BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi,
Tomul LX (LXIV), Fasc. 3, 2014
Secţia
CONSTRUCŢII DE MAŞINI

MILLING OF THE FLAT SURFACES BY USING MILLING CUTTERS WITH SPHERICAL HEAD AND THE UNDISENGAGED CHIP MODELING USING 3D GRAPHICS SOFTWARE

BY

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Received: November 10, 2014
Accepted for publication: November 24, 2014

Abstract. In a previous paper it was studied the variation of the surface area and volume of an uncut chip, related to the axial depth of the cut and the depth on tooth. If the machined surface is more complex than a slot we need another process parameter: radial depth of cut. Using same 3D software program it was calculated the uncut chip surface and volume variation in the plane surfaces milling process, related to the three parameters presented above. Exact value of uncut chip area can be used to calculate cutting forces. Coefficients of the milling force can be found by experimental cutting tests, using as theoretical support a mechanistic model developed by Koenigsberger and Sabharwal (1961), developed later by Altintas (2000). As we know the milling force has a key role in predicting the machining error, the milling surface integrity and vibrations.

Key words: uncut chip thickness; cutting force; uncut chip area.

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1. Introduction

Using papers of Iwabe *et al*. (2006) and Cosma (2007a; 2007b) we created the model of uncut chip areas generated by intersecting cutting chip with a rotating vertical plane (the same as mill cutting edge with helix angle $i = 0$) presented in Figs. 1,…,6.

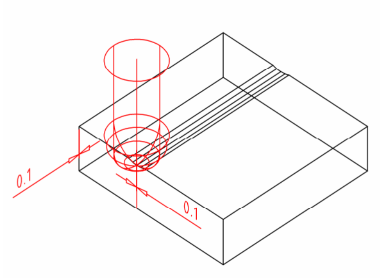

Fig. 1 – 3D CAD model.

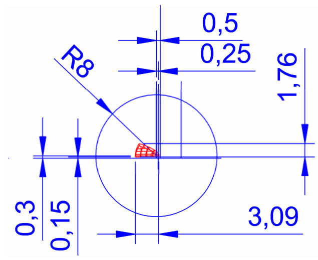

Fig. 2 – Chip dimensions.

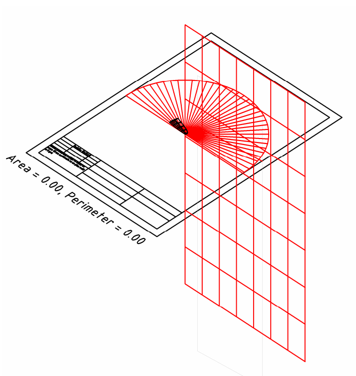

Fig. 3 – Chip and cutting plane.

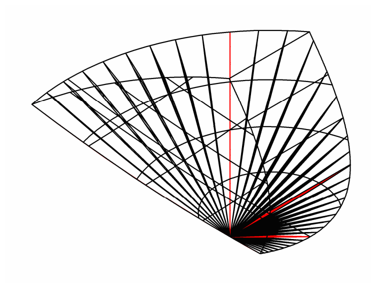
Fig. 4 – Uncut chip areas variation - obtained with 3D software.

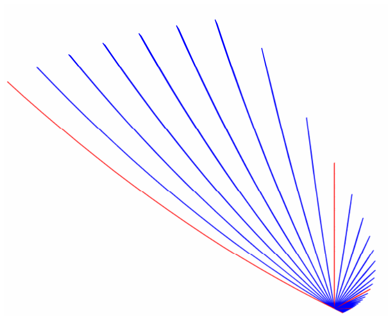
Fig. 5 – Uncut chip sections.

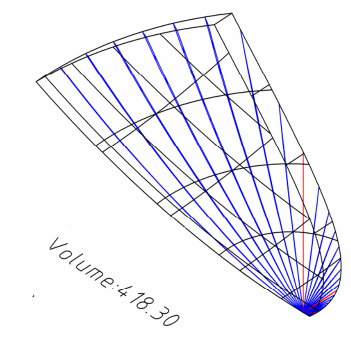

Fig. 6 – Uncut chip volume.

2. Numerical Values and Graphical Presentation of Uncut Chip Areas Variation

Samples of table with calculated data for uncut chip areas and perimeter are presented in Table 1.

Table 1
Variation of Uncut Chip Area Both Perimeter for Axial Depth of Cut 0.1 mm, Feed per tooth 0.1 mm and Radial Depth of Cut 0.1 mm

Cutting plane increment [degree]	Uncut chip area [mm^2] Scale 20:1	Real uncut chip area [mm^2]	Perimeter Scale 20:1	Real perimeter value [mm]
0	0.000	0.0000	1.5	0.0750
5	0.000	0.0000	1.57	0.0785
10	0.000	0.0000	1.66	0.0830
15	0.000	0.0000	1.76	0.0880
85	0.020	0.0001	5.51	0.2755
90	0.020	0.0001	6	0.3000
95	0.030	0.0001	6.56	0.3280
175	0.350	0.0009	50.78	2.5390
180	0.000	0.0000	50.6	2.5300

Graphical presentation of data from Table 1 is in Fig. 7.

