The effect of multi-layer surface coatings of carbide inserts on the cutting forces in turning operations

Author:
Wang, Jun

Publication details:
Journal of Materials Processing Technology
v. 97
pp. 114-119

Publication Date:
2000

Journal of Materials Processing Technology, Vol 97 (2000), pp. 114-119.

The effect of multi-layer surface coatings of carbide inserts on the cutting forces in turning operations

J. Wang*
School of Mechanical, Manufacturing and Medical Engineering,
Queensland University of Technology,
GPO Box 2434, Brisbane, Qld. 4001, Australia.

Abstract
In this paper, the effects of multiple layer hard surface coatings of cutting tools on cutting forces in steel turning are presented and discussed based on an experimental investigation with different commercially available carbide inserts and tool geometries over a range of cutting conditions. The cutting forces when turning with surface coated carbide inserts are assessed and compared qualitatively and quantitatively with those for uncoated tools. It shows that hard surface coatings reduce the cutting forces, although the reduction is marginal under lighter cutting conditions. The cutting force characteristics for surface coated tools are also discussed and show similar trends to those of uncoated tools.

Keywords: Turning; Machining; Cutting forces; Surface coatings; Carbide inserts

1. Introduction

Machining is a versatile shaping process of major importance for component manufacturing. The importance of machining in modern automated manufacturing systems has in fact increased due to the significant increases in the production times and the need to offset the high capital investment in these modern systems.

The need for improving the technological performance of machining operations as assessed by the forces, power, tool-life and surface finish has long been recognized to increase the economic performance of the machining operations. As such, continual improvements in the technological performance of machining operations have been sought through research and development including new and more wear resistant tool materials as well as new geometrical tool designs. One of the important cutting tool improvement in recent years has been the introduction of hard surface coatings on the substrates such as carbides. Hard coatings such as TiN, TiC and Al_2O_3 have been used and claimed to significantly improve the tool-life, enabling components to be machined at higher ‘economic’ speeds. It has also been claimed that such coatings reduce the forces and power due to lower friction coefficients on the rake face. However, it is interesting to note that the investigations on hard surface coatings of cutting tools were predominantly orientated towards the various aspects of wear patterns [1, 2]. Little has been reported on the quantitative assessment and information of hard surface coatings in terms of cutting forces to guide the selection and design of machine tools, cutting tools and fixtures as well as the selection of economic cutting conditions.

* Fax: +61-7-3864 1469, Email: j.wang@qut.edu.au.

This paper attempts to study the cutting forces when steel turning with multi-layer surface coated carbide inserts and to assess qualitatively and quantitatively the superiority of hard surface coatings over uncoated carbide tools based on an experimental investigation. The trends of the cutting forces as well as their improvements by hard coatings will be discussed under different cutting conditions and tool geometries. Finally, empirical equations for predicting the cutting forces will be established for practical applications. For these purposes, the few reported studies on this topic are reviewed first.

2. Review of previous investigations

Verezub [3] has conducted extensive experimental 'classical' orthogonal cutting tests with TiN coated carbide and high speed steel (HSS) tools. He attempted to study the effects of hard surface coatings on the cutting forces and the fundamental quantities of machining, such as the shear angle and friction angle, with a view to developing force predictive models for the various practical machining operations. While many plausible trends have been found on the quantitative effects of surface coatings on the force components as well as friction and shear angles for both carbide and HSS substrates, there is still a lack of fundamental explanations of these effects. Furthermore, this study, though more scientific in force prediction, is distant from practical needs and considerable work is required before any predictive models can be developed.

Karapantev [4] has investigated the influence of CVD (Chemical Vapor Deposition) coatings on the cutting forces at different tool wear stages when turning a plain carbon steel. He considered four different grades of carbides as the substrates and the results show that for unworn tools, all of the hard coated tools have lower average power forces than uncoated tools, ranging from less than 1% to about 24%. There appears to be no definite trends as to which coatings and substrates yielded the best results. The effect of coatings on the feed and radial force components for unworn tools is even less certain, coatings sometimes giving higher forces and sometimes lower forces. In addition, Karapantev has considered only one tool geometry and one combination of feed, depth of cut and cutting speed.

