COMPARISON OF PERFORMANCE OF AUSTRIAN MADE SI_3N_4 – NITRIDE CERAMIC TOOLS USED TO MACHINE GREY CAST IRON WORK-PIECE MATERIALS

J. Kovalcík, J. Cuban
Department of Machining and Assembly
Technical University of Liberec, Czech Republic

e-mail address: jaroslav.kovalcik@centrum.cz

This article presents comparisons of cutting performance of Austrian made – Si_3N_4 nitride ceramic – inserts used in machining a Type 422425 grey cast iron work-piece materials. Three commercial ceramic inserts Type FMG121C, FMG122C, and FMG134C were tested. Experiments were focused on tool life tests. A comparison approach involved exponents of Taylor's type equations over an optimized cutting tool interval i.e. one constant depth of cut of 1mm, one constant feed rate of 0.2 mm/rev and the three cutting speeds 250, 320 and 380 m/min. Results were obtained from linear regression. Also conducted was an evaluation of intervals of reliability as well as corresponding standard deviations for each regression coefficient in experimental Taylor's equations. The experiments allowed to compare, from statistical perspectives, at a 95 and greater confidence level, the trends and quantities of experimental cutting inserts. The results showed that a Type FMG122C ceramic insert had the most superior performance compared to other two types of experimental ceramic inserts investigated in this study.

Keywords
Metal machining, ceramic inserts, grey cast iron, work-piece material, tool life, Taylor's logT-log v regression lines, trends and quantities, statistical anylyses

1. Introduction

Generally, ceramic cutting tool inserts (CTI) are acknowledged especially for good machining performance where the exceptionally high speeds and high temperatures are of major concerns [Audy 1996]. Good wear resistance due to durability of such tools improves tool life and allows for using cutting speeds up to 1000 $m.min^{-1}$. Other advantages of the ceramic materials are their improved resistance to high temperatures up to 1750°C. According to literature source (Humar 2008) the cutting ceramics can be divided to an oxide group or a nitride group based on Al_2O_3 or Si_3N_4 components, respectively. The nitride cutting ceramics (NCC) have been found, when compared to the oxide cutting ceramics, better in terms of improved heath shock resistance. However they exhibited lower chemical stability when machining steel work piece materials.

At a department of Technical University of Liberec (Czech Republic) in machining / metrology laboratories, several graduation theses' topics were set up to investigate and compare the cutting performance of three nitride ceramic cutting inserts of a square shape. The commercial names of the inserts were FMG121C, FMG122C and FMG134C, and they were from an Austrian Research Institute.

Consequently, the prime concern of this study was to carry out the comprehensive tool life tests. It was decided to run long-term tests to examine the life span of the cutting tool inserts. It was noted that that such tests are expensive ad time consuming (Audy 1996, 2002), however, on other hand they provide much accurate results ([Audy *et al* 2002], and [Audy 2003], [Humar 2008], [Beno 1999]) than the short-term tests.

2. Reported Data on Tool Life Tests: An Abbreviated Literature Review

Tool life, *T*, is the time required to reach a critical amount of tool wear, *e.g.* VB, [Audy 1996]. Tool wear is characterized by changes in the shape of the tool during cutting, resulting from gradual loss of the tool material and/or its deformation [Audy 1996]. Generally, flank wear, VB, is the best know type of tool wear the width of which can be relatively easily measured. This type of wear is responsible, at the least, for poor surface finish or creating poor tolerances [Audy 1996]. The tool life depends mostly on cutting speeds, v_C, as well as on depths of the cut, a_P, and feed rates, *f*.

The tool life, T [min], is expressed as a time, which is responsible for continuous growth of tool wear, VB_{CONT}. The following Equation 1 relates the tool life with tool wear in terms of time to achieve the minimum and maximum level of the flank wear, VB.

$$T = t_1 + \left[\frac{t_2 - t_1}{VB_2 - VB_1}\cdot(VB_{KRIT} - VB_1)\right] \text{[min]} \qquad (1)$$

where :
t_1 [min] and t_2 [min] represent particular time needed to achieve the nearest minimum value of VB_{CONT} i.e. VB_1 and the nearest maximum value of VB_{CONT} i.e. VB_2, respectively.

