OPTIMISED MACHINING OF FIBRE REINFORCED MATERIAL

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Abstract: *Fibre reinforced materials are getting more and more important for European manufactures. Coming from automotive and aviation industry nowadays also SMEs have to deal with these high tech materials.*
One of the biggest problem for such companies is the little experience they have in milling these materials. First cutting tests nearly ever result in very bad surface qualities and then companies often stop their efforts.
The focus of the cornet project HPM was to overcome these hindrances for SMEs. The biggest problem therefore is the delamination of upper and lower layer during the cutting process. The Institute for Production Engineering developed a method to reach optimised surface qualities according to the application for different types of fibre reinforced materials like Aramid and Dyneema.
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1. Introduction

During the last years European Manufacturers increasingly have had to deal with low wage labour markets. Companies from these markets originally came from mass production with low accuracy requirements now turning into production of sophisticated parts. In order to be able to deal with this circumstances European manufacturers have to move to the production of parts made of completely new materials. Finding correct cutting parameters for new materials requires big effort; on the one hand due to different cutting tests that have to be done and on the other hand because of the specific know-how that has to be reached in order to optimize results.

There exists a wide range of different fibres, from glass fibres over carbon fibres to special fibres like Aramid, or renewable primary products like hemp fibres. This article focuses on the milling of Aramid and Dyneema fibre reinforced materials.

One of the biggest problems for small and medium sized enterprises is the lack of experience they have in milling such materials. Very often companies stop their efforts because of cutting tests result in insufficient surface qualities. The biggest problem is the delamination of upper and lower layers during the cutting process. The Institute for Production Engineering developed a method to reach optimised surface qualities for the different types of fibre reinforced materials mentioned above. Taking advantage of these developments European SMEs should be able to meet future requirements in milling such high tech materials.

2. Problem definition

As mentioned above it is particularly the delamination of upper and lower layers that constitutes the biggest problem when milling fibre reinforced materials (Fig. 1). Our target was to keep the delamination less than 0.3mm.

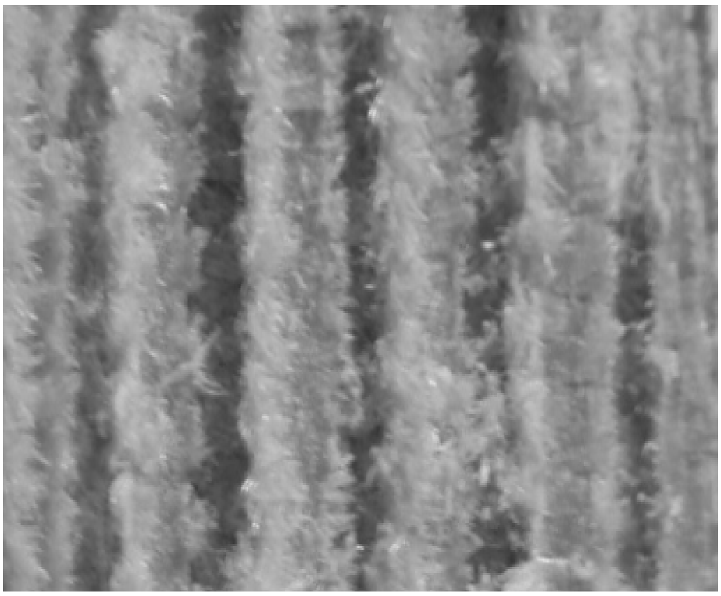

Fig. 1. Delamination of Aramid fibres

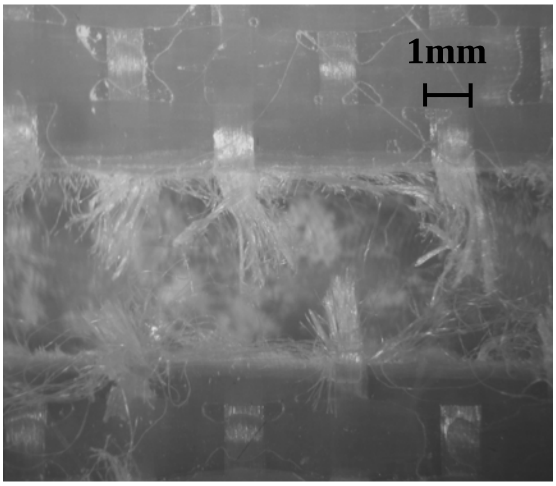

Fig. 2. Delamination of Aramid strands (Microscope view)