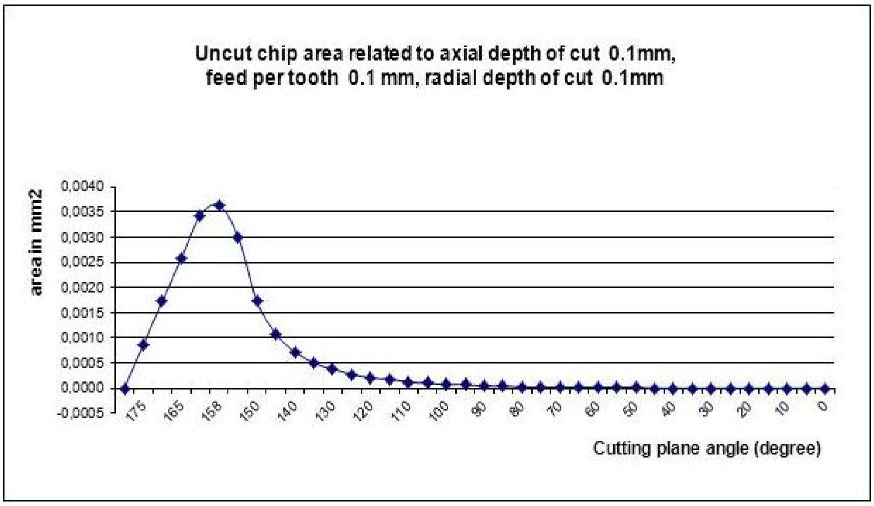

Fig. 7 – Graphical variation of uncut chip area for: axial depth of cut 0.1 mm, feed per tooth 0.1 mm, and radial depth of cut 0.1 mm.

Keeping axial depth of cut constant (0.1 mm) both radial depth of cut constant 0.1 mm and varying feed per tooth (0.1-0.5 mm/tooth) we obtained for uncut chip area numerical values from Table 2 and graphical presentation in Figs. 8 and 9.

Table 2

Numerical Values of Uncut Chip Area and Perimeter for Axial Depth of Cut 0.1 mm, Radial Depth of Cut 0.1 mm and Feed per tooth (*0.1- 0.5*) *mm/tooth*

Vertical plane rot [°]	Uncut chip area *f*=0.1 mm (20:1)	Real uncut chip area [mm^2]	Uncut chip area *f*=0.2 mm (20:1)	Real uncut chip area [mm^2]	Uncut chip area *f*=0.3 mm (20:1)	Real uncut chip area [mm^2]	Uncut chip area *f*=0.4 mm (20:1)	Real uncut chip area [mm^2]	Uncut chip area *f*=0.5 mm (20:1)	Real uncut chip area [mm^2]
0	0.000	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0000
5	0.000	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0000
85	0.020	0.0001	0.030	0.0001	0.020	0.0001	0.020	0.0001	0.010	0.0000
90	0.020	0.0001	0.030	0.0001	0.030	0.0001	0.030	0.0001	0.030	0.0001
95	0.030	0.0001	0.040	0.0001	0.050	0.0001	0.050	0.0001	0.060	0.0002
155	1.200	0.0030	2.230	0.0056	2.850	0.0071	3.230	0.0081	3.480	0.0087
160	1.370	0.0034	2.650	0.0066	3.480	0.0087	3.680	0.0092	3.750	0.0094
165	1.030	0.0026	2.060	0.0052	3.050	0.0076	3.720	0.0093	3.720	0.0093
175	0.350	0.0009	0.690	0.0017	1.030	0.0026	1.340	0.0034	1.590	0.0040
180	0.000	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0000