Taylor´s log transformed life data and role of the exponent „m"

It is generally acknowledged that when conducting the experimental tool life tests in terms of life values in e.g. minutes recorded over a number of different speeds it is possible to get Taylor's Type trends for a graphic comparison *i.e.* qualitative analysis, before starting investigations of intercepts and slopes as well as their relevant statistical significance. This log transformed linear trend shows regression lines and the scatter associated with the experimental cutting tools examined, for all the log transformed life data at each log transformed speed value [Audy 2003]. Some examples are shown in the following Figures 1 and 2.

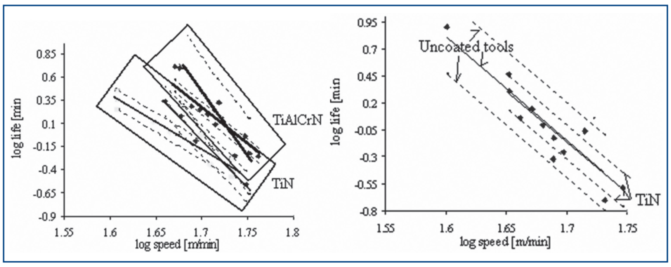


Figure 1. *Effects of composition of (Ti,Al,Cr)N and TiN coatings, left, and TiN coated and uncoated drills when dry drilling grey cast iron.ngs on drill life [Audy et al 2002], and [Audy 2009] when dry drilling grey cast iron.*

The Figure 1 reffers to dry machining of greay cast iron. From Figure 1 left it is evident that TiAlCrN drills outperformed the TiN drills by a factor of 2.3 . In contrast, the TiN were not succesfull in dry machining of grey cast irom because they failed to outperform the uncoated tools ([Audy et al 2002], and [Audy 2009]).

Figure 2 shows an example of drill life values in holes and in minutes which were recorded for a number of different speeds in order to get empirical drill-life – speed equations and to compare the effect of the three coatings and one M35 HSS tool material substrate on the drill-life. The full test results for the coated and the uncoated GP-twist drills of the nominal diameters of 6mm are given in source

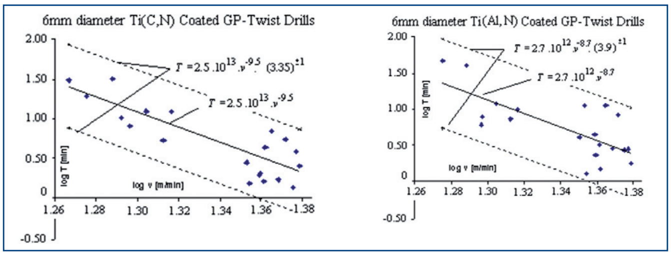


Figure 2. *An example of empirical Taylor-type relationship between drill life and cutting speed for the uncoated (a), TiN coated (b), Ti(C, N) coated (c) and Ti(Al. N) coated (d), drills, adopted from source [Audy 2007].*

[Audy 2007]. From these graphs it si apparent that these data fall on reasonably sharp lines for each drill tested suggesting that the well known Taylor-type equation can be considered to apply.