The forces during the chipping process are too high to be absorbed by the matrix, normally being a type of epoxy resin. As a consequence the fibres or singular fibre strands (Fig. 2) come loose from the laminate. Another reason is that Aramid and Dyneema fibres are not as stiff as e.g. glass fibres. This makes them quite difficult to cut without any support of the delaminating matrix. In order to prevent delamination, either the matrix, especially the upper and lower layer, or the fibres themselves, have to be made stiffer and therefore easier to cut. Both ways have been analysed and are detailed below.

3. Material

Before describing the different tests, there is given a short overview of the various fibre materials that are available on the market and which of those have already been tested (Flemming et. al., 1995; Flemming et. al., 1996; Ehrenstein, 2006):

- Glass fibres: They are yarned from melted glass with a steady round diameter of 3.5 to 24 µm. The covalent linkage between oxygen and silicon is responsible for their strength. Different types of glass, E-glass (electrical glass – good isolator), R/S-glass (resistant/strength – high-strength glass), C-glass (high chemical resistance), ECR-glass (a mixture of strength and chemical resistant E-glass) and AR-glass (alkali-containing glass), are used to make glass fibres.
- Carbon fibres: Because of their graphite structure they are very strong and stiff. Mostly they are made of Polyacrylnitril (PAN) rather than of pitch. There are different types of carbon fibres available: HT (high tensile), HS (high strength), HM (high modulus), UHM (ultra high modulus).
- Aramid fibres: Other common names are for example Kevlar® and Twaron®. Aramid fibres are linear organic polymers with high tensile load and stiffness with oriented covalent linkages along fibre axis. The fibres are made of Polyphenylenterephthalamid (PPTA) in a wet spinning process. During the manufacturing process the E modulus, both tensile and breaking

elongation can be influenced. These fibres are lighter than glass and carbon fibres but not UV-resistant.

- Dyneema fibres: These UHMPE-fibres (ultra high molecular polyethylene fibres) are mainly used as reinforcing fibres. Besides Dyneema, Spektra is another type of UMHPE-fibre

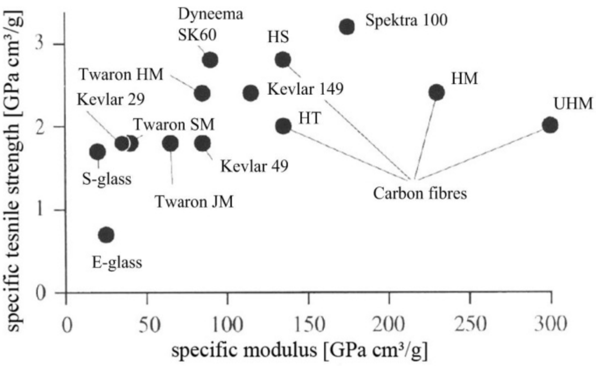

Fig. 3. Specific properties of fibres (Ehrenstein, 2006)

Fig. 3 shows the specific properties of fibres used for reinforced materials. The reason why mainly glass fibres and carbon fibres have been examined in a number of different tests is because they are the most common ones, and this is also why there already exist some descriptive literature for cutting processes on them.

In most cases the matrix, required to link the fibres to each other as well as to keep them in place within the material, is a kind of thermoplastic resin or thermosetting plastic (like epoxy resins). The adhesion between fibre and matrix is decisive for the tensile and strength of the whole fibre reinforced material.

The biggest difficulties in cutting fibre reinforced materials occur when dealing with Aramid and Dyneema fibres, so we decided to keep a special focus on them.

