

Impact of Grinding Wheel Position on Flute Profile of End mill and Cutting Process

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Abstract. The article provides the research on flute profile of end mills. The flute profile of a specified end mill design is affected by grinding wheel position relative to end mill workpiece in grinding operation. Different profiles were obtained, their rake surfaces and cross section areas were compared. Temperatures and cutting forces were evaluated via finite element analysis for these profiles in case of titanium alloy and heat-resistant alloy machining. Finally, the impact of flute profile on cutting process was assessed.

1. Introduction

The manufacturing process of jet turbine engine (JTE) parts is constantly improving. The improvements include the increase of productivity and decrease of production costs. The productivity can be augmented by cutting conditions and special design of cutting tools but it is limited by the properties of so-called hard-to-machine materials [1, 2]. For example, properties of titanium alloys are also developing [3] which is likely to lead to their poorer machinability. The enhancement of manufacturing process [4] implies improvement of milling operations. The most complicated milling operations occur while 5-axis machining of free-form parts [5], i.e. blades, blisks.

The solid carbide end mills are extensively used in all metal cutting operations during the manufacturing process of JTE parts made of hard-to-machine materials: 3-axis and 5-axis; finishing, semi-finishing and roughing operations. Researchers have paid attention to end mill designing and constructional parameters choice [6, 7] as well as to special end mills design [8]. Some research is devoted to perspective designs of milling cutters [9, 10] for increased stability of the cutting process varying helix angle and pitch angle of the end mill. Also, there are articles on design and tool wear and their impact on temperature in tool-workpiece interface [11].

The design of the solid carbide end mill or the range of end mills for hard-to-machine materials begins with the selection of constructional parameters. For the cylindrical part of an end mill the parameters are outer diameter, number of teeth, rake angle, helix angle, core diameter and clearance angle. Manufacturers' standards or some national standards may serve as the source of constructional parameters. For a wide group of materials and applications the recommendations for the design and constructional parameters are usually of general character. Besides the set of these constructional parameters does not allow to evaluate a unique flute profile. A specified set of these parameters may result in a number flute profiles. The flute profile is affected by constructional parameters and also manufacturing technology. In case of using an NC tool grinding machine manufacturing technology



determines grinding wheel type, dimensions and position relative to the workpiece. The workpiece is usually a cylindrical solid carbide rod ground to h6 or h5 tolerance.

Numerous research is devoted to the adjustment of grinding wheel position. Article [12] represents the method of flute grinding with the standard forms of grinding wheel enabling to obtain the desired flute width. The method of wheel position calculating obtained in the article [13] provides a more precise method of rake angle evaluation. Some research focuses on calculating the grinding wheel profile to obtain the desired flute, for instance, article [14] describes such method for special flutes. Also, a flute is a complex surface, thus the appropriate method of flute measurement should be considered providing high precision [15].

To summarise there is a gap in research on the impact of grinding wheel position on the flute profile in case of predefined constructional parameters. Moreover, the effect of various flute profiles on the cutting process has not been estimated. Specifically it concerns the effect of the rake surface of flute (surface in the environment of the cutting edge).

The purpose of this paper is to evaluate the impact of design parameters and grinding operation of end mill on the rake surface profile and evaluate the impact of this profile on the cutting process.

2. Method

The process of designing a range of end mills starts with the choice of the representative end mill with predefined outer diameter. Other end mills would be generated based on the representative mill. The outer diameter of the representative end mill is chosen equal to 12 mm. It is necessary to follow the certain algorithm of choosing and conforming parameters to design the end mill. Also, it is essential to know that the design is directly connected to manufacturing technology. Therefore the design of the end mill is produced via the "System for NC codes preparation". This system is provided with the "VIZAS" VZ-630F4 tool grinding machine.

At the first step, the system requires values of constructional parameters of the end mill to be specified. At this stage, end mill outer diameter, number of teeth, rake angle, helix angle, core diameter, clearance surface width and clearance angle should be determined in order to define flute profile. Other constructional parameters do not affect the flute. At the second step the types and dimensions of the grinding wheels' set are entered. In case of standard wheel's application for flute grinding 1A1 or 1V1 the wheel types can be applied. 1V1 type was applied for further research. The third step considers the cutting conditions to be determined.

