DEVELOPMENT OF A CUTTING TOOL FOR COMPOSITES WITH THERMOPLASTIC MATRIX

Petr Masek, Pavel Zeman, Petr Kolar
Czech Technical University in Prague
Research Center of Manufacturing Technology
Prague, Czech Republic

e-mail: p.masek@rcmt.cvut.cz

Fibre reinforced thermoplastic composites (FRTC) are becoming an increasingly important material for a wide range of applications. Thus, the demand for high performance tools for machining of this material is increasing. The main goal of the presented research results is to decrease cutting costs during trimming operations of thin plates and to increase the quality of machined composite materials by suitable shape, geometry and material of the cutting tool and by suitable cutting conditions. Statistical methods were used in order to obtain the control factors (cutting conditions) which are the most important for machining FRTC. Subsequently, an optimal adjustment of cutting conditions was identified. The paper is a brief summary of the cutting tool development. It includes important parts of tests and their results as well as some interesting findings implicit in experiments and measuring.

Keywords:
thermoplastic composite, cutting tool, cutting conditions, development, milling

1. Introduction

Machining of composite materials is nowadays an issue which includes mainly cutting tool lifetime and surface quality of machined parts. This development was focused on the milling of FRTC materials. Different applications for using these materials need different composition of composites materials. Composite materials usually consist of a polymeric matrix and fibre reinforcement. A thermoplastic matrix of composite materials with fibre reinforcement is rather different from thermoset polymers. Thermosetting matrices are more brittle than thermoplastic and during machining create chips like dust [Peters 1998]. Exhausting is necessary if this type of composite is machined. Thermoplastics are softer and more ductile. Small chips are created during machining. The amount of dust is minimal and consists mainly from debris of broken fragile fibres. Temperature must be carefully observed. If the temperature of machining exceeds the glass transition temperature for a given polymeric matrix, the composite loses its mechanical properties. Polymeric materials do not conduct heat very well. Heat concentration in the cutting area occurs during machining at high cutting velocities. The matrix became soft and molten. 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 [Quadrini 2007].

There are many variants of fibres in these two main groups and other groups such as aramide, basalt and natural fibres. Two mostly used types of fibres are carbon fibres and glass fibres. Carbon fibres are tougher and conduct heat better than glass fibres. The type of reinforcement also influences the behaviour of the composite during milling. The fibres are very hard and abrasive. They cause rapid wear of the cutting tool. The content and orientation of fibres in composites influence tool life time and surface quality (delamination, burrs creation) as well [Sheikh Ahmad 2009]. There are three main types of reinforcement in the case of fabric: unidirectional, multidirectional and woven reinforcement [Ehrenstein 2009].

This paper focuses on the milling of FRTC materials. Milling of composite materials is a branch which is primarily focused on trimming of flat or curved panels as parts of planes, cars and industrial and energetic devices. Other milling operations are milling of internal shapes and holes and slotting. The trimming operation of flat panels was chosen in this paper because it is the most representative technology of the milling of FRTC materials. The main task was to improve the surface quality and productivity and decrease costs which are connected with this type of machining.

Some papers have been focused on milling of composite materials. The results presented in these papers affected the design of our experiment. The up milling was identified as better than down milling for better surface roughness [König 1985] but the situation is different for the delamination of composite. Down milling was slightly better in Coligan and Ramulu paper [Colligan 1991]. This paper was also focused on the orientation of the fibres in the composite and various types of delamination. Cutting speed and feed rate was identified as relevant for testing on the basis of the Davim's experiments. The feed rate was more significant than the cutting velocity but both were statistically significant. The delamination and cutting forces were smaller when the feed rate was smaller [Davim 2004]. The depth of cut could be also relevant for testing. The surface roughness is influenced by depth of cut [Sheikh Ahmad 2009].

The tests were divided into two stages. The first one was oriented to the test of standard commercially available tools which were recommended by producers for machining of polymeric composites. Six tools were chosen from the wide portfolio of cutting tools on the market as suitable representatives (Fig. 1). The second stage focused on testing new cutting tools which were proposed on the basis of the test in the first stage.