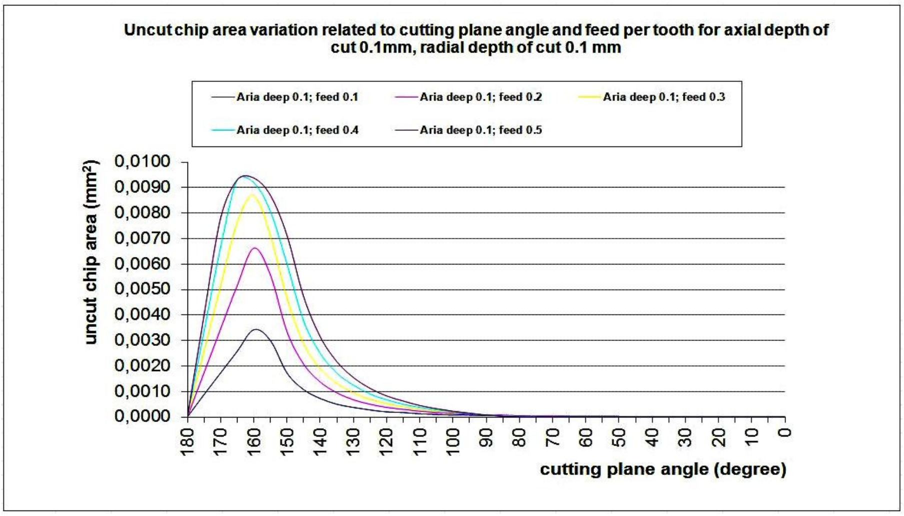

Fig. 8 − Graphical variation of uncut chip area for: axial depth of cut 0.1 mm, radial depth of cut 0.1 mm and feed per tooth (0.1 - 0.5) mm/tooth.

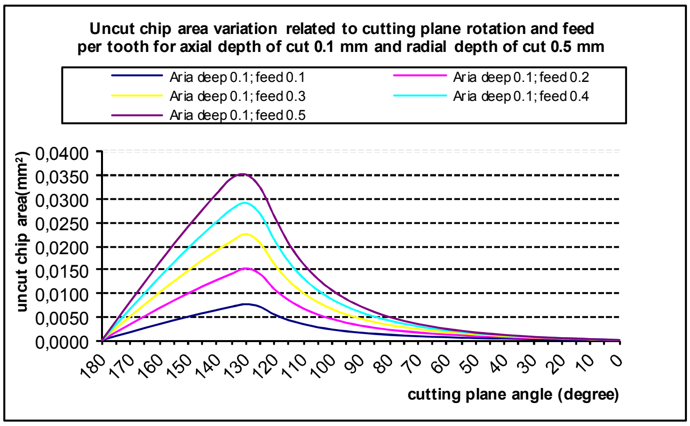

Fig. 9 − Graphical variation of uncut chip for: axial depth of cut 0.1 mm, radial depth of cut 0.5 mm and feed per tooth (0.1 - 0.5) mm/tooth.

Keeping axial depth of cut constant at 0.1 mm and changing feed per tooth (from 0.1 mm to 0.5 mm) and radial depth of cut (from 0.1 to 0.5 mm) we obtained for uncut chip area numerical values included in Table 3 and graphical presentation from Figs. 10 and 11.

Table 3

Numerical Values of Uncut Chip Area for: Feed per tooth 0.1 mm/tooth, Axial Depth of Cut 0.1 mm and Radial Depth of Cut (*0.1 - 0.5*) *mm*

Vertical plane rot [°]	Uncut chip area *rd*=0.1 mm (20:1)	Real uncut chip area [mm^2]	Uncut chip area *rd*=0.2 mm (20:1)	Real uncut chip area [mm^2]	Uncut chip area *rd*=0.3 mm (20:1)	Real uncut chip area [mm^2]	Uncut chip area *rd*=0.4 mm (20:1)	Real uncut chip area [mm^2]	Uncut chip area *rd*=0.5 mm (20:1)	Real uncut chip area [mm^2]
0	0.000	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0000
5	0.000	0.0000	0.000	0.0000	0.000	0.0000	0.010	0.0000	0.010	0.0000
10	0.000	0.0000	0.000	0.0000	0.010	0.0000	0.020	0.0001	0.030	0.0001
85	0.020	0.0001	0.080	0.0002	0.190	0.0005	0.340	0.0009	0.530	0.0013
90	0.020	0.0001	0.100	0.0003	0.220	0.0006	0.400	0.0010	0.620	0.0016
95	0.030	0.0001	0.120	0.0003	0.270	0.0007	0.480	0.0012	0.750	0.0019
155	1.200	0.0030	1.690	0.0042	1.690	0.0042	1.690	0.0042	1.690	0.0042
160	1.370	0.0034	1.370	0.0034	1.370	0.0034	1.370	0.0034	1.370	0.0034
165	1.030	0.0026	1.030	0.0026	1.030	0.0026	1.030	0.0026	1.030	0.0026
175	0.350	0.0009	0.350	0.0009	0.350	0.0009	0.350	0.0009	0.350	0.0009
180	0.000	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0000