Then the modelling of cross section and whole end mill is executed. This stage implies modelling of flute profile and flute's rake surface which is likely to have a crucial impact on the cutting process. The system provides adjusting the core diameter and the swivelling angle of grinding wheel relative to workpiece axis. Core diameter should not be changed as a constructional parameter. Swivelling angle is the B angle (angle of B axis) of the prescribed machine tool and it generally differs from helix angle of the end mill. Figure 1 represents the respective wheel and workpiece position in flute grinding. Finally, the NC code can be generated for NC tool grinding machine.

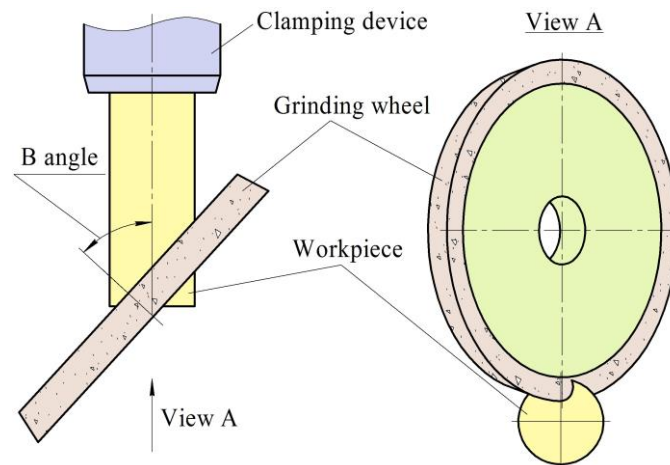


Figure 1. Wheel position in flute grinding operation.

Adjusting swivelling angle six different profiles (six sections) with the same rake angle and core diameter were generated. Rake angle was 9° whereas B angles were 42.4° , 45.0° , 47.4° , 50.0° , 52.5° and 55.5° . The area of each cross section was assessed. The seventh section was modelled as a cutter with constant rake angle. The profile for 45.0° B angle is shown in Figure 2a.

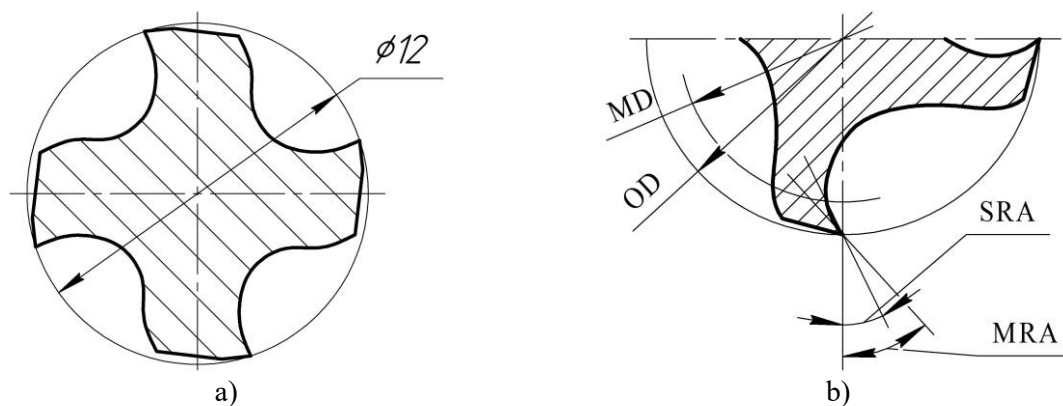


Figure 2. Generated profile and rake angle measurement: a) Profile generated for representative end mill; b) rake angle measurement (OD – outer diameter of the end mill, MD – diameter of measurement, SRA – specified rake angle, MRA – measured rake angle)

Rake angle measuring method should be taken into account. Figure 2b illustrates the difference between specified rake angle and measured rake angle which can derive from the difference in diameters. In “System for NC codes preparation” rake angle is specified at the outer diameter (OD) while Walter tool measuring machine provides measuring on a certain diameter. For instance, if OD equals 12 mm then the diameter of measurement is set as 11 mm. The additional eighth section with 12° rake angle on OD was modelled. For this section the rake angle on the diameter of measurement equals 9° .