The value of an exponent, *m,* is another performance measure mentioned in the catalogues of the producers of CTI's. Generally, the greater the value of the exponent, *m,* the steeper the gradient α of the log T-log v transformed line (see Table 1), which makes CTI's being more sensitive to both scatter and tool life quantity with the inceases in cutting speeds.

m [–]	α [°]	tool material
8–12	83–86	tool steel
5–8	79–83	high-speed steel
2.5–5	68–79	sintered carbides
1.2–2.5	50–68	ceramic tools

Table 1. *The values of the exponent „m" for different tool materials*

A linear regresession approach

A linear regression approach will be used for calculating the coefficients of the experimental type Taylor´s equations for all cases showing the linear trends between the log *T* data when plotted against the log *v* data with the log data of tool wear, *VB*, being a function of the log time data, *t, i.e.* log *VB* = f (log *t*). The corresponding regression coefficients, *a* and *b*, of the log *T* (log *VB*) – log *v* data plots (in a form of linear trends) will be determined from Equations 2 and 3, according to sources [Andel 2007] and [Turcek 2002].

$$b = \frac{\left(\sum x\right)\cdot\left(\sum y\right) - n\sum xy}{\left(\sum x\right)^2 - n\sum x^2} \tag{2}$$

$$a = \frac{1}{n}\left(\sum y - b\sum x\right) \tag{3}$$

The regression coefficients, *a* and *b,* relate to Taylor's exponent, *m*, and corresponding constants, C_T , C_V , as shown in Equations 4, 5 and 6, respectively.

$$m = -b \tag{4}$$

$$C_T = 10^a \tag{5}$$

$$C_V = C_T^{\ 1/m} \tag{6}$$

Statistical approach

Standard deviations were calculated and used to assess the scatter in the as measured data with respect to central mean line. Estimation of standard deviation of the coefficient, *a i.e.* s_a) was determined by employing Equation 7, according to the literature source [Andel 2007].

$$s_a = \sqrt{\frac{\sum (y_i - Y_i)^2}{n-2}} \cdot \sqrt{\left[\frac{1}{n} + \frac{\bar{x}^2}{\sum x^2 - \frac{\left(\sum x\right)^2}{n}}\right]} \tag{7}$$

where:

x represents the average value of autonomous variable of *x; y_i* relates to the experimental values; Y_i associates with the values determined by regression formula for corresponding values of x_i*; n* is the number of values

The standard deviation of the coefficient, *b i.e.* s_b, is determined by using the Equation 8.

$$s_b = \frac{\sqrt{\frac{\sum (y_i - Y_i)^2}{n-2}}}{\sqrt{\left[\sum x^2 - \frac{\left(\sum x\right)^2}{n}\right]}} \tag{8}$$

This enabled to determine the intervals of reliability for all the values of the coefficient, *b*, by using relevant standard deviations for the corresponding exponent, *m*, represented by *b* as shown in the following Equations 9.

$$L_{(b)1,2} = b \pm s_b \cdot t_\alpha \tag{9}$$

In this Equation the t_α represents the critical value of the Student ´s separation for the a.data while v equals to = n – 2. The n associates with the number of as measured values.

3. Experimental Details

Experimental details associated with the experimental arrangement, work-piece materials cutting tools and equipment used are described below.

Work-piece material, cutting tool and testing equipment

A Type 422425 grey cast iron was used as an experimental work-piece material for the metal machining tests. The testing specimens were prepared by centrifugal casting into sand molds. Before conducting the actual cutting tests the work-piece materials had their surface machined off in order to remove the sand and impurities from casting. This involved turning the work-piece materials using a tool equipped with CTI sintered carbides. The process is depicted by a simple sketch in Figure 3 with reference to the literature source [Kovalcík 2008].

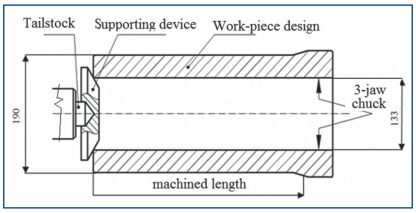


Figure 3. *A sketch showing the actual design of experimental work-piece material, after source [Kovalcík 2008].*

A type SU 50 turning lathe with power of 11kW was used to carry out the cutting tests. The lathe did not allow continuous changing of speed rates for changes in diameters of work-piece materials reduced during individual cutting tests. Consequently, the average cutting speed of v_{cp} determined from individual cutting speeds v_{Cmin} and v_{Cmax} was used for further analysis. Although the cutting speed depended on the actual work-piece diameter in real time of machining the differences between minimum and maximum values of cutting speeds ($v_{Cmax} - v_{Cmin}$) used were up to about 20 m.min^{-1}.