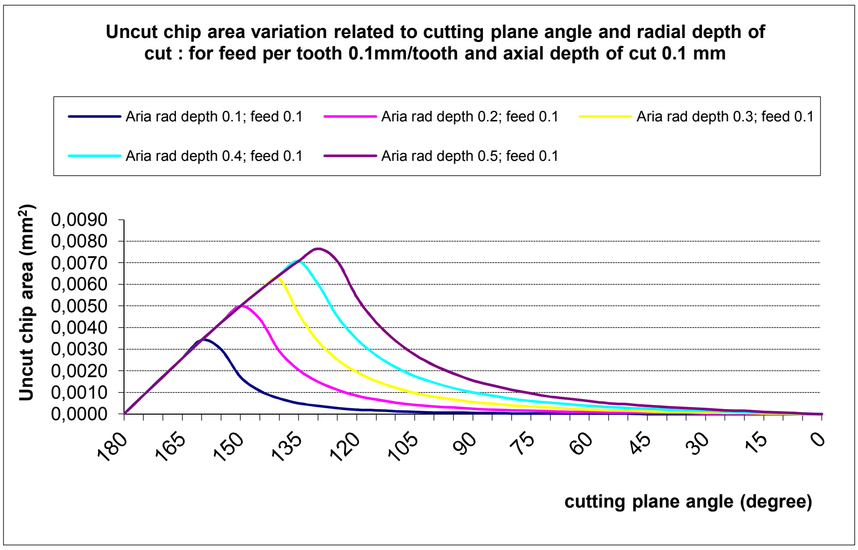

Fig. 10 − Graphical variation of uncut chip area: at constant axial depth of cut feed per tooth 0.1 mm/tooth, and radial depth of cut (0.1 - 0.5) mm.

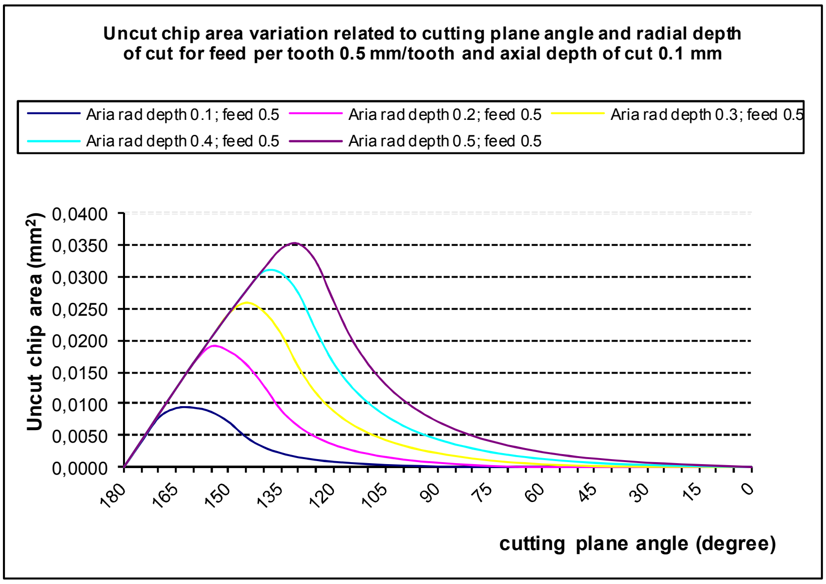

Fig. 11 − Graphical variation of uncut chip area: at constant axial depth of cut 0.1 mm, feed per tooth 0.5 mm/tooth, and radial depth of cut (0.1 - 0.5) mm.

In Table 4 we presented numerical values for uncut chip area in ball end milling process at constant axial depth of cut 0.1 mm x constant feed per tooth and variable radial deep of cut.

In Table 5 we presented numerical values for uncut chip area in ball end milling process at constant axial depth of cut 0.5 mm x constant feed per tooth and variable radial deep of cut.

Table 4

Variation Domain for Uncut Chip Area in Ball End Milling Process for: Constant Axial Depth of Cut x Constant Feed per tooth for Variable Radial Deep of Cut

Axial depth of cut=ct. [mm]	Feed per tooth [mm/tooth]	Radial depth [mm]	Uncut chip area variation [mm^2]
0.1	0.1	0.1 → 0.5	0.0034-0.0077
	0.2	0.1 → 0.5	0.0068-0.0153
	0.3	0.1 → 0.5	0.0087-0.0226
	0.4	0.1 → 0.5	0.0093-0.0293
	0.5	0.1 → 0.5	0.0094-0.0353

Similar numerical and graphical results were obtained using constant depth of cut at 0.5 mm, as in Figs. 12 and 13, changing feed per tooth (from 0.1 mm to 0.5 mm) and radial depth of cut (from 0.1 to 0.5 mm).