After that, the process of milling titanium alloy Ti6Al4V and heat-resistant alloy Inconel 718 was modelled using “Deform” finite element analysis software. Peak (maximum) temperatures and peak tangential cutting forces were evaluated. The model of orthogonal cutting was modified for milling process, i.e. the depth of cut was linearly decreasing from the feed value to zero on the whole length of cut. Length of cut was calculated on the basis of mill diameter and depth of cut. Feed per tooth was 0.08 mm/tooth, milling depth was 2 mm for both materials while cutting speed was 60 m/min for

Ti6Al4V and 90 m/min for Inconel 718. It is also essential to use the verified cutting model for more reliable results [16, 17].

Two additional tests were performed with the feed 0.16 mm per tooth for sections 3 and 8.

3. Results

Rake angles on different measuring diameters and cross section areas were evaluated for obtained profiles. The angles are presented in Table 1.

Table 1. Measured rake angles.

Section	B angle	Diameter of measurement, mm					Cross section area, mm ²
		12.0	11.5	11.0	10.5	10.0	
1	42.4°	9.0	7.6	5.7	3.5	1.1	70.5
2	45.0°	9.0	6.8	5.1	3.6	2.4	68.7
3	47.4°	9.0	6.5	4.4	2.6	1.2	67.3
4	50.0°	9.0	7.5	6.7	4.1	1.9	65.1
5	52.4°	9.0	7.8	5.8	3.6	1.3	61.0
6	55.0°	9.0	5.9	4.1	2.2	0.6	61.1
7	—	9.0	9.0	9.0	9.0	9.0	—
8	47.4°	12.0	10.5	9.0	7.2	4.9	66.5

Section 7 is the cutter with constant rake angle therefore cross section area and B angle could not be evaluated. After that finite element modelling was conducted for these sections. Figure 3 and 4 demonstrate the cutting process of Ti6Al4V and Inconel 718 respectively for section 3 after 1.75 mm of cut with the feed 0.08 mm/tooth.

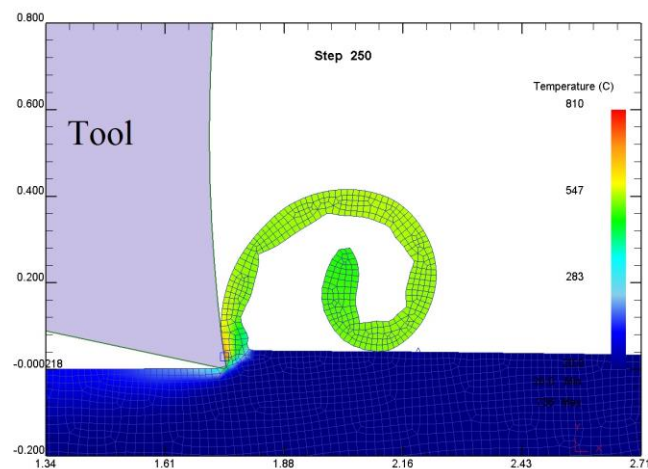


Figure 3. The modelling process of cutting Ti6Al4V with the tool derived from section 3.

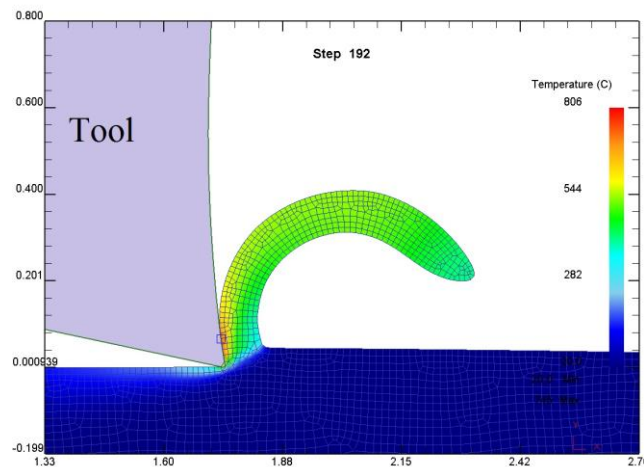


Figure 4. The modelling process of cutting Inconel 718 with the tool derived from section 3.