Mohmoud [5] has also used turning as a means for testing hard coated carbide tools using seven combination of tool geometry, types of coatings and substrates from one tool manufacturer. Various cuts were made with mild steel, En 8 steel and stainless steel, all under lubricated conditions. Unfortunately, the mixture of the parameters and variables make definitive comparisons difficult and, hence, very few conclusions can be drawn.

The influence of hard surface coatings on the performance of double rake cutting tools has been studied by Fowler *et al*. [6]. They used cutting tools with primary rake angles of between −10° and −40° together with a range of land widths and a secondary rake angle of +5°. One batch of tools was retained in the uncoated condition, while a second batch was coated with 8-12 μm single layer of TiN. Both batches were used to cut normalised steel tube under orthogonal cutting conditions. The only definite conclusion from these tests is that the force behavior of coated double rake tools is different from that of uncoated tools which are otherwise similar.

Other attempts to study hard tool surface coatings are also reported. Byeli *et al*. [7] have investigated the cutting performance of lathe tools with single and multiple hard layers of different thicknesses. They found that the three force components showed no significant difference as the coating thickness was varied. In the experiments conducted by Byrne *et al*. [8] in face milling high nickel content soft magnetic materials with TiN coated HSS inserts, they claimed that hard coated cutters required lower forces and hence less energy. Unfortunately, the authors have not provided any numerical data to quantify this claim.

It is interesting and surprising to note that very few attempts have been made to study the effect of hard surface coatings on measured forces in practical machining operations. From the limited published work, it appears that the coating type and substrate influence the forces in machining and this influence behaves differently for different tool geometry, cutting conditions and work material. However, these factors do not seem to have been studied in a sufficient way to make a clear statement about the nature of these influences.

3. Experimental work

The machining experiments were conducted on a Takisawa TSL-1000 lathe turning a CS1020 bright mild steel bar. The chemical composition of the work material is 0.20% C, 0.25% Si, 0.50% Mn, 0.04% P and 0.04% S, and the yield strength is 290 MPa with a hardness of 125 BHN. Four different inserts of two different geometries identified by the types of SCMT and CNMM were selected and all were supplied by Sandvik Australia Pty. Limited. For each geometry, uncoated as well as CVD triple coated inserts with $TiC+Al_2O_3+TiN$ (TiN being the top coating) of totally 8 μm were used. The tool material/substrate for all the inserts is a grade P35 carbide. The Sandvik type SSBCR-2020-K12 and type PCLNR-2020-K12 tool holders were used for SCMT and CNMM types of inserts, respectively. The detailed geometry of all the tools used are given in Table 1. This selection enables the effect of surface coating to be evaluated under different tool geometries and different cutting conditions.

<take in Table 1>

For each tool geometry and surface condition, three levels of feed per revolution (0.13, 0.17 and 0.21 mm) and three levels of depth of cut (0.5, 1.0 and 2.0 mm) were tested under two levels of cutting speed (108 and 206 m/min). The tangential, feed and radial force components were measured using a Kistler type 9257A three-component piezo electric dynamometer. The induced force signals from the dynamometer were amplified by three Kistler type 5001 charge amplifiers, each connected to an output channel of the dynamometer, before recorded for processing and analysis. During the course of the experiments, the tool inserts were checked frequently for wear and, if the wear became significant in affecting the cutting forces, the insert was indexed or replaced. Using the measured values of the force components, the superiority of multiple layer hard surface coatings over the uncoated tools are assessed for different tool geometry and cutting conditions, and the characteristics of the cutting forces with respect to the cutting conditions when turning with surface coated tools are studied as follows.