The CTI had square-cross sections with the dimensions of 12.7x12.7 [mm] and the thickness of 4.76mm. The inserts were clamped to a Type Narex 2525 PN3850.1 right cutting turning tool holder. The tool holder had the following geometry $\alpha_O = 6°$, $\gamma_O = -6°$, $\lambda_S = -6°$ and $\kappa_r = 75°$. Referring to Audy (1996) the selection of tool angles has an effect on surface finish produced by th ecutting tools as well as on the tool life. The diameter of the work-piece, the capacity and the conditions of the machine, and the workpiece material properties play the key roles in th eselection of proper tool, and its geometry. Accorging to [Audy 1996] the cutting rake angle (γ) influences the cutting process and chip formation. In these experiments it was decided to use a negative rake angle. It was because this geometry allows for rough machining and for machining short chipping materials. Also the negative angle makes the cutting insert more resistant to vibrations and prolongs the tool life [Audy 1996]. The back rake angle (λ) can be positive or negative. In these experiments a decission was made to employ the negative back rake angle becasue of its ability to preserve the point of the cutting edge from the impact stresses. The clearance angle (α) affects the tool / work piece operating temperature and the tool life [Audy 1996]. Generally, the large clearance angle involves increased risk of edge break down. Dangerous vibrations can be eliminated by setting the tool points above the centre of the work-piece, which gives a smaller clearance angle [Audy 1996]. Finally, the approach angle (κ) affects the chip thickness. A large approach angle gives thick chips. A small approach angle reduces chip thickness, but improves an increase of the radial force [Audy 1996].

For measuring the flank wear values of VB [mm], it was decided to use a Type Carl-Zeiss JENA workshop microscope with accuracy of measurement up to 0.01 mm.

Cutting conditions

The 'dry' turning test experiments were conducted at constant cutting conditions, namely, a depth of cut, a_p, of 1 mm; and the feed rate, f, of 0.2 mm/rev. The cutting speeds changed from 250 m.min^{-1} to 380 m.min^{-1}. The metal machining speeds used in the turning experiments related to the revolutions of lathe chuck and actual changes in the diameter of work-piece materials in real time of machining i.e. v_{C1} = 250 m.min^{-1} (n=450 rpm), v_{C2} = 320 m.min^{-1} (n=560 rpm), and v_{C3} = 380 m.min^{-1} (n=710 rpm).

Work-piece material: Quality assurance

Brinell tests were conducted to measure the hardness data from experimental work-piece materials and hence assess their homogeneity (quality) for metal machining tests. The hardness values ranged 254 and 282 HB for each experimental work-piece material confirming their quality [Kovalcik 2009] and suitability for the tests.

4. Experimental Findings: Results and their analysis

Table 2 lists the experimental data from three CTI tools referring to their tool life and wear at different cutting speeds.

CTI	v_C [m.min^{-1}]	VB [mm]		t [min]		T [min]
		VB_1	VB_2	t_1	t_2	
FMG121C	254.1	0.38	0.51	27.1	30.9	30.6
	320.6	0.35	0.50	3.2	9.4	9.4
	370.8	0.47	0.56	9.7	12.1	10.5
FMG122C	244.7	0.41	0.53	165.6	173.3	171.4
	338.3	0.48	0.64	112.1	118.1	112.9
	420.6	0.40	0.53	95.1	97.4	96.9
FMG134C	251.3	0.37	0.50	38.1	49.5	49.5
	319.8	0.42	0.51	18.1	23.9	23.3
	367.9	0.47	0.58	23.2	25.5	23.8

