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MILLING TOOLS FOR CUTTING OF FIBER-REINFORCED PLASTIC

Composites with thermoplastic matrix are used in a wide range of applications. Their production and application volume grows every year. The need for precision machining of a near-net-shape workpiece is a topical subject, which concerns many cutting tool developers. The main challenge lies in the combinations of the long tool life and perfectly machined surface of composite workpiece without the burrs or delamination. The fulfilment of these two options needs using of the specific cutting geometry and very stiff and solid material of the cutting tool which is resistant against the abrasion of the filament. This paper presents a case study for comparison of cutting tools for edge trimming operations. The burr size and the tool lifetime were evaluated for milling of two types of fibre reinforced thermoplastic composite materials: PPS/C and PEEK/C. The total machining costs were computed for specific cases.

1. INTRODUCTION

The number of fibre reinforced thermoplastic composite (FRTC) applications is increasing. The main applications are used in the automotive and aerospace industry. The great advantage of FRTC is in manufacturing processes; final products can be directly formed from the semiproduct (thermoforming in a press) or directly consolidated (winding or tape placement using local consolidation by a laser or a gas). The processes are in comparison with thermoset solution significantly faster and cleaner. Additional advantage in these materials is in a possibility to combine the technologies (e.g. winding and thermoforming; thermoforming and inserting), to produce complex components in series of quick operations. For finishing of the components, machining still remains an important technology.

The presented paper focuses on a milling of FRTC components. The combination of a tool material, tool geometry and cutting conditions strongly influences the cutting tool life and surface quality of the machined parts. The task is complex due to the wide range of structure of the machined components. As each component can be made with a different

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lay-up from a different semiproducts and different fibres and matrix material, the cutting conditions for achievement of the best cutting quality and tool lifetime can differ significantly.

From the group of fibres used in FRTC applications, the most important are high-strength carbon fibres (T300, T700, AS4) and E-type glass fibres. Both types are hard and abrasive. The components can be processed either from unidirectional tapes or woven fabrics; the structure of these semiproducts has a strong influence for the cutting conditions in addition to the layers'lay-up.

A wide range of polymers are used for FRTC, from "low-performance polymers" like PP, PA6, PA12 to high-performance polymers like PPS, PEEK or PEKK. Since the thermoplastic matrix is soft and ductile, small chips are created during machining. Temperature of the cutting process is critical parameter during machining of these thermoplastics. If the temperature of machining exceeds the melting temperature for crystalline thermoplastic materials, the molten chips can adhere to each other, to the material and also to the cutting tool. It leads to a decrease in the surface quality of the composite and a decrease in the cutting tool lifetime.

Detailed literature reviews on machining composite materials can be found in [1–6]. However, the main focus of many authors is on carbon fibre reinforced plastics (CFRP) with the epoxy matrix. The significance of fibre orientation is highlighted as an important factor when machining CFRPs. Ferreira et al [7] optimized tool and cutting condition for CFRP turning. They recommended PCD (PolyCrystalline Diamond) tool with positive face angle for longer tool life and best surface quality. Colligan and Ramulu [8],[9] characterised typical forms of CFRP delamination during contour milling. They also mentioned importance of the top laminate layers support for delamination minimization. Hintze et al [10] described novel method for analysing top layer delamination in milling of CFRP tape in an experimental study. Davim [6] presented the advantages of the double helix tool design edge trimming of CFRP. Chatelain and Zaghbani [11] identified the cutting force as good indication of cutter performance during stable trimming of the CFRP. They also recommend positive tool rake angle for reduction of cutting forces and delamination. Kalla et all [12] and Karpat [13] proposed mechanistic cutting force model for milling of CFRP with respect to the fibre orientation. Karpat and Polat [14] applied this force model also on double helix tool design.

As was mentioned, the materials with thermoplastic matrix (FRTC) have different properties than materials with epoxy matrix. Although the published results regarding the influence of fibre orientation and its abrasiveness to the tool wear remain valid, the burr formation of the thermoplastic matrix will be different. Masek et al [15] presented advantages of double helix tool design for FRTC trimming. Strong influence of the cutting edge geometry on the workpiece surface quality. The focus of this paper is on finding out the optimal cutting geometry and the cutting tool material for a good workpiece surface quality high quality cut and low total machining costs. The paper is focused on edge trimming of the PEEK/C and PPS/C FRTC which are most often applied in the industry.