Peak temperatures were calculated in the tool-chip interface. Tangential cutting forces applied to the end mill's tooth were assessed. The modelled peak temperatures and tangential forces are represented in Table 2 for both materials.

Table 2. Peak temperatures and tangential forces obtained in modelling.

Section	Ti6Al4V		Inconel 718	
	Peak temperature, °C	Peak tangential force, N	Peak temperature, °C	Peak tangential force, N
1	786	106.5	764	154.6
2	795	108.0	774	162.3
3	777	106.7	786	162.2
4	785	106.2	768	157.2
5	783	102.4	783	156.3
6	773	109.4	767	159.2
7	788	106.8	787	154.3
8	780	104.4	757	148.3
3 (0.16 mm/tooth)	888	178.9	867	317.2
8 (0.16 mm/tooth)	888	177.1	857	286.9

Maximum contact length (CL) was measured for processes with 0.16 mm/tooth feed. In case of titanium alloy machining maximum CL was 0.09 mm, while in heat-resistant alloy machining CL equaled 0.12 mm.

4. Conclusion and discussion

As could be seen from Table 1 the measured rake angles decrease with descending of the measuring diameter. This evolution of rake angle results in different profiles and rake surfaces. The first derivation from the evolution is the diverse cross section areas. Section area tends to rise with the decrease of B angle. Thus the rigidity of cutting tool rises. The second derivation is the possible impact on the cutting process.

Peak temperatures given in Table 2 for Ti6Al4V alter from 773 °C to 795 °C for sections obtained by varying B angles, for the cutter with constant rake angle (section 7) and for section 8 in case of 0.08 mm/tooth feed. The difference in temperatures is only 3%. For the process with 0.16 mm/tooth feed the temperatures are equal. The research on temperatures reveals that there is no any crucial impact of rake surface in the chosen range of angles on the peak temperature in Ti6Al4V machining.

The peak temperature varies within the range of 4% during heat-resistant alloy machining. Temperature tends to be higher when rake angle decreases faster (for rake angles assessed at 11.5 OD).

The impact of rake surface in Inconel 718 machining is more noticeable in comparison to Ti6Al4V machining.

For Ti6Al4V maximum tangential cutting force for sections from 1 to 8 varies in the range of 6% with a weak correlation between it and rake angle change. This can be due to the small dimension of contact length compared to the length of rake surface where measurements occurred. In other words, on the measured contact length rake angle appears to be constant for different profiles. The considerable increase in feedrate might have an impact on forces obtained for different sections but increased feedrate is unlikely to be used in real machining practice for titanium alloys. Higher feedrates could be implemented in aluminum alloys machining.

Peak tangential cutting force in Inconel 718 machining demonstrates the fall while rake angle on 11.5 mm OD remains higher than 7° and conversely force increases with decrease of rake angle. For modelled sections 1-8 the force range is within 9%. This can be due to higher contact length in comparison to titanium alloy. Also cutting conditions affect the correlation between rake angle and peak temperatures or cutting forces. Preliminary tests run on Inconel 718 with 60 m/min cutting speed revealed no significant correlation.

In conclusion, it should be noted that simple specification of constructional parameters values does not enable to obtain the most effective end mill design. Temperatures and cutting forces can be affected by rake surface under certain cutting conditions. Higher rigidity can be achieved altering wheel position in flute grinding operation.

Using this method of the end mill design improvement the most sustainable design can be achieved and also metal cutting process can be enhanced. It is particularly important for stable hard-to-machine materials milling.

Acknowledgments

This work was supported by the Ministry of Education and Science of the Russian Federation in the framework of the implementation of the Program “Research and development on priority directions of scientific-technological complex of Russia for 2014-2020”.