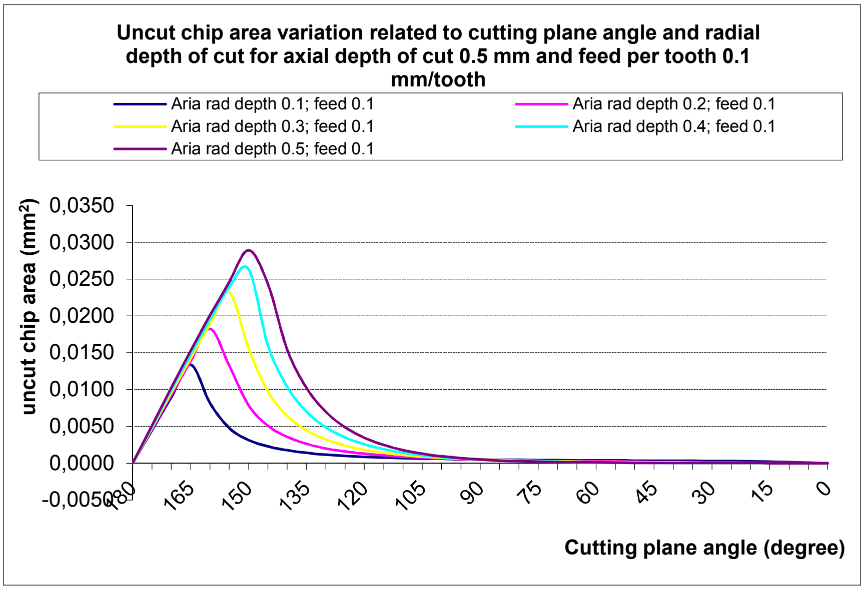

Fig. 12 − Graphical variation of uncut chip area: at constant axial depth of cut 0.5 mm, feed per tooth 0.1 mm/tooth, and radial depth of cut (0.1 - 0.5) mm.

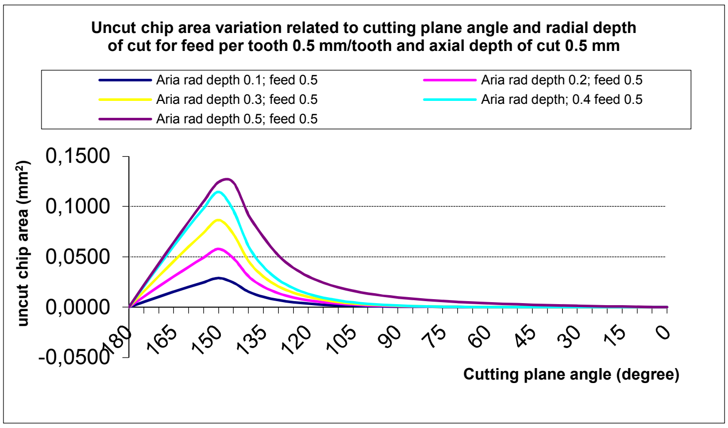

Fig. 13 − Graphical variation of uncut chip area: at constant axial depth of cut 0.5 mm, feed per tooth 0.5 mm/tooth, and radial depth of cut (0.1 - 0.5) mm.

Table 5

Variation Domain for Uncut Chip Area in Ball End Milling Process for: Constant Axial Depth of Cut x Constant Feed per tooth for Variable Radial Deep of Cut

Axial depth of cut=ct. [mm]	Feed per tooth [mm/tooth]	Radial depth [mm]	Uncut chip area variation [mm^2]
0.5	0.1	0.1 → 0.5	0.0136-0.0305
	0.2	0.1 → 0.5	0.0261-0.0597
	0.3	0.1 → 0.5	0.0369-0.0881
	0.4	0.1 → 0.5	0.0461-0.1147
	0.5	0.1 → 0.5	0.0534-0.1312

In Tables 4 and 5 we have only geometrical variation of uncut chip area in ball end milling process for: constant axial depth of cut and feed per tooth *versus* variable radial depth of cut. Technological parameters such as: spindle speed, cutting direction (up or down milling), lead and tilt tool angles (which have no effect on uncut chip area geometrical parameters were neglected). If in precedent paper, for slot milling, we found that for constant axial cutting deep of 0.1 mm x variable feed per tooth in domain (0.1-0.5 mm) *versus* constant feed per tooth of 0.1 mm x variable axial cutting deep in domain (0.1-0.5 mm) maximum area has the same numerical value, in this case the situation is different. For axial depth of cut 0.1 mm and feed per tooth 0.5 mm x radial depth of cut in domain (0.1-0.5 mm), uncut chip area is (radial depth 0.1 mm → uncut chip area 0.0094 mm^2; radial depth 0.2 mm → uncut chip area 0.0192 mm^2; radial depth 0.3 mm → uncut chip area 0.0260 mm^2; radial depth 0.4 mm → uncut chip area 0.0312 mm^2; radial depth 0.5 mm → uncut chip area 0.0354