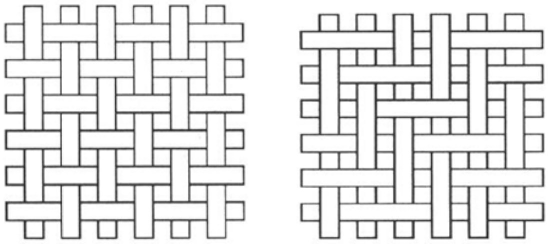

Fig. 4. Plain weave (left hand) and twill weave (right hand) of fibres

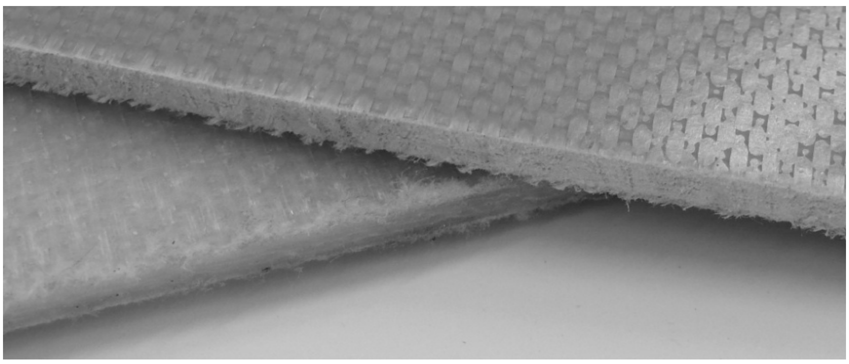

Fig. 5. Dyneema (left hand) and Aramid (right hand) plate

The tested Aramid fibre reinforced material (Fig. 5) was a plate of 16 layers Aramid fibres with a standard epoxy resin and plain weave (Fig. 4) interlace. It has a fibre ratio of 50.3 Vol. % and a thickness of 3.5 mm. The Aramid fibre used is Style 160 UD (company S*wiss-composite*) with a grammage of 163 g/m². The shoot has a yarn count of 23 tex and the warp 166 tex. Each layer has an offset of 45° to the former layer.

The tested Dyneema fibre reinforced material (Fig. 5) was a plate of ten layers Dyneema fibres with a standard epoxy resin and twill weave (Fig. 4) interlace. It has a fibre ratio of 47 Vol. % and a thickness of 3.5 mm. The Dyneema fibre used is Dyneema SK60 (company *C.Cramer & Co*) with a grammage of 180 g/m². Both, the shoot and the warp have a yarn count of 132 tex. Each layer has an offset of 45° to the former layer.

4. State of the art in cutting Aramid and Dyneema

Considering that there is hardly any descriptive literature on cutting processes for Aramid and Dyneema in general, and for milling in particular, we analysed literature for the milling of glass and carbon fibre reinforced materials. Most manuscripts deal with lifetime behaviour of milling cutters but not with getting optimised surface qualities. In order to increase the lifetime of milling cutters when cutting glass fibres, special PCD (polycrystalline diamond) milling cutters are used. However, the problem with PCD milling cutters is that you can not get a very sharp cutting edge (big chip and clearance angle) which is necessary to get a sharp cutting line on the material. Therefore solid carbide tools are used in order to reach these geometry requirements (Neitzel & Schlimbach 2003). The biggest cutting problems with Aramid and Dyneema are (Wiendl, 1987):

- Distinctive delamination
- Insufficient surface quality
- Low durability

In order to reduce delamination it's recommended to cut with high cutting speed and low feed rate. However, also the ratio and orientation of fibres are very important for optimised results.

5. Tests at the Institute of Production Engineering

The first step was to test different milling cutters by milling linear grooves with different cutting parameters. We varied the cutting speed from 100 up to 1,000 m/min and the feed rate from 0.1 up to 15 m/min. To be able to test different milling cutters we contacted several international tool resellers. In total we tested 13 different milling cutters, some of them explicitly recommended for the milling of fibre reinforced materials with different geometries and numbers of cutting edges. All tests ended with more or less the same result: very bad surface (more than 1 mm delamination) quality due to delamination of the upper fibre layer. Especially tests with micro toothed milling cutters for glass and carbon fibre reinforced materials resulted in low quality surfaces.

Like mentioned above, it is necessary to use milling cutters with a very sharp cutting edge. For final tests we have chosen a one edge solid carbide milling cutter, actually intended for the milling of aluminium, with a lip angle of 60° (clearance angle 16°; chip angle 14°). Although the results with this milling cutter were better, they were not satisfying. In particular there is a very evident difference between cutting in direction and rectangular to direction of upper layer fibre strands as shown in Fig. 6. Therefore it's necessary to find a solution which leads to optimised results independent of direction of fibre strands.