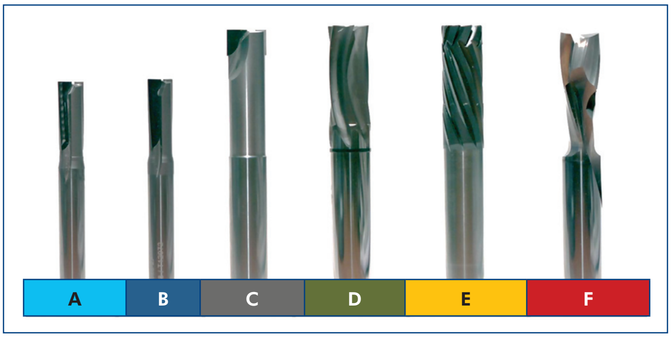


Figure 1. *Six chosen cutting tools.*

Identification of cutting tool	Number of teeth	Diameter [mm]	Material of cutting edge	Clearance angle	Rake angle	Helix angle
A	2	8	PCD	17.84	5.06	5.09
B	2	8	PCD	17.16	–15.58	5.13
C	2	12	PCD	10.09	0.37	2.53
D	6	12	Carbide with diamond coating	11.28	20.72	16.03
E	9 x 2	12	Carbide with diamond coating	8.68	12	20.17
F	2 x 2	12	Carbide with Ti28 coating	22.34	21.64	17.83

Table 1. *Parameters of tested cutting tools.*

2. Test of standard commercially available tools

Commercial tools which were chosen for testing in the first stage are standard tools recommended by different companies for the trimming operation. The tools were compared in terms of cutting forces, surface roughness and burr creation. The Taguchi design of experiment (DOE) was used [Taguchi 1987]. It allows a reduction in the number of necessary experiments in the test by consolidating some less important effects of interactions with the main effects. The control factors for this experiment were cutting velocity, feed per tooth, radial depth of cut, milling strategy and surface ply orientation. Two interactions were chosen on the basis of preliminary tests. The first one was interaction between the feed rate per tooth and cutting velocity. The second one was interaction between the feed per tooth and radial depth of cut. They were chosen on the basis of the ANOVA test results and heredity of significance. This means that if the control factors are very statistically significant, it is possible that their interaction will be also statistically significant. The DOE is in Tab. 1.

Run ID	A (f_t)	B (v_c)	AB	C (a_e)	AC	D (strat.)	E (ply orient.)
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

Table 2. *Taguchi DOE.*

The DOE needs two levels of control factors and chosen interactions. Levels for each control factor were chosen as shown in Table 2.

Parameters/Factors	Unit	Symbol	Levels	
			Level 1	Level 2
feed per tooth	mm	f_t	0.05	0.1
cutting speed	m/min	v_c	150	300
depth of cut	mm	a_e	1	3
strategy	–	–	Up milling	Down milling
ply orientation	–	–	PW	PX

Table 3. *Machining parameters and their levels.*

The polyphenol sulfide (PPS) with woven carbon fibres reinforcement was used as tested material. The test Material had 5-harness satin weave structure. Two different orientations of surface plies PW and PX were cut (Fig. 2).

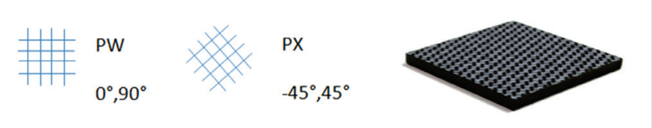


Figure 2. *Diagrams of surface ply orientation PW and PX and specimen of PPS/C on the right.*

2.1 Results and discussion for commercial tools

The statistical comparison fails for measuring of burrs. The method of measuring used is significantly influenced by the place of cutting on the specimen and the definition of the photograph. The resolution ability of this method is decreased by this. It was not possible to apply the S/N ratio method in regard to small differences between results in the experiment runs for all tools. But there was an obvious difference between the results for all tools (Fig. 3). The higher positivity of the rake angle caused elimination of burr creation.

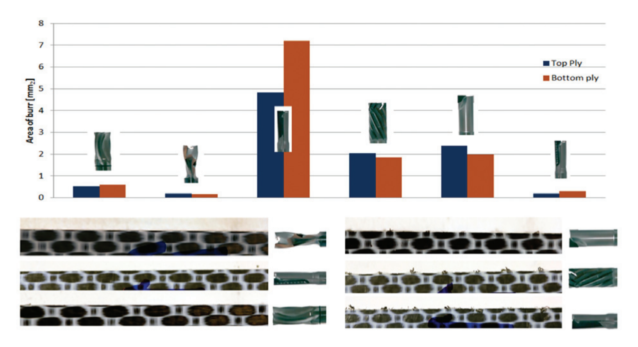


Figure 3. *Direct comparison of burr area.*

It is possible to deduce significance of the cutting tool and its geometry in the case of burr creation from the previous diagram. The values of data could be averaged in order to unambiguously determine the suitability for cutting-off of burrs. We can see that cutting tool "F" has the most suitable geometry. This cutting tool has a very sharp geometry. It has a very positive geometry of rake and clearance angle, more than 20° and the helix angle is 18°. This might be the most superior choice for cutting tool which creates clear edges without burr.