The paper presents experimental comparison of four prototype tools and one commercial available tool for FRTC edge trimming. PCD and carbide tools with various coating are used in the test. The burr size, the tool life and the total cutting costs are

compared for the different tool designs. The paper is organized as follows: description of tools for experimental comparison is in the chapter 2. Results of the burr creation test during milling of the PEEK/C with unidirectional AS4 fibres are presented in the chapter 3. The PEEK has high toughness that can cause a big burr if the tool geometry is not optimal. In the chapter 4, the tool life of the tool with the lowest burr was tested for edge trimming of PEEK/C with unidirectional AS4 fibres and PPS/C woven with T300 fibres. The important difference is in the fibre structure (unidirectional vs. woven) and its abrasiveness. The total cutting costs are compared in the chapter 5 for complex evaluation of the presented results.

2. DESCRIPTION OF TESTED TOOLS

Five types of the milling tool were used for the tests. Four of them are prototypes produced with respect to the existing production technology of PCD and cemented carbide tools. Thus, tool geometry, number of teeth, material and coating are different. The last tool is standard commercial available tool used as a reference tool for the tool comparison. The cutting tool parameters are in Table 1. The positive geometry of the PCD tools is an issue.

Table 1. Cutting tools used in the experiment

Name	DEMO1	DEMO2	DEMO3	DEMO4	Standard tool
Material	PCD	Carbide	PCD	PCD	Carbide
Coating	Uncoated	CVD diamond c.	Uncoated	Uncoated	Titanium-based c.
Diameter	12mm	12mm	12mm	8mm	12mm
No. of teeth	4	5	1	2	2
Clearance angle*	10.5/10.6	13.8/6.1	11/10.9	14.5/14.9	22.6/20.4
Rake angle*	2.2/3.9	20.1/20.2	4.4/4.5	2.6/3.8	21.2/25.7
Helix angle*	16.6/15.9	20.1/27.9	10/9.9	4.9/5.7	17.9/17.9

* Measured values on the top/bottom teeth.

Since the PCD wafer is flat, the positive rake angle is done by tilting of the PCD wafer in the tool body. The rake angle is not constant because the tool has also a non-zero helix angle of the flat PCD wafer. The presented standard carbide tool with the titanium-based coating represented the best commercially available tool [15] as a reference for the experimental tools.

3. BURR CREATION TESTS

The four experimental cutting tools (DEMO tools – Table 1) were tested in terms of the size of burr firstly. The experiment conditions are described in Table 2. The PEEK/C with unidirectional AS4 fibres in a ply was used for these tests.

The tested method was focused only on the burr formation. There were not observed any problems with delamination. The burr formation was measured by the evaluation of photographed pictures. The picture of the composite coupon edge were took. The burr was separated from the rest of the picture. Since the size of one pixel of the image was known, it was possible to evaluate size of burr in square millimetres.

Table 2. Cutting conditions for the burr creation test

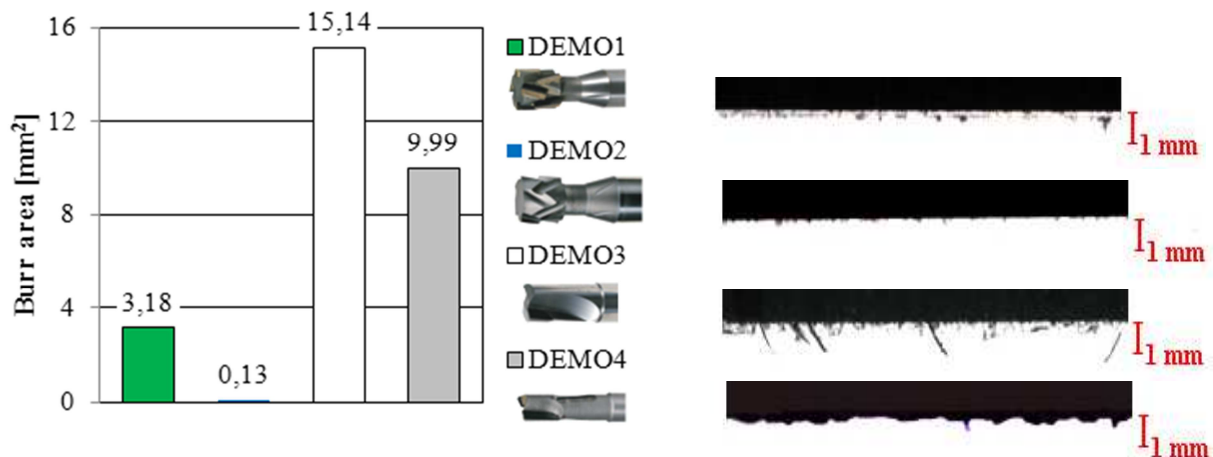| Axial depth of cut a_p[mm]	Radial depth of cut a_e[mm]	Cutting speed v_c[m/min]	Feed per tooth f_t[mm]
5	3	400	0,05