References

- [1] Ezugwu EO, Bonney J, Yamane Y. An overview of the machinability of aeroengine alloys. *J Mater Process Technol* 2003;134(2):233-253.
- [2] Arrazola P-J, Garay A, Iriarte L-M, Armendia M, Marya S, Le Maître F. Machinability of titanium alloys (Ti6Al4V and Ti555.3). *J Mater Process Technol* 2009;209(5):2223-2230.
- [3] Grechnikov FV, Khaimovich AI. Raising the fatigue resistance of titanium alloys by high-speed deformation in the range of polymorphic transformations. *Met Sci Heat Treat* 2016;57(11-12):726-730.
- [4] Vdovin RA, Smelov VG, Bolotov MA, Pronichev ND. Paths of Improving the Technological Process of Manufacture of GTE Turbine Blades. *IOP Conference Series: Materials Science and Engineering* [Internet]. IOP Publishing; 2016 Aug;142:012073. Available from: <http://dx.doi.org/10.1088/1757-899X/142/1/012073>
- [5] Khaimovich IN, Surkov OS, Khaimovich AI. Practice in the application of specialized technologic process patterns of 5-axis machining operation of blade rings of blisks. *Russ Aeronaut* 2016;59(1):112-117.
- [6] Jiang Z, Sun J, Xiong Q, Wang L, Li J. Structural design of groove and micro-blade of the end mill in aluminum alloys machining based on bionics. *Int J Adv Manuf Technol* 2017;88(9-12):3343-3356.
- [7] Skuratov DL, Zhidyaev AN, Sazonov MB. Solid carbide end mills tool life increase in titanium alloys machining by design development and rational choice of geometrical parameters. *Res J Appl Sci* 2014;9(11):767-770.
- [8] Liu X, Fan M, Ji W, Wang G, Chen T. Research on models of design and NC manufacturing for ellipsoid end mill. *Int J Adv Manuf Technol* 2016;85(9-12):2729-2744.

- [9] Suzuki N, Ishiguro R, Kojima T. Design of irregular pitch end mills to attain robust suppression of regenerative chatter. *CIRP Ann Manuf Technol* 2016;65(1):129-132.
- [10] Yusoff AR, Sims ND, Turner S. Experimental Validation of Chatter Stability for Variable Helix Milling Tools. IOP Conference Series: Materials Science and Engineering [Internet]. IOP Publishing; 2011 Dec 8;26:012010. Available from: <http://dx.doi.org/10.1088/1757-899X/26/1/012010>
- [11] Evdokimov DV, Skuratov DL, Fedorov DG. Influence of tool wear on the heat-flux distribution and temperature at the contact surfaces in the end milling of OT4 titanium alloy. *Russ Eng Res* 2016;36(4):324-327.
- [12] Ren L, Wang S, Yi L, Sun S. An accurate method for five-axis flute grinding in cylindrical end-mills using standard 1V1/1A1 grinding wheels. *Precis Eng* 2016;43:387-394.
- [13] Nguyen V-H, Ko S-L. A New Method for Determination of Wheel Location in Machining Helical Flute of End Mill. *J Manuf Sci Eng Trans ASME* 2016;138(11).
- [14] Li G. A new algorithm to solve the grinding wheel profile for end mill groove machining. *Int J Adv Manuf Technol* 2017;90(1-4):775-784.
- [15] Pechenin VA, Bolotov MA, Ruzanov NV, Yanyukina MV. Optimization of measurements of the geometry of parts with complex surfaces. *Meas Tech* 2015;58(3):261-268.
- [16] Malakizadi A, Hosseinkhani K, Mariano E, Ng E, Del Prete A, Nyborg L. Influence of friction models on FE simulation results of orthogonal cutting process. *Int J Adv Manuf Technol* 2017;88(9-12):3217-3232.
- [17] Bil H, Kiliç SE, Tekkaya AE. A comparison of orthogonal cutting data from experiments with three different finite element models. *Int J Mach Tools Manuf* 2004;44(9):933-944.