Table 2. *The values of calculated durability of compared CTI*

It needs to be noted that the flank wear of 0.5 mm was chosen by the author as the criterion for considering the cutting tool to be worn to a level of not being suitable any more for economic machining. It needs to be noted that the author compared the cutting performance (tool–life) and wear of both oxide based and nitride based ceramic cutting inserts – up to about 20 inserts in each group. During this 'pilot' study – it was found that the oxide based ceramic inserts exhibited lower tool life compared to nitride based ceramic inserts. Speaking in terms of flank wear for the oxide based ceramic inserts the $VB_{Critical}$ ranged from 0.29 to 0.35mm while for the nitride based ceramic inserts this range was greater, from 0.32 to 0.54, indicating such better wear resistance and greater tool-life.

Experimental Taylor´s type equation: exponent, m, and the CV and CT constants

Taylor´s type exponent, *m*, and the corresponding constants, C_T and C_V, were calculated using Equations 4, 5, and 6. Into these equations the *x* data were substituted in a way that x=log v_C; for v_C data see Table 2. The *y* data associated with the tool life *i.e.* y = log T; T – see Table 2.

CTI	a	b	m	C_V	C_T
FMG121C	8.74	–3.04	3.07	750.11	5.45 E+08
FMG122C	4.78	–1.07	1.07	29246.08	6.08 E+04
FMG134C	6.59	–2.05	2.05	1625.77	3.90 E+06

Table 3. *Tabulated summary of resulting values*

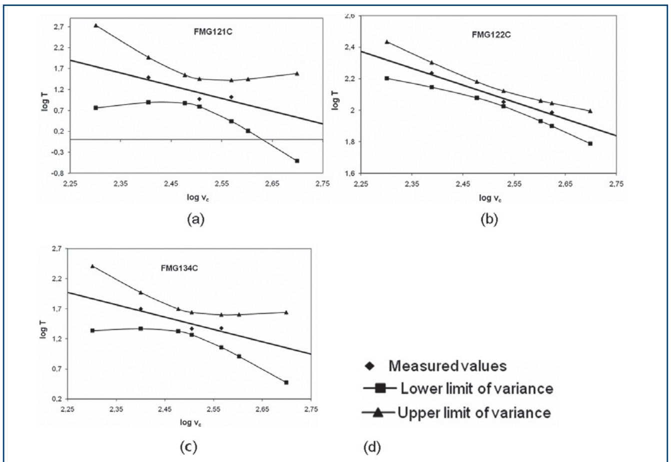
Table 3 lists quantities of *a, b, m*, C_T and C_V calculated using Equations 6 and 7 with respect to Taylor´s type equations of experimental values listed earlier in Table 2.

Standard deviations and intervals of reliability

Standard deviations of regression coefficients, *a* (s_a), *b* (s_b), were calculated using Equations 7 and 8, respectively. Intervals of reliability of regression coefficients *a i.e.* $L_{(a)1,2}$ was calculated using Equation 9. The critical value of Student´s separation, $t_\alpha(n)$, relevant to the intervals of reliability was determined from statistical tables (Anděl, 2007) for the following set up the degree of freedom f=1 and Q=90% (α*=0,2), *i.e.* $t_{0,2}(3)$=3.078 according to the source (Andel 2007). Resulting values of standard deviations of regression coefficients, *a* and *b*, including the the corresponding intervals of reliability for the exponent, *m*, of the Taylor´s type equations are shown in the following Table 4.

CTI	Standard deviations		Interval of reliability	
	s_a	s_b	m	
FMG121C	3.92	1.57	1.79	7.87
FMG122C	0.41	0.16	0.57	1.57
FMG134C	2.15	0.86	0.61	4.71

Table 4. *Standard deviations and corresponding intervals of reliability for the three experimental CTI*



$$FMG\ 121C: y = -3.1x + 8.7 \Rightarrow \log T = -3.1 \log v_C + 8.7364$$
$$FMG\ 122C: y = -1.1x + 4.8 \Rightarrow \log T = -1.1 \log v_C + 4.7838$$
$$FMG\ 134C: y = -2.1x + 6.6 \Rightarrow \log T = -2.1 \log v_C + 6.5911$$