mm^2). Minimum value is 0.0094 mm^2 and maximum value is 0.0354 mm^2. For axial depth of cut 0.5 mm and feed per tooth 0.1 mm x radial depth of cut in domain (0.1-0.5 mm), uncut chip area is (radial depth 0.1 mm $\rightarrow$ uncut chip area 0.0136 mm^2; radial depth 0.2 mm $\rightarrow$ uncut chip area 0.0190 mm^2; radial depth 0.3 mm $\rightarrow$ uncut chip area 0.0234 mm^2; radial depth 0.4 mm $\rightarrow$ uncut chip area 0.0272 mm^2; radial depth 0.5 mm $\rightarrow$ uncut chip area 0.0305 mm^2). Minimum value is 0.0136 mm^2 and maximum value is 0.0305 mm^2. Simply from geometrical point of view the regression for first set of data was given by equation: $y = 0.064x + 0.005$ and for the second set by $y = 0.042x + 0.0101$. The slope in first case is greater than in second one so the uncut chip area and cutting forces will increase faster. In HSM (high speed machining) where are recommended as cutting parameters small axial depth of cut and high feed per tooth, for better surface quality and high productivity, condition is satisfied only for (axial depth of cut 0.1 mm; radial depth of cut 0.1 mm and feed per tooth 0.5 mm where uncut chip area is minimum 0.0094 mm^2). That is only a theoretical result and must be confirmed in real cutting conditions.

3. Numerical Values and Graphical Presentation of Uncut Chip Volume Variation

Numerical variations of uncut chip volume related to feed per tooth x radial depth of cut, for constant axial depth of cut 0.1 mm are presented in Table 6.

Table 6

Variation of Uncut Chip Volume for Variable Feed per tooth x Constant Radial Depth of Cut and Constant Feed per tooth x Variable Radial Depth of Cut (*Constant Axial Depth of Cut 0.1 mm*)

Feed per tooth [mm/tooth] X	Radial depth of cut [mm] Y	Obs. Volume max. [mm^3]
0.1		X/0.1-(0.0010-0.0042)
0.2		X/0.2-(0.0020-0.0091)
0.3	constant	X/0.3-(0.0030-0.0140)
0.4		X/0.4-(0.0040-0.0189)
0.5		X/0.5-(0.0049-0.0237)
	0.1	0.1/Y-(0.0010-0.0049)
	0.2	0.2/Y-(0.0019-0.0098)
constant	0.3	0.3/Y-(0.0028-0.0146)
	0.4	0.4/Y-(0.0036-0.0192)
	0.5	0.5/Y-(0.0042-0.0237)

Numerical variations for constant axial depth of cut 0.5 mm is presented in Table 7.

Table 7

Variation of Uncut Chip Volume for Variable Feed per tooth x Constant Radial Depth of Cut and Constant Feed per tooth x Variable Radial Depth of Cut (*Constant Axial Depth of Cut 0.5 mm*)

Feed per tooth [mm/tooth] X	Radial depth of cut [mm] Y	Obs. Volume max. [mm^3]
0.1 0.2 0.3 0.4 0.5	constant	X/0.1-(0.0064-0.0302) X/0.2- (0.0117-0.0548) X/0.3-(0.0163-0.0796) X/0.4-(0.0212-0.1043) X/0.5- 0.0262-0.1289)
constant	0.1 0.2 0.3 0.4 0.5	0.1/Y-(0.064-0.0262) 0.2/Y-(0.0128-0.0523) 0.3/Y-(0.0189-0.0782) 0.4/Y- (0.0247-0.1038) 0.5/Y- (0.0302-0.1289)

Variation of uncut chip volume for variable feed per tooth x constant radial depth of cut (constant axial depth of cut 0.1 mm) has a graphical correspondence in Fig. 14.

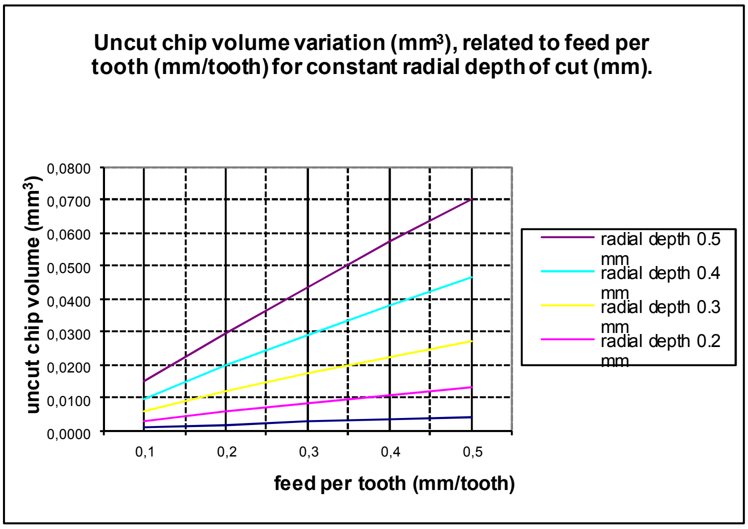

Fig. 14 − Variation of uncut chip volume for variable feed per tooth x constant radial depth of cut, in domain (0.1-0.5 mm). Data from Table 6.

Variation of uncut chip volume for constant feed per tooth x variable radial depth of cut (constant axial depth of cut 0.1 mm) has a graphical correspondence in Fig. 15.