Fig. 1. Comparison of burr creation on the PEEK/C material for prototype tools and example of burr creation

The results for all tools can be seen in Fig. 1. The results are influenced by the combination of the rake angle size and the helix angle size. The smallest burr size was

created by the DEMO2 tool. This tool has the most positive rake angle of all tested tools and also a large helix angle of about 20° concurrently. The DEMO1 tool had a relatively low rake angle value but a helix angle of 16° helped to decrease the burr size.

The DEMO3 and DEMO4 tools had worse results. Both the tools had a low rake angle and also low helix angle. A considerable number of non-cut fibres can be seen in the case of cutting with the DEMO3 tool. This tool was excluded from next tests due to insufficient ability to cut off fibres.

4. TOOL LIFE TESTS

The tool life tests were done on the PPS/C and the PEEK/C materials. The cutting conditions used in this test are presented in the Table 3. The excluded DEMO3 tool was replaced with the standard tool mentioned in chapter 1 as a reference tool.

Table 3. Cutting conditions for lifetime tests

Axial depth of cut a_p[mm]	Radial depth of cut a_e[mm]	Cutting speed v_c[m/min]	Feed per tooth f_t mm]
5	3	300	0.05

4.1. TOOL LIFE AT THE PPS/C CUTTING

The PPS/C composite with the satin woven and T300 carbon fibres was used for the experiment. The results are in Fig. 2. An optical microscopy was used for evaluating of the flank wear according ISO 3685.
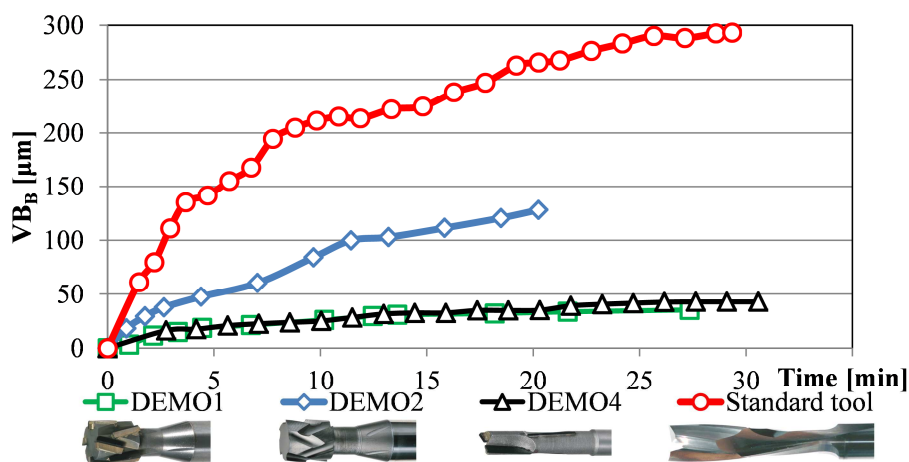

Fig. 2. Tool flank wear for PPS/C cutting

As can be seen, the PCD tools (DEMO1, DEMO4) reached approx. 6 times lower flank wear than the carbide tool with diamond coating (DEMO2). The flank wear of PCD tools was approx. 8 times lower in comparison with the carbide tool with the titanium-based coating (standard tool). The surface roughness and burr occurrence increased with flank wear. It is necessary to keep the sharpness of the cutting edge during milling to prevent burrs and decreasing of surface roughness.