(e)

Figure 4. *Graphic dependence of log T values plotted against the log vC values for all three CTI, (a to c); including sybols (d) and corresponding Equations(e).*

Qualitative trends and Corresponding Equations

The experiments were conducted at three cutting speeds, namely, v_{C1} , v_{C2} , $v_{C3.}$ It has been recognised that cutting forces and hence the cutting power decrease with greater values of cutting speeds [Audy 1996, 2002]. The later has positive effects on machining time *i.e.* the greater the speed the shorter the time per component leading to improved efficiency of metal machining operations. In order to investigate interval refering to cutting efficiency of each CTI, it was necessary to extend the cutting speeds from 200 to 500 $m.min^{-1}$ as depicted in Figure 4. This range in graphic representations of log T values plotted against different log v values represented the upper and lower limits where the tool life pattern and quantities were identified in terms of variances and reliability.

Selection of optimum cutting speeds for economic machining

In this paper the best cutting efficiency was examined over a small range of machining intervals including a number high machining speeds, see Table 5. In addition, the experiments were carried out for tool life spans, *T*, of 3, 5 and 10 minutes.

CTI	*T [min]*		
	3	*5*	*10*
	v_{cT} [m/min]		
FMG121C	520	440	350
FMG122C	10480	6450	3400
FMG134C	950	740	530

Table 5. *The values of the cutting speeds vcT for selected tool life data.*

From Table 5 it is evident that the optimum tool life data, *T [min],* for efficient machining was determined and it associated with T being in the range from 3 to 5 minutes. In this interval the profitable durability of the tool edge corresponds to higher machining speeds. In contrast, the speed had to be reduced quite drastically in order to increase the tool life to about 10 minutes.

5. Conclusions

The cutting efficiency of the three CTI was experimentally assessed and compared using the linear regression analysis, coupled with the method of the smallest squares. It allowed establishing the trends, and calculating the corresponding standard deviations, regression coefficients as well as the intervals of reliability.

A Type FMG122C CTI appeared to be the best cutting insert showing the lowest *m* value (=1.04) of the experimentally gained Taylor´s type equation. This tool was found to be less sensitive to the cutting speeds. Also, it exhibited several times better tool life compared to the other two cutting inserts tested under same cutting conditions. It means that for the tool life ranging from 3 to 5 minutes the cutting speeds, $v_{cT,}$ were in the interval of 6450 to 10 480 m/min which is considered as high-speed machining. Moreover, the standard deviation for the coefficient of the linear regression, *b*, which is related the exponent of Taylor´s equation *m*, from Equation 4, was 0,16 (=s_b). The latter was the lowest compared to other CTI's and it also associated with exceptionally good interval of reliability m = 0.57 to 1.55, see Table 4. This was depicted in Figure 4 (b) where the smallest scatter relates to better reliability and hence greater accuracy of machining.

A Type FMG134C CTI appeared had the *m* value of 2.05, and the corresponding interval of reliability ranging from 0.61 to 4.71 (see Table 4). The standard deviation for the coefficient of the linear regression, *b*, which is related the exponent of Taylor´s equation *m* was $s_b = 0.86$ (see Table 4) This related to a great scatter depicted graphically in Figure 4. With the actual tool life ranging from 3 to 5 min the corresponding interval of cutting speeds, $v_{cT,}$ ranged from 740 to 950 $m.min^{-1}$ (see Table 5). These machining speeds were much lower (and hence less efficient) than those of a Type FMG122C CTI .

Finally, a Type FMG121 CTI exhibited the value of the exponent of Taylor´s equation m=3.07 (see Table 3) and the corresponding interval of reliability *m* ranging from 1.79 to 7.87 (see Table 4). The standard deviation of the coefficient of the linear regression *b*, which related to the exponent of the Taylor´s equation *m* was s_b=1.57 (see Table 4). This was the worst inaccuracy in the interpolation from all of compared CTI's for experimental cutting speeds used (see Figure 4). Within tool life *T* ranging from 3 to 5 minutes the cutting speeds were in the interval of v_{cT} = 440 to 520 $m.min^{-1}$ (see Table 5). This interval was the smallest and hence the worst form all three CTI's investigated.