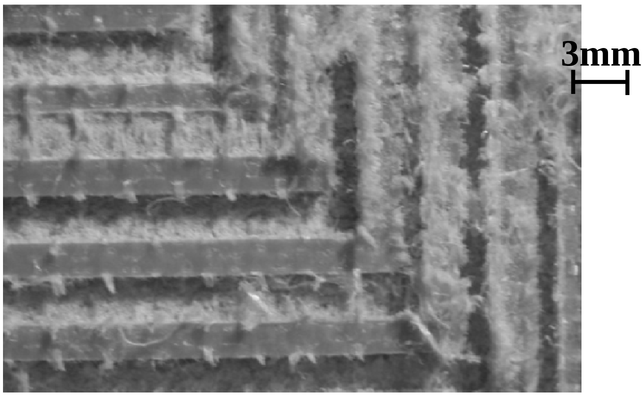

Fig. 6. Delamination in direction (left hand) and rectangular to direction of upper layer fibre strands (right hand)

As very next step we had to develop a solution for restraining fibres avoiding the cutting edge of the milling cutter. To reach this goal two ideas were developed:

- making the fibre stiffer by external cooling
- finding a mechanical way to fix the fibres in the matrix

First we tried to make the fibre itself stiffer by using CO_2 cooling. It's possible to reach temperatures lower than -50°C. Despite the low temperature the stiffness of the fibres was not sufficient enough to guarantee easier cutting and consequently increased surface quality. In Fig. 7 the process of cutting with CO_2 cooling is shown on the left and the results of these tests on the right. We've certainly tested different cutting parameters, but unfortunately each configuration was resulting in the same bad surface quality. Therefore external cooling can't be considered an adequate solution to reach the set targets.

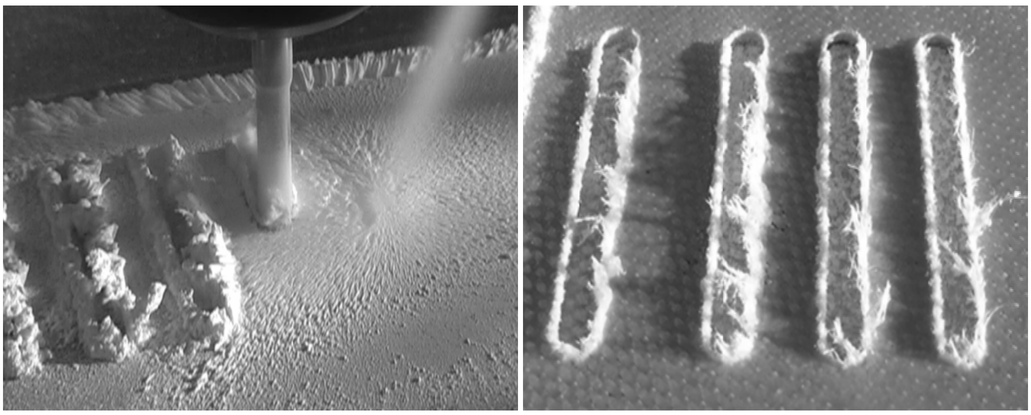

Fig. 7. Cutting Aramid fibres with CO_2 cooling

The second idea was to fix the fibres mechanically within or on the matrix. Therefore the manufacturer of the test material produced some plates with different upper and lower layers that are easier to cut. These plates consist of:

- 16 layers of Aramid fibres with lacquer coating as upper and lower layer
- 16 layers of Aramid fibres with polyester fibres as upper and lower layer
- 16 layers of Aramid fibres with glass fibres as upper and lower layer

Tests carried out using the new material showed that the surface qualities are better than in former tests but still not satisfying. That's why we took a step further in mechanical fixing and pasted up a thin aluminium plate on the upper layer and fixed the entire "test compound" on a plate of plastic with a double-face scotch tape in order to mill through the whole compound (Fig. 8).

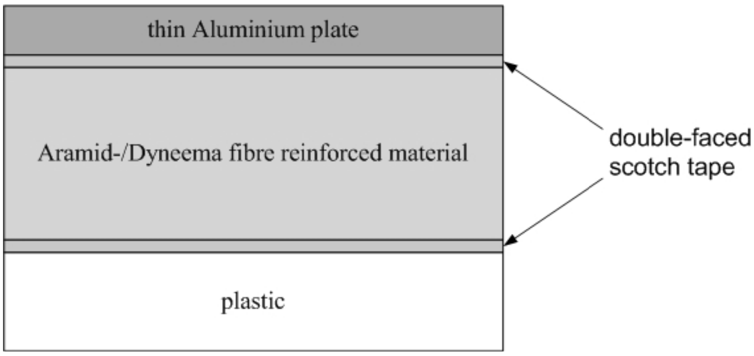

Fig. 8. Test compound

To reach an optimised surface quality without having regard to the orientation of fibres (Fig. 9) we decided to mill circles with a diameter of 26 mm in order to eliminate the influence of orientation of fibres and fibre strands.