These tests show the good tool life of the PCD tools. The DEMO1 tool has higher productivity because of a higher number of teeth. The DEMO1 and the DEMO2 tool were tested also for trimming of PEEK/C because these materials have a high number of teeth for high productivity milling.

4. 2. COMPARISON OF TOOL LIFE IN THE PEEK/C AND PPS/C

The multidirectional PEEK/C composite (layers orientation [(0/45/-45/90)]2s) with AS4 fibres was used for the experiment. The results are presented in Fig. 3. The DEMO1 and DEMO2 tools were only used. They have potential for high productivity because of a higher number of teeth. The results were compared to the previous results in PPS/C cutting. The cutting tool DEMO4 was drop out in this tests due to its high burr formation in previous tests.
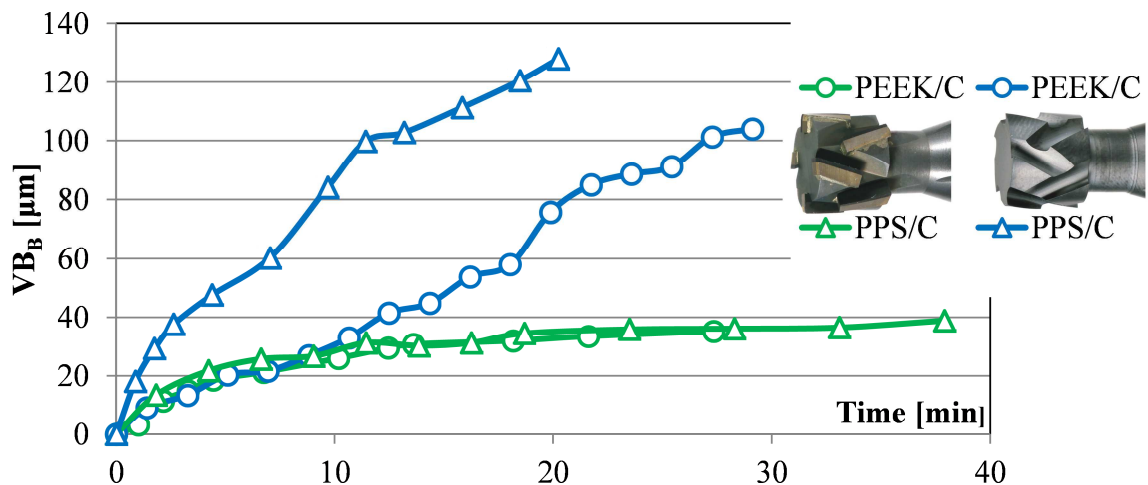

Fig. 3. Tool flank wear for trimming of PEEK/C and PPS/C materials

As can be seen in general, the PCD tool (DEMO1) had lower flank wear in comparison to the coated carbide tool. The Fig. 3 shows that PCD flank wear was similar for both tested composite materials although they had different fibre structure (unidirectional/woven structure) and type.

On the other hand, the different intensity of flank wear can be seen in the case of coated carbide tool (DEMO2). The flank wear during milling of PPS/C was almost

double in comparison to PEEK/C machining. The fibre volume was the same in both materials. The T300 carbon fibres in PPS/C and the AS4 carbon fibres in PEEK/C have similar material properties. PPS/C has woven structure of fibres. PEEK/C includes unidirectional fibres. This fact shows a strong effect of the fibre structure on the diamond coated tool but not on the PCD tool.

5. TOTAL CUTTING COSTS

The economic balance was calculated for cutting tools DEMO1, DEMO2 and the reference standard tool for their complex comparison. The price of the tool, machine tool, labour and running costs was included in the calculation.

The price of the tools and the lifetime results used for the calculation are summarized in Table 4. Three different categories of machine tools were taken into account (Table 5). The relative overhead costs OCR [EUR/cm^3] are computed using economic data on tool cost, machine tool cost, machine tool consumable costs and labour cost. The value is relative because it is per 1cm^3 of the machined material.

Table 4. Overview of economic parameters for the tool comparison

Name	DEMO1	DEMO2	Standard tool
Tool material	PCD**	Diamond coated carbide	Titanium-based coated carbide
Tool price CT	€444	€195	€170
Tool life $T0.1$* [min]	100**	11.5	2.7
Volume of machined material MRT [cm^3]	4775	686	64.5

*$T_{0.1}$ is the tool lifetime for cutting tool flank wear VB_B = 0.1mm. This value of the flank wear is the limit for high quality cut.