4. Results and discussions

4.1 Comparison of cutting forces for coated and uncoated tools

Comparisons between the cutting force components for surface coated and uncoated cutting tools under the same cutting and tool geometrical conditions have shown that for all the 18 combinations of the cutting conditions, the feed forces F_x and radial forces F_y for coated tools are respectively lower than those of uncoated tools, though in a few cases these reductions are very marginal. Similar trends have been found for the power or tangential force component F_z, whereby the F_z values for the coated CNMM type of inserts are lower than those of uncoated tools in 17 out of 18 cases while in the remaining case the difference is not discernible. When steel turning with SCMT type of inserts, the hard coatings again yielded lower power force component in 17 out of 18 combinations of the cutting conditions. In only one of the 18 cases was the power force 0.03% higher than that of the uncoated inserts, which may be considered as 'by chance'.

Quantitative comparisons have been made based on the percentage increase in each of the three cutting force components for uncoated inserts with respect to the corresponding force values for surface coated tools, e.g.

$$\%\ F_x\ \ increase = \frac{F_{x(uncoated)} - F_{x(coated)}}{F_{x(coated)}} \cdot 100\% \qquad (1)$$

where the subscripts coated and uncoated indicate the force components for coated and uncoated tools, respectively. Fig. 1 shows these comparisons in the form of histograms. It is noticed that the tools with coated SCMT type of inserts resulted in only slight improvements for the three force components with the highest occurring at the feed force F_x of 5.87% on average with a range of 0.3% and 14.3%. The corresponding values for the radial force component are 5.58% on average ranging from about 0 to 14.1%. Surprisingly, the average reduction in the power force F_z is only about 3% with a range of –0.03% and 7.2%.

<take in Figure 1>

By contrast, the statistical results show that the force improvements by surface coatings on CNMM type of inserts are considerably higher than those of the SCMT type of inserts. Specifically, the uncoated CNMM inserts have yielded feed forces F_x which are 15.37% higher on average than their coated counterpart with a range of about 2.5% and 38%. The improvements in the radial forces F_y when using coated inserts are also considerable with over 10% on average and ranging from less than 1% to 26%. Even for the power force F_z the overall results showed an average of 7.4% improvement when using coated inserts with a range of about 0% and 16.5%.

It appears that under the current testing conditions, the use of surface coatings results in higher reduction in the feed force than the other two force components, while the power force is the least beneficiary. It is also apparent from this study that the improvements in the cutting forces depend on the tool geometry. For the CNMM type of inserts which have a negative normal rake angle and hence produce larger cutting forces, the force reductions when using hard coatings are more considerable than the SCMT inserts with a positive normal rake angle. In addition, it is worthwhile to look at the effect of tool surface coatings on the cutting forces under different cutting conditions.

Table 2 summarises the effect of cutting conditions (*f*, *d* and *V*) on the percentage deviations of the cutting forces with coated and uncoated CNMM type carbide inserts. It can be seen that in general the percentage deviations for the three force components increase with increases in feed per revolution and depth of cut and with a decrease in the cutting speed. This trend is evident from the group of data with respect to the feed per revolution, whereby as the feed changes from 0.13 to 0.21 mm/rev. the percentage deviation of the feed force component increases from about 7% to about 25%. Similar trends can be noted for the radial and tangential force components. It is also evident from the table that with the same increment of feed rate, the percentage deviations of the cutting forces increase in larger rates when *f* changes from 0.17 to 0.21 mm/rev. than those when *f* changes from 0.13 to 0.17 mm/rev.. The reverse trends have been found with respect to the depth of cut *d*. It is noticed that an increase in *d* from 1 mm to 2 mm only causes marginal rise (about 1.1%) in the percentage increase in the feed force F_x, compared to a 12.5% rise when *d* changes from 0.5 mm to 1 mm, while the percentage increases in the radial and tangential forces become smaller. An increase in the cutting speed is associated with a drop in the percentage deviations for all the three force components, as can be seen from the table, although such changes are small, particularly for the tangential force F_z. Consequently, large reductions in the cutting forces by using tool surface coatings can be expected at higher feed and depth of cut and lower cutting speed which result in larger cutting forces.