It is possible to say after comparison of Fig. 3 with Table 3 that the rake angle together with the clearance angle may be the most important factor for removing burr. This is true for cutting tool "F", "D" and "A". The slight positivity of the rake angle and helix angle are probably of benefit. Cutting tool "E", which also has high values of the rake angle and helix angle, is limited by a high number of teeth. Flutes of the cutting tool are not sufficient for removing chips. It could be the reason for the deterioration of cutting-off of the top and bottom burr on the specimen. Cutting tool "B" has a rake angle equalling 0. Its results are similar to cutting tool "E" in the case of burr. Cutting tool "B" has the most unsuitable geometry. Its negative geometry of the rake angle, small helix angle and the fact that the helix only has a sense in one direction (compressed helix) causes the creation of large burr on the bottom edge of the composite.

The surface of composites differs from the surface which is created after machining metals. While metals are homogenous, composites consist of fibers which are very hard and brittle and a matrix which is rather yielding. It is possible to observe small holes on the machined surface after milling. These holes were formed by pulling out of the bonds of the fibers or destroying these bonds. A photograph of these holes was taken by a confocal microscope (see Fig. 4).

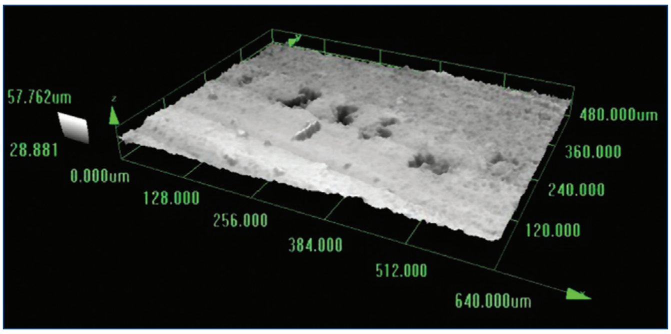


Figure 4. *Holes on the machined surface from confocal microscope, zoomed 480x.*

The holes are not bigger than 70 μm in diameter. The holes are impossible to see by the naked eye but they can have a significant influence on the evaluating of surface roughness. The stylus tip on the pick-up of Surtronic 3+ has a radius of the tip 5 μm. It is possible that the stylus tip may go down the hole. Some of these holes are almost 30 μm deep and evaluating of *Rz* surface roughness may be probably influenced by this [Masek 2012].

The statistical evaluation of surface roughness was made for both tools. The differences between results in runs were too small and this was the reason why the S/N ratio failed (Fig. 5). It is not possible to decide which factor was more significant than others. It was also impossible to decide how beneficial the chipbreaker was in the case of surface roughness. The differences between cutting tools were smaller then differences between runs and both were smaller than the measuring device uncertainty of measurement.

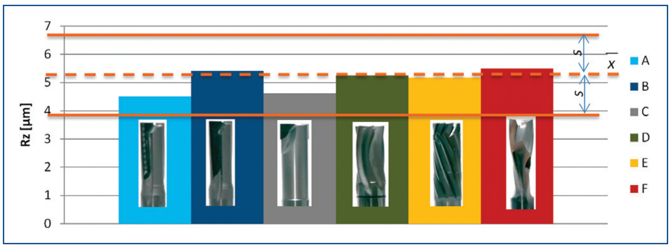


Figure 5. *Comparison of the Rz parameter for all tools in each run of experiment.*

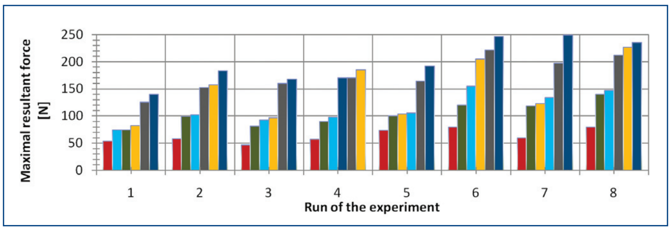
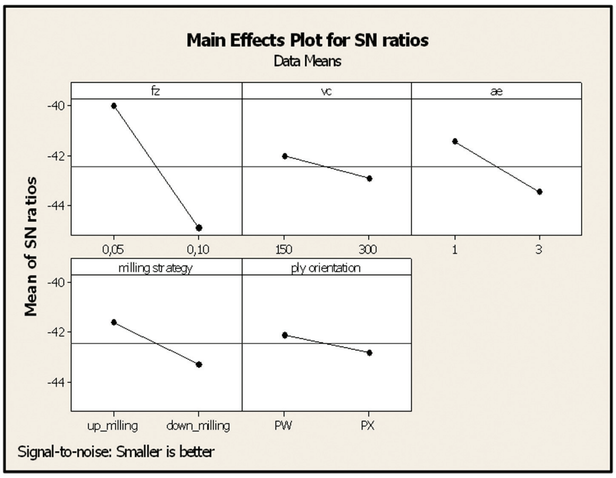