**Value of tool life for PCD was predicted on the basis of measured data from Fig. 3 as the worst tool life possible.

Table 5. Prices of the various types of machine tools

Machine tool	3 axis CNC machine tool	3 axis CNC machining centre	5 axis CNC machine centre
Machine features	Automatic tool change, 9 tool magazine	Automatic tool change, 24 tool magazine, automatic pallet change	Automatic tool change, 30 tool magazine, automatic pallet change
Machine tool price	€150,000	€230,000	€350,000
Machine tool overhead costs $OC*$	29 €/hour	36 €/hour	47 €/hour
Spindle speed	15,000rpm	20,000rpm	17,000rpm

* Computed for the three shift operation, 8 hours per shift, depreciation duration of 3 years, consumables costs (cutting fluids, pressurized air etc.) 9 EUR/hour, 254 working days per one year.

On the basis of the data mentioned in Table 5, it is possible to calculate the overhead costs (*OC)* of the complete machine tool including labour cost and consumable costs using this equation:

$$OC = \frac{Machine\ tool\ price/depreciation\ time}{working\ days \cdot shift \cdot 2} + labour\ cost\ per\ hour + machine\ tool\ working\ cost\ [€/hour]. \tag{1}$$

The volume of the removed material per cutting edge life *MRT* can be computed as follow:

$$MRT = a_e \cdot a_p \cdot f_t \cdot t \cdot T_{0.1} \cdot n \cdot 10^{-3}\ [cm^3], \tag{2}$$

where *ae* is radial depth of cut [mm], *ap* is axial depth of cut [mm], *ft* is feed per tooth [mm], *t* is number of teeth, *n* is rotation speed [rpm].

The relative overhead costs per 1 cm³ of removed material (*OCR)* is a sum of overhead costs and cutting tool cost:

$$OCR = \frac{c_T}{MRT} + OC \cdot \frac{T_{0.1}/60}{MRT}\ [€/cm^3] \tag{3}$$

where CT is milling cutter price [€].

The relative overall cutting costs are compared in Fig. 4. As can be seen, the tool relative costs are dominant in the final value. It means the machine tool costs are not of great importance. The PCD tool is the most effective cutting tool as for cost saving. The estimated tool life of the PCD tool is almost ten times higher than the tool life of diamond coated cutting tools and almost 40 times higher than the tool life of the titanium coated tool. This fact is the key feature for the whole cost calculation. The long life of the PCD tools is the main benefit that compensates the tool high purchase price. The economic return period of the tool price is quite short as can be seen in Fig. 5, where the cutting total costs are compared.
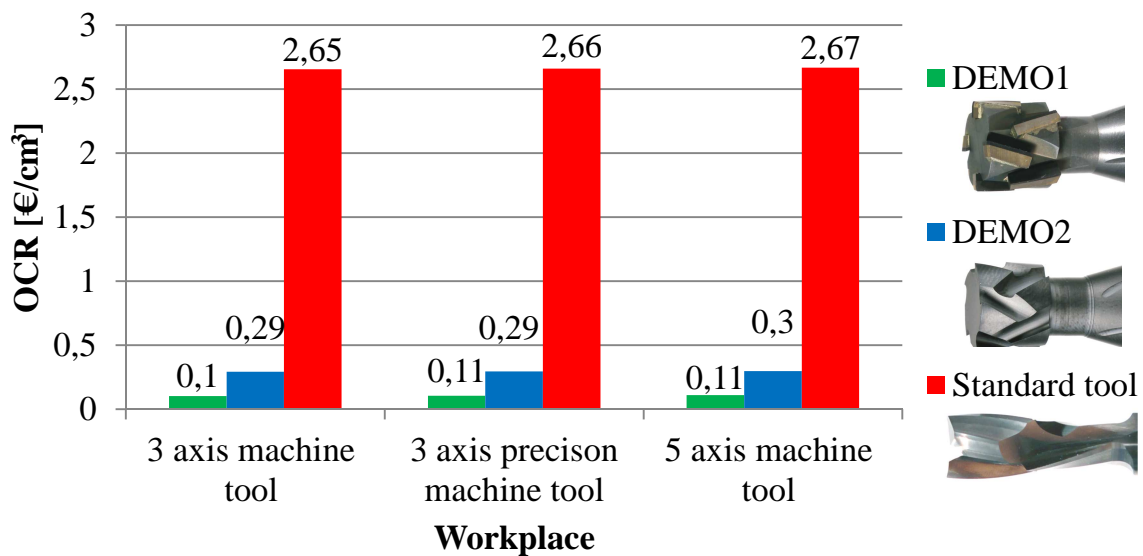