<take in Table 2>

4.2 Characteristics of cutting forces for surface coated tools

The characteristics of cutting force components with respect to the cutting conditions and tool geometry in turning operations have been studied extensively with uncoated carbide tools [9, 10]. However, whether these characteristics are still applicable for hard surface coated tools needs to be studied.

Fig. 2 shows the trends of the cutting force components with respect to the cutting conditions when bar turning with surface coated tools. It can be seen in general that for both types of inserts, the three force components increase with an increase in the feed and depth of cut. Although an increase in the cutting speed results in a slight decrease in the tangential component of the cutting force, F_z, it does not show significant effect on the feed force, F_x, and radial force, F_y, components, as evidenced in Figs. 2(c) and (d). These trends follow earlier findings on uncoated carbide tools [9, 10]. It is also noted that with an increase in the feed, the rate of change for the tangential force F_z is greater than those of the other two force components, as shown in Figs. 2(a), (c) and (d). As the depth of cut increases, the tangential force F_z increases almost linearly, so does the feed force F_x, as shown in Fig. 2(b). It is interesting to note from this figure that the curves of feed force and radial force intersect at a *d* value between 0.5 mm and 1 mm. This is due to the fact that at smaller depth of cut, the active nose radius edge, which is corresponding to small (or negative) cutting edge angles, is of a larger proportion of the entire active cutting edge. These small cutting edge angles result in radial force component F_y larger than feed force F_x. As the depth of cut increases, the proportion of the active nose radius edge becomes smaller so that the side cutting edge with a large cutting edge angle re-distributes the feed and radial forces, resulting in larger feed force than the radial force. This again follows the trends for uncoated tools.

<take in Figure 2>

Although comparisons of cutting forces between the two types of inserts are difficult due to their difference in more than one geometrical angles, it is noticeable from Figs. 2(a) and (b) that all the three force components for the SCMT type of inserts are smaller than those of the CNMM inserts. This is mainly attributed to the negative normal rake angle of the CNMM inserts, although the differences in the inclination and cutting edge angles of the two types of inserts may also contribute to the differences in the cutting forces.

<take in Table 3>

For practical applications, empirical force equations have been established from the experimental data for the coated and uncoated cutting tools, as given in Table 3. Regression analysis has shown that these models have high coefficients of determination from 96.7% to 99.7%. These equations are valid for the tool-workpiece combination and the ranges of cutting conditions considered in the present study. Based on the well-known logarithmically linear relationship between the cutting speed and cutting forces, the cutting speed has also been included in the force equation as a variable, despite the insignificant effect of cutting speed on the cutting forces.

5. Conclusions

An experimental investigation on the effect of cutting tool hard surface coatings on the cutting forces and the associated force characteristics when turning a mild carbon steel has been presented. It has been shown that multi-layer hard surface coatings of cutting tools reduce the cutting forces while the percentage reduction increases with an increase in the force components. Apart from the coating type and substrate, the tool geometry and cutting conditions have been found to be important factors affecting the quantitative reductions of cutting forces by tool hard surface coatings. This study has also shown that the characteristics of the cutting force components for coated tools follow the patterns for uncoated tools although the numerical values are different. The empirical cutting force equations presented can be used for the selection and design of machine tools, cutting tools and fixtures as well as for the optimization of cutting conditions in process planning.

References

[1] Karapantev, K., On the character of side flank wear of T5K10 indexable carbide inserts, *J. Maschinostroene*, 1979, pp. 554-558.

[2] Karapantev, K., On some aspects of the wear pattern of CVD coated indexable carbide inserts investigated with a scanning electron microscope, *Proc. 3rd European Meeting on Chemical Vapour Deposition,* Switzerland, 1980.

[3] Verezub, S., *A study of the effect of TiN coating and substrate on the orthogonal cutting performances,* M. Eng. Sci. thesis, The University of Melbourne, 1996.

[4] Karapantev, K., Investigation on the cutting forces in machining with CVD coated indexable carbide inserts, *Annals of CIRP*, Vol. 29(1), 1980, pp. 89-96.