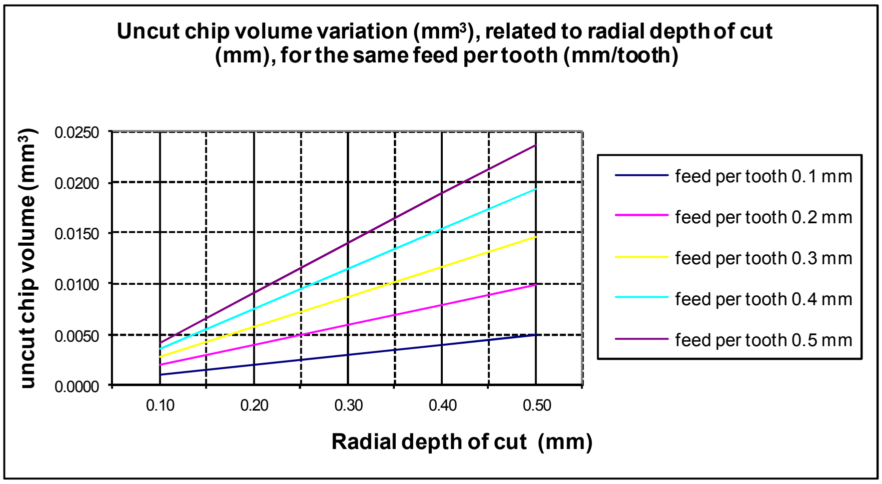

Fig. 15 − Variation of uncut chip volume related to radial depth of cut for constant feed per tooth, in domain (0.1-0.5 mm/tooth). Data from Table 6.

Variation of uncut chip volume for variable feed per tooth x constant radial depth of cut (constant axial depth of cut 0.5 mm) has a graphical correspondence in Fig. 16.

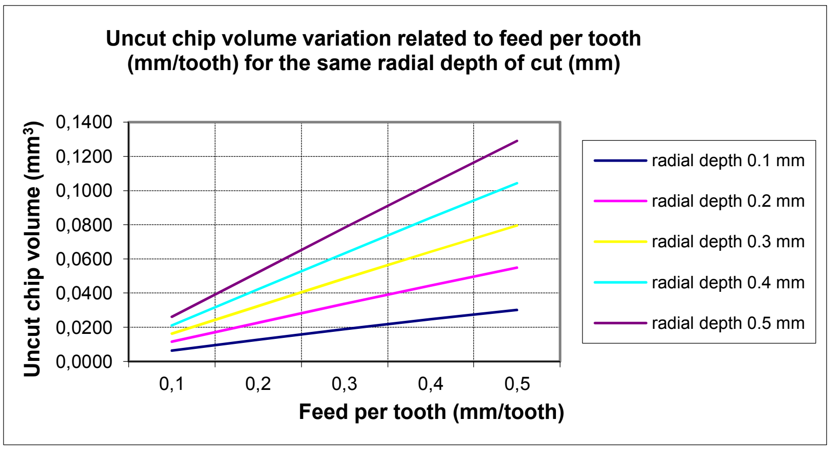

Fig. 16 − Variation of uncut chip volume for variable feed per tooth x constant radial depth of cut, in domain (0.1-0.5 mm). Data from Table 7.

Variation of uncut chip volume for constant feed per tooth x variable radial depth of cut (constant axial depth of cut 0.5 mm) has a graphical correspondence in Fig. 17.

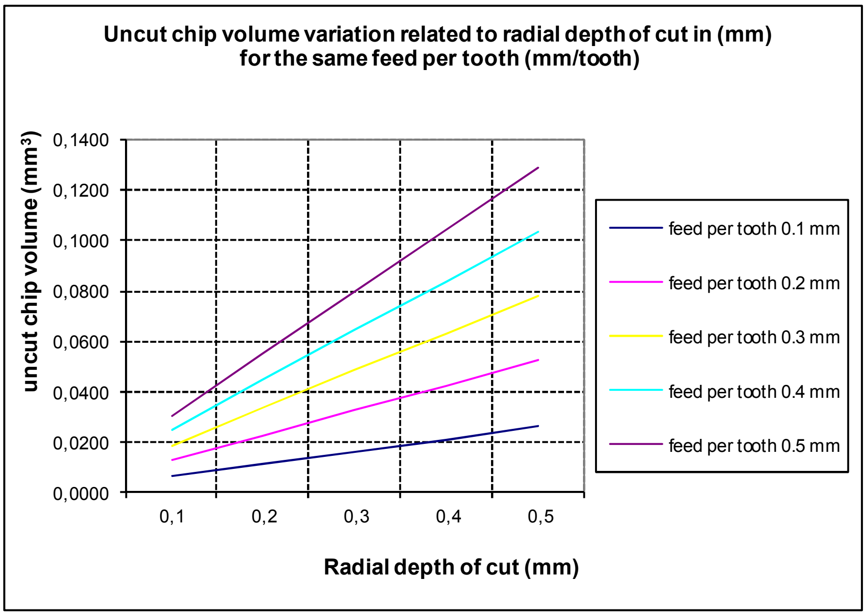

Fig. 17 – Variation of uncut chip volume for variable radial depth of cut x constant feed per tooth, in domain (0.1-0.5 mm/tooth). Data from Table 7.