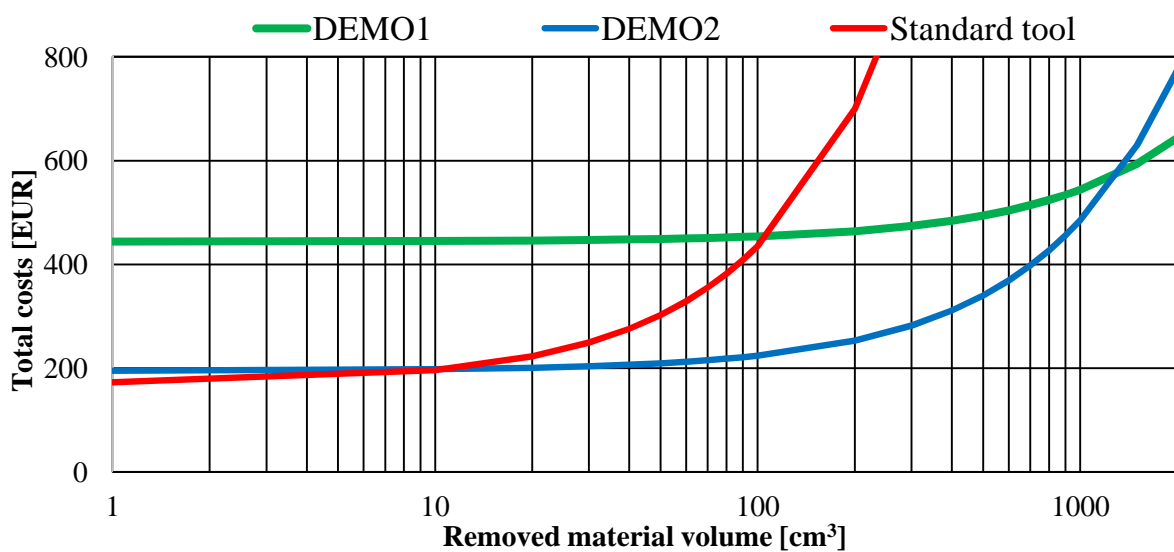Fig. 4. Comparison of the relative overall cost rate for edge trimming of PPS/C

Fig. 5. Comparison of the total cutting costs for edge trimming of PPS/C

6. SUMMARY AND CONCLUSION

The cutting tool development is a complex task which includes technological and economic evaluation of proposed tool designs. The cutting tool for composite materials should be cost-effective and give very good surface quality.

The tool for FRTC edge trimming has to have very positive geometry, sharp cutting edge and double helix design. These features are the key factors for achieving the high quality cut with small burr and without non-cut fibres. The workpiece surface quality is influenced by the combination of the rake angle size and the helix angle size. The smallest burr size is created by the tool with a positive rake angle of approximately 20° and also a large helix angle of approximately 20°. The cutting speed is limited by the FRTC melting point. The cutting speed top values can be up to 300m/min. However, the feed per tooth should remain about 0.05 mm. The higher values of the feed per tooth cause large burr and low surface quality for all tool types and geometries.

Since fibres are abrasive, application of PCD tools is suitable. The main issue is production of the double helix PCD tools because it is challenging to adjust all tool tips into the right positions. On the other hand, PCD tools have a long tool life, which results in low cutting costs for high volume production. They tool life is not affected by the kind of the fibre structures in composite. The diamond coated carbide tools are an economical alternative to piece and low-series production. The surface quality can be increased and burr size decreased using more positive geometry produced by laser micromilling on the PCD tips. This is a topic for further research.

The double helix carbide tools are an alternative solution for piece and low-series production. It is possible to reach high workpiece surface quality due to complex cutting edge geometry with the positive rake angle. The carbide tools are sensitive to the fibre structure. The woven structure causes bigger flank wear than unidirectional fibres.

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