Finally it needs to be concluded that in these experiments the excellent cutting speed ranges were found for CTI's made of NCC for the machining of grey cast iron. The Type FMG122C CTI has the best tool life for more advanced cutting speeds compared to other CTI made of oxide cutting ceramics under the same conditions. These findings were in agreement with other similar data published by [Kovalcik 2008] and [Dlouhy 2001].

Acknowledgement

This paper relates to the work on the MSM 4674788501 project which is financed MSMT ČR and FT-TA4/105 project which is financed by the Ministry of Industry and Trade. Finally,

The author would like to thank the Austrian Research Institute „Österreichisches Forschungszentrum Seiberdorf", for supplying the cutting tools and supporting this testing programme.

References

[Andel 2007] Andel, J.: *Statistical methods.* MATFYZPRESS, Prague, 2007

[Audy 1996] Audy J.: *Assessment of Metal Machining Process Parameters and the Development of Adaptive Control*" PhD Thesis, The University of South Australia, 1996

[Audy et. al. 2002] Audy J., Harris S.G., Audy K., Brinkies H., Doyle E.D., McKenzie D.R.: *Performance Evaluation of Cathodic arc Evaporated (CAE) TiAlCrN Coated General Purpose Twist Drills When Dry Machining Grey Cast Iron*, 5th Conference on "*Behaviour of Materials in Machining*", Chester, UK, 11–14 November, 2002

[Audy 2003] Audy J.: *The Influence of Hard Coatings on the Performance of Twist Drills*", Thesis for Master of Engineering Science in Research, The University of Melbourne, Australia, 2003

[Audy 2007] Audy, J.: *A Study of the Effect of Coatings on the Drill Life*", Manufacturing Engineering, No. 1, Vol. VI, Slovakia, 2007

[Audy 2009] Audy, J.: *Analysis of Importance of Tool Coatings in Metal Machining,* Manufacturing Engineering, No. 3, Vol. VIII, Slovakia, 2009

[Beno 1999] Beno, J.: *Theory of metal cutting.* VIENALA, Kosice, 1999.

[Dlouhy 2001] Dlouhy, R.: Comparative durability tests of cutting tool insert´s made of nitride ceramic. MSc Thesis. TU FS Liberec, 2001.

[Humar 2008] Humar, A.: *Materials for cutting tools.* 1. vyd. MM publishing. Prague, 2008. ISBN 978-80–254–2250–2., 2008

[Kovalcik 2008] Kovalcik, J.: *The analytical-synthetic study of the set of ceramic cutting inserts.* MSc Thesis. TU FS Liberec, 2008.

[Kovalcik 2009a] Kovalcik, J.: *Long-term durability tests cutting tool insert`s made of oxide cutting ceramic with zirconium machining of steel 12050.1.* Manufacturing Engineering. roč. 7, 2009, No. 2. s. 18 – 30, 43, 2009

[Kovalcik 2009b] Kovalcik, J.: *Comparison of cutting tool insert´s made of oxide cutting ceramic machining of grey cast iron.* Engineering technology, No. 1, 2009

[Turcek 2002] Turcek, P.: *Durability tests of cutting tool insert´s made of nitride ceramic.* MSc Thesis]. TU FS Liberec, 2002.

Contacts

Dipl. Ing. Jaroslav Kovalcík, Dipl. Ing. Jirí Cuban
Department of Machining and Assembly
Technical University of Liberec
Studentska 2, 461 17 Liberec 1, Czech Republic
tel.: +420 48 53 53 369, e-mail: jaroslav.kovalcik@centrum.cz
www.kom.tul.cz