4. Conclusions

From Tables 6 and 7 and also, from Fig. 14 - Fig. 17 the following conclusions can be drawn:

1) axial depth of cut equal to 0.1 mm:

– feed per tooth (0.1 mm/tooth) - radial depth of cut (0.1 mm) lead to a volume of chips: 0.0020 mm^3;

– radial depth of cut (0.1 mm) - feed per tooth (0.1 mm/tooth) lead to a volume of chips: 0.0010 mm^3.

Thus, increasing feed per tooth is more important than increasing radial depth of cut (Fig. 14);

2) if:

– feed per tooth (0.1 mm/tooth) - radial depth of cut (0.5 mm) lead to a volume of chips: 0.0049 mm^3;

– radial depth of cut (0.1 mm) - feed per tooth (0.5 mm/tooth) lead to a volume of chips: 0.0042 mm^3.

Thus, increasing feed per tooth is more important than increasing radial depth of cut (Fig. 15);

3) if the values increase (feed=0.5 x radial depth=0.5) it follows that volume became equal (the effect of increasing feed per tooth is more important at different small values);

4) if axial depth of cut equal to 0.5 mm:

− feed per tooth (0.5 mm/tooth) - radial depth of cut (0.1 mm) lead to a volume of chips: 0.0302 mm^3;

− feed per tooth (0.1 mm/tooth) - radial depth of cut (0.5 mm) lead to a volume of chips: 0.0262 mm^3.

Thus, increasing feed per tooth is more important than increasing radial depth of cut, when is a great difference between values, (Fig. 16);

5) if:

− radial depth of cut (0.1 mm) - feed per tooth (0.5 mm/tooth) lead to a volume of chips: 0.0302 mm^3;

− radial depth of cut (0.5 mm) - feed per tooth (0.1 mm/tooth) lead to a volume of chips: 0.0262 mm^3.

Thus, increasing feed per tooth is more important than increasing radial depth of cut, when is a great difference between values, (Fig. 17).

The obtained results recommend to raise feed per tooth for greater MRR (volume of uncut chip/time), but we must find the real effect using a plan of experiences with real cutting data.

Technologically we must realize an optimization of cutting process parameters to guarantee a maximum productivity with great surface integrity and minimum energy consumption. To achieve that goal we must compare the results at geometrical considerations with the results of real cutting tests.

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FREZAREA SUPRAFEȚELOR PLANE CU AJUTORUL FREZELOR CU CAP SFERIC ŞI MODELAREA AŞCHIEI NEDETAŞATE FOLOSIND UN SOFT DE GRAFICĂ 3D

(Rezumat)

Scopul studiului este de a determina pentru anumite condiții de aşchiere precise (freză sferică cu raza R = 8 mm, adâncimi de aşchiere din gama 0.1-0.5 mm, avans pe dinte din gama 0.1-0.5 mm/dinte şi avans transversal din gama 0.1-0.5 mm) volumul şi aria exactă a secțiunilor prin aşchie. Este cunoscut faptul că între forța de aşchiere şi secțiunea prin aşchie există o dependență directă. Aceasta poate fi exprimată printr-o relație matematică sub forma unei sume de produse dintre aria secțiunii instantanee prin aşchie, respectiv lungimea tăişului aflat în aşchiere şi o serie de coeficienți (determinați experimental). Folosind modelarea 3D se pot determina valorile instantanee ale secțiunii prin aşchie şi volumul acesteia, care vor fi folosite ulterior la calculul forțelor de aşchiere şi a cantității de material aşchiat în unitatea de timp. Studiul scoate în evidență variația secțiunii aşchiei pentru diferite regimuri, funcție de: avansul pe dinte, avansul transversal, precum şi de adâncimea de aşchiere. Regimul cu adâncimi de aşchiere mici şi avansuri pe dinte mari este specific prelucrărilor cu viteze mari de aşchiere (HSM). Strict din punct de vedere geometric volumul aşchiei creşte mai repede cu avansul pe dinte decât cu avansul transversal ceea ce duce la necesitatea unor determinări experimentale în vederea verificării corectitudinii modelului. Scopul modelării şi al verificărilor practice este de a găsi un optim al parametrilor de aşchiere care să asigure o calitate crescută a suprafeței prelucrate şi în acelaşi timp o productivitate crescută cu consum energetic minim.