Figure 6. *Results of maximal resultant forces for all tools and all runs.*

The smallest resultant forces were gained by cutting tool “F” as can be seen from Fig. 6. The resultant forces were up to 60 N for low feed rates and up to 80 N for high feed rates. The highest resultant forces were obtained during milling by cutting tool “A”, where the cutting forces were at a level from 150 to 190 N for low feed rates and from 190 to 250 N for higher feed rates, i.e. almost 3 times higher values of the resultant force. Again, the most suitable and the least suitable cutting tools were determined, this time for the maximal peaks of the resultant force. This result corresponds to the results of burr evaluation. Other cutting tools deserve deeper analysis because their rank of suitability was not definitive for all runs of this experiment. It is possible to estimate from the diagram that generally, cutting tools “E” and “B” were less suitable and tools “D” and “A” were more suitable, as in the case of burr evaluation.

S/N ratio was made in order to identify the most significant control factors. The most significant control factor was feed per tooth for most cutting tools. Another result was only for ”D”. It had radial depth of cut as the most significant factor probably due to a high number of teeth. It is recommended to machine with low feeds. All tested tools reached smaller forces for low level of feed per tooth in the test. Radial dept of cut and milling strategy were similarly significant. The optimal milling strategy was up milling. Cutting velocity influenced forces less than expected. Low velocities can be recommended as suitable for trimming. Orientation of fibres was almost insignificant for most cutting tools.



Response table for S/N ratio – smaller the better

Level	f_t	v_c	a_e	Milling strategy	Ply Orientat.
1	-40.00	-41.99	-41.44	-41.61	-42.10
2	-44.90	-42.91	-43.46	-43.28	-42.79
Delta	4.90	0.92	2.02	1.67	0.69
Rank	1	4	2	3	5

Figure 7. *An example of S/N ratio evaluation for resultant cutting force – cutting tool “C”.*

On the basis of the first block of test, the most effective parts of cutting tools were determined. A compressive helix was effective in the case of burr reduction. The upper plies are compressed into the composite. Created burrs are then easier to cut by the next tooth. The best cutting tools in terms of small cutting forces and burrs had a very positive rake and clearance angle. The longest lifetime of the cutting tool can be achieved only with diamond coating on the carbide substrate or with PCD materials. Tools with PCD were not conspicuously worn and the diamond coated tool only slightly after completion of the first block.

3. Proposal of new tools

Two prototype tools were developed using information from preliminary tests of commercial milling tools. The main difference in the tool design is cutting edge material and geometry. Both cutting tools had a compressive helix. One was cemented carbide with diamond coating and the second one was carbide tool with soldered

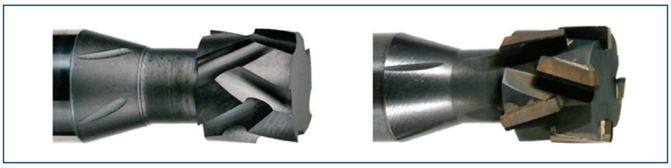


Figure 8. *New developed cutting tools DEMO1 (left), DEMO2 (right).*

Identification of cutting tool	Number of teeth	Diameter [mm]	Material of cutting edge	Clearance angle	Rake angle	Helix angle
DEMO1	5 x 2	8	Carbide with diamond coating	13	20	20
DEMO2	4 x 2	8	PCD	16	3	16

Table 4. *Parameters of new cutting tools.*

PCD tips. A maximum number of teeth was designed for the diameter of 12 mm in order to meet the requirements of high positivity of cutting angles and helix for maximizing cutting tool productivity.

The rake angle for the PCD cutting tool was only 3°. The reason for this were difficulties in production. PCD tips are made as flat plates. Higher positivity of the rake angle can be reached only by sloping the PCD tip in the carbide bed. That means that the rake angle was variable along the whole length of the helix and 3° of the rake angle was only in the cutting plane.

