6. Formation of delamination by straight edges (top) and the prevention of delamination by Gühring's new blade geometry (below)

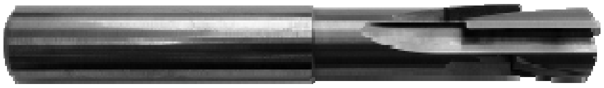


Fig. 5.7. Gühring PCD Mill with new cutting edge geometry

Fig. 5.8. Mill with diamond coating and new Gühring cutting edge geometry

Guhring developed in its centre of excellence for composite materials a new cutter with a new cutting edge arrangement. Two edges are placed in a spiral angle of 25° to each other and it also has the well-known of carbide end mills and reamers uneven distribution of the cut on the periphery. The advantages of this new geometry are

- No premature delamination tendency;
- Extremely quiet operation, even in unstable clamping;
- Delamination free processing;
- High tool life.

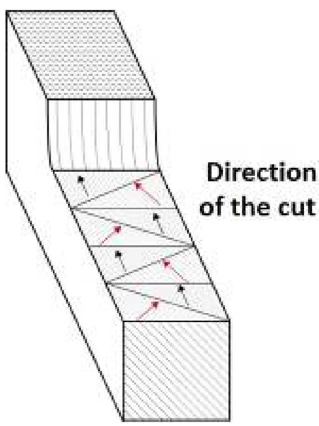


Fig. 5.9. Force direction of new cutting edge geometry

In combination with air cooling through special backwards cooling channels and a corresponding exhaust system it can be processed without contaminating the ambient air. High disposal costs for coolants can be saved, because the machines do not need to be designed for emulsion cooling. Besides the processing advantages the new Guhring CFRP cutter reduces also the investment in the machines considerably.

CFRP materials, because their advantageous properties such as high stiffness and strength, as well as the very small weight, find more and more applications in the automotive, power engineering, shipbuilding, and the leisure industry. Gühring develops continuously in its centre of excellence for composite materials more efficient tools for the machining process of this high-tech material.

6. CONCLUSIONS

Guhring's approach is the holistic tool development and optimization.

During the drilling of unidirectional CFRP carbide tools with radius geometry and "fish-tail" thinning are particularly suitable to prevent delamination.

For the drilling of CFRP stacks tools with additional chip breaker in the flute generate very small chips and hole qualities of IT8.

The super-hard "Signum" layer allows very long tool life and allows the regrinding and recoating of carbide tools for machining CFRP.

Regarding the milling of CFRP, the use of the new suction cooling system has proven to lead to a drastic reduction in heat.

Multi-fluted PCD milling cutters clearly reduced cutting forces with up to 6-times longer tool life.

For milling of carbon fibre composites with high delamination tendencies the new edge arrangement of the compression mill is an effective tool.

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