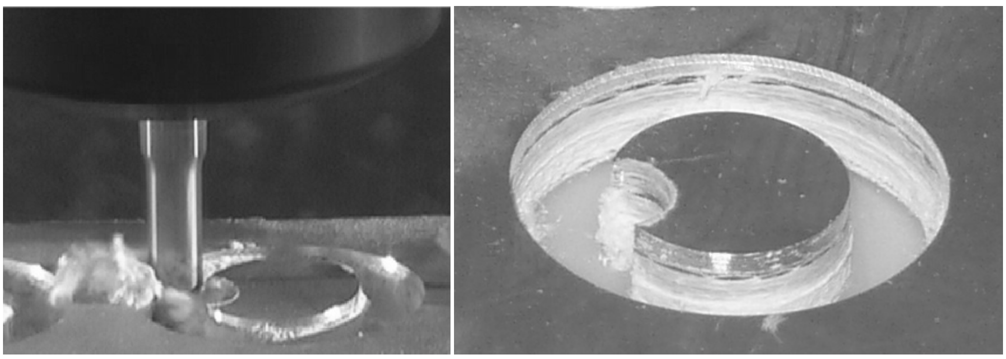

Fig. 9. Final cutting tests in progress (left hand) and finished (right hand)

The thickness of the scotch tape has great influence on the delamination. As intersection the delamination is about as big as the thickness of the scotch tape. It is also necessary to be careful that the adhesive force of the tape is high enough to hold the aluminium plate on the material, as otherwise the delamination would be much bigger. The tape effectively used had a thickness of 0.1mm.

With the final test configuration we achieved a delamination of about 0.1mm with all materials. The used cutting speed was 190 m/min and the feed rate was 250mm/min. The very best results were obtained with Dyneema and Aramid with polyester fibres as upper and lower layers (Fig. 10). Compared with the first results

(Fig. 1 and Fig. 2) we were able to reduce delamination from several millimetres to less than 0.1mm.

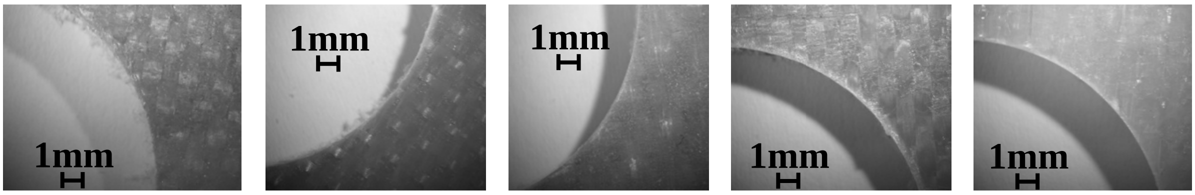

Fig. 10. Final results (from left to right: Aramid with Lacquer coating, Aramid with glass fibre layer, Aramid with polyester layer, standard Aramid, standard Dyneema)

6. Conclusion

In particular the upper and lower layers have the biggest influence on the surface quality when cutting fibre reinforced materials. As especially the milling of Aramid fibre reinforced materials requires a very sharp cutting edge (big clearance and chip angle and small lip angle), it is necessary to use solid carbide milling cutters. The cutting depth shall not be less than 1 mm; otherwise there would be a higher risk of delamination, as the matrix would not be stiff enough to absorb the forces released during the chipping process.

Pasting up an aluminium plate, fulfilling the hypothesis of mechanically fixing the upper and lower layer, is not useful solely for Aramid and Dyneema: Tests on milling glass fibre reinforced materials came to the same positive results.

7. Outlook

Our next step in cutting fibre reinforced materials is to develop a special tool to make the pasting up of aluminium plates unnecessary. This tool has to be suitable for all kinds of fibre reinforced materials and has to face the aspect of optimised surface quality.

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