Both cutting tools were tested on high performance material PEEK/C. PEEK is a polymer matrix characterized by higher toughness and higher melting point and glass transition temperature than PPS. The reinforcement was multidirectional and carbon fibres were AS4. Criteria of testing were mainly burr creation and tool life time.

3.1 Results and discussion for new tools

The burr area was measured for both the new cutting tools and the best commercial tool "F" for comparison. The results of the test are in Fig. 9. The cutting tool DEMO2 created big burrs along the whole length of the specimen as is shown in the same figure. The burrs were bigger for small feed per tooth than for high in the case of this tool. Tool DEMO2 had a small rake angle and it could be the cause of the bad results in terms of the burr creation. The results of the new carbide tool with diamond coating and commercial "F" are almost the same. Both tools had a very positive cutting edge, which was beneficial for successful cutting–off of burrs.

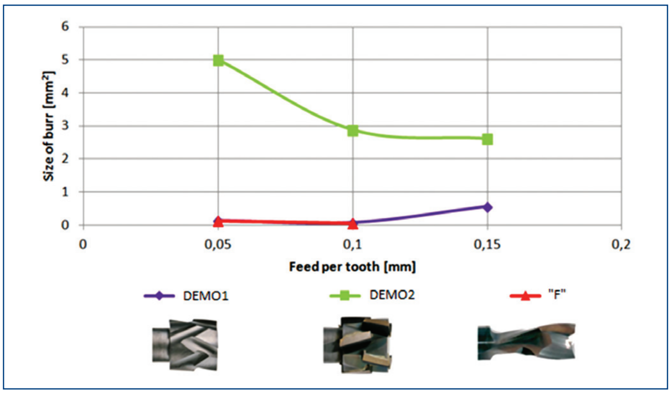


Figure 9. *Creation of burrs – Comparison of the new cutting tools and cutting tool "F".*

The next comparison was focused on the tool life time tests. The testing was made under the same cutting conditions and these were: Feed per tooth 0.1 mm, cutting velocity 300 m/min, radial depth of cut 3 mm, down milling, and the surface ply orientation PW.

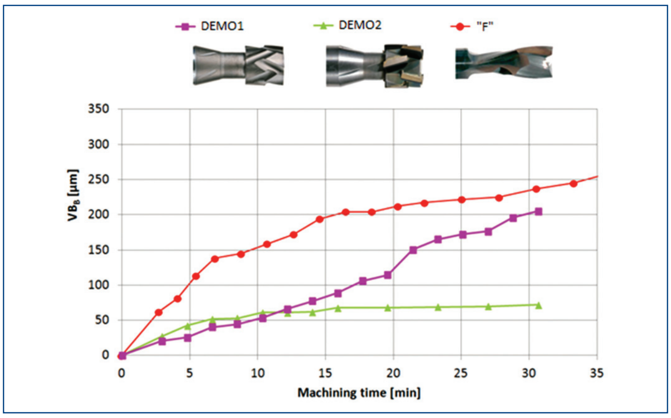


Figure 10. *Tool lifetime tests – Comparison of the new cutting tools and cutting tool "F".*

The cutting tool with soldered PCD tips had the best abrasion resistance. It is one of the hardest materials used for cutting. The wear of cutting tool DEMO2 is less than 70 μm on the flank after 30 minutes of machining. The cutting tool with diamond coating had a less rapid process wearing off. The flank wear increased almost linearly for the diamond coated tool whereas the flank wear of the PCD tool almost did not rise after 10 minutes of machining. A titanium coating of cutting tool "F" was worn rapidly. The flank wear of this tool was more than twice as much for new tools after ten minutes of machining. The intensive wearslowed down after then the titanium coating disappeared and the cutting edge began abrading. This situation was observed also for DEMO1 but first after 20 minutes of machining (Fig. 11).

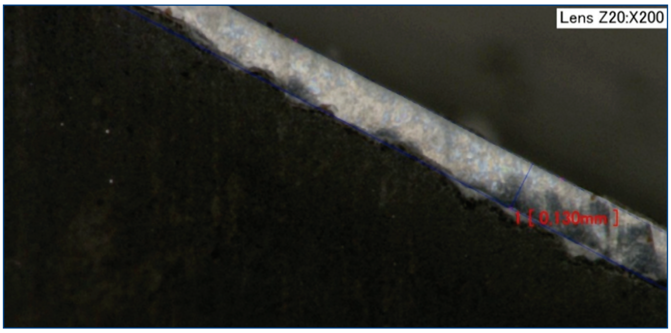


Figure 11. *Abrasion wear of DEMO1 cutting tool.*

4. Conclusions

The test of commercial cutting tools were made in order to find the best cutting shape geometry and cutting material for machining FRTC materials. The best choice is a very positive rake and clearance angle, compressive helix and very hard cutting material such as PCD or diamond coating on a carbide substrate.

Cutting forces were very small during trimming of FRTC materials. If the cutting forces are very small, the differences between various cutting conditions may be also very small in the statistical evaluation. This was caused by vibrations which distorted all measurement, namely measurement of multitooth cutting tools. It made the results of evaluated S/N ratios slightly confusing for weak control factors.

Surface roughness was influenced by many factors. Nevertheless, measurements showed that surface roughness Rz was smaller than 6 μm for all tools. Unfortunately, the differences between measurements were too small and the S/N ratio could not be evaluated.

The burr-less machined edge of the composite was obtained only when the tool had high positivity of the rake and clearance angle. It is easy to reach a high positive angle on carbide tools but they only have limited tool lifetime. PCD tools have much longer lifetime but there is an issue with the small positivity of the rake angle. The burrs were bigger for PCD tools.

Results from testing of standard commercially available tools were used for the design of two new specific tools. Both the new designed tools have double helix design for minimizing burr size. The first one has diamond tips and 4 teeth. The tool geometry creates medium burr because of a less positive rake angle (the tip itself has a rake angle of 0°; the positive rake angle is achieved just by declining the tip in the tool body). The tool life time is very long because of the application of PCD. The cutting productivity is very high because of the high number of teeth.

The other one is made from cemented carbide with a diamond-like coating. The ground geometry generates small burr because of non-changing positive cutting edge geometry. The tool life time is approximately 10 times lower than in the case of PCD. The carbide cutting edge with the diamond-like coating has lower performance than the diamond cutting edge. The cutting productivity is very high because of the high number of teeth.

Acknowledgements
The authors would like to thank the European Community for funding the large-scale EU project „FibreChain – Integrated Process Chain for Automated and Flexible Production of Fibre-Reinforced Plastic Products“ as part of the European Community's Seventh Framework Programme under grant agreement no. 263385.

References

[Coligan 1991] Colligan, K. and Ramulu, M., Delamination in surface plies of graphite/epoxy caused by the edge trimming process, Processing and manufacturing of composite materials – ASME, Washington: PED-CP.49/MD-Vol. 27, 1991.

[Davim 2004] Davim, P. J., Reis, P. and Antonio, C. C., A study on milling of galss fiber reinforced plastics manufactured by hand-lay up using statistical analysis (ANOVA), Porto, Portugal: Elsevier – Composite structures 64, 2004, pp. 493-500.

[Ehrenstein 2009] Ehrenstein, G. W., Polymer Composites (in Czech), Prague: Scientia, 2009. ISBN 978-80-86960-29-6.

[König 1985] König, W., et. al, Machining of fibre reinforced plastics, CIRP Annals – Manufacturing Technology, Vol. 34, No. 2, pp. 537-548, 1985.

[Masek 2012] Masek, P., Zeman, P. and Kolar, P., Technology optimization of PPS/C composite milling using Taguchi method, MATAR2012, Prague, September 2012, pp. 1-8

[Peters 1998] Peters, S. T., Handbook of Composites, London: Chapman and Hall, 1998.

[Quadrini 2007] Quadrini, F., Squeo, E. A., and Tagliaferri, V., Machining of glass fiber reinforced polyamide, Rome, Italy: eXpress Polymer letters Vol. 1, No.12, 2007.

[Sheikh-Ahmad 2009] Sheikh-Ahmad, J. Y., Machining of polymer composites, New York: Springer Science + Business Media, 2009. e-ISBN 978-0-387-68619-6.

[Taguchi 1987] Taguchi, G. and Konichi, S., Taguchi methods, Orthogonal arrays and linear graphs, tools quality engeneering, MI: ASI Press, 1987.

Contacts

Ing. Petr Masek, Research Center of Manufacturing Technology
Czech Technical University in Prague, Faculty of Mechanical Engineering
Horska 3, Prague 2, 128 00, Czech Republic
tel.: +420 221 990 945, +420 224 359 348
e-mail: p.masek@rcmt.cvut.cz, www.rcmt.cvut.cz