[5] Mohmoud, E., *Machining with titanium nitride-coated metal cutting tools*, Ph.D. Thesis, The University of Aston in Birmingham, 1988.
[6] Fowler, J.O., Draper, W.A. and Derricott, R.T., Influence of hard surface coatings on performance of double rake cutting tools, *Towards Improved Performance of tool Materials*, Metals Society, London, 1982, pp. 21-27.
[7] Byeli, A.V., Makushok, E.M., Markov, G.V. and Minevich, A.A., Flank and crater wear of cemented carbide tools with multilayer coatings, *International Tribology Conference*, Brisbane, 1990.
[8] Byrne, G. and Bienia, B., Tool-life scatter when milling with tin coated HSS indexable inserts, *Annals of CIRP*, Vol. 40(1), 1991, pp. 45-48.
[9] Oxley, P.L.B., *The mechanics of machining: an analytical approach to assessing machinability*, Ellis Horwood, 1989.
[10] Wang, J. and Mathew, P., Development of a general tool model for turning operations based on a variable flow stress theory, *Int. J. Mach. Tools Manufact.*, Vol. 35, 1995, pp. 71-90.

Table 1. Tool geometry and surface conditions used in the tests.

Tool material	Insert type	Surface condition	Corner radius	Normal rake angle	Inclination angle	Cutting edge angle
P35	SCMT	coated	0.8 mm	8°	0°	75°
P35	SCMT	uncoated	0.8 mm	8°	0°	75°
P35	CNMM	coated	0.8 mm	-1°	-6°	95°
P35	CNMM	uncoated	0.8 mm	-1°	-6°	95°

Table 2. Effect of cutting conditions on the percentage deviations of coated and uncoated tool cutting forces (CNMM type inserts).

		% F_x increase		% F_y increase		% F_z increase	
		range	average	range	average	range	average
	0.13	2.72-14.83	6.98	2.84-18.14	6.66	0-11.55	4.59
f (mm/rev)	0.17	3.48-24.43	14.38	0.44-14.81	6.27	1.48-11.48	6.57
	0.21	2.48-38.05	24.79	0.55-26.10	17.48	5.06-16.49	11.04
	0.5	2.48-18.88	6.64	0.55-22.06	8.66	5.06-11.55	7.05
d (mm)	1.0	3.85-31.66	19.17	2.95-19.36	11.01	0-16.49	8.69
	2.0	7.38-38.05	20.31	0.44-26.10	10.75	1.21-15.49	6.45
V (m/min)	108	2.72-38.05	17.07	2.95-26.10	10.83	2.75-15.49	7.59
	206	2.48-31.66	13.67	0.44-19.98	9.44	0-16.49	7.20

Table 3. Empirical equations for turning CS1020 mild steel.

Coated SCMT inserts	Coated CNMM inserts
$F_x = 281.84 d^{1.19} f^{0.413} V^{0.0079}$	$F_x = 338.84 d^{1.20} f^{0.393} V^{-0.0079}$
$F_y = 282.04 d^{0.503} f^{0.583} V^{0.0556}$	$F_y = 288.40 d^{0.392} f^{0.569} V^{0.0595}$
$F_z = 1288.25 d^{0.894} f^{0.684} V^{-0.0337}$	$F_z = 1513.56 d^{0.997} f^{0.664} V^{-0.0595}$
Uncoated SCMT inserts	**Uncoated CNMM inserts**
$F_x = 287.43 d^{1.202} f^{0.469} V^{0.036}$	$F_x = 891.25 d^{1.29} f^{0.699} V^{-0.0635}$
$F_y = 275.42 d^{0.525} f^{0.519} V^{0.0516}$	$F_y = 489.78 d^{0.408} f^{0.763} V^{0.0437}$
$F_z = 1258.93 d^{0.967} f^{0.665} V^{-0.0238}$	$F_z = 2137.96 d^{0.994} f^{0.803} V^{-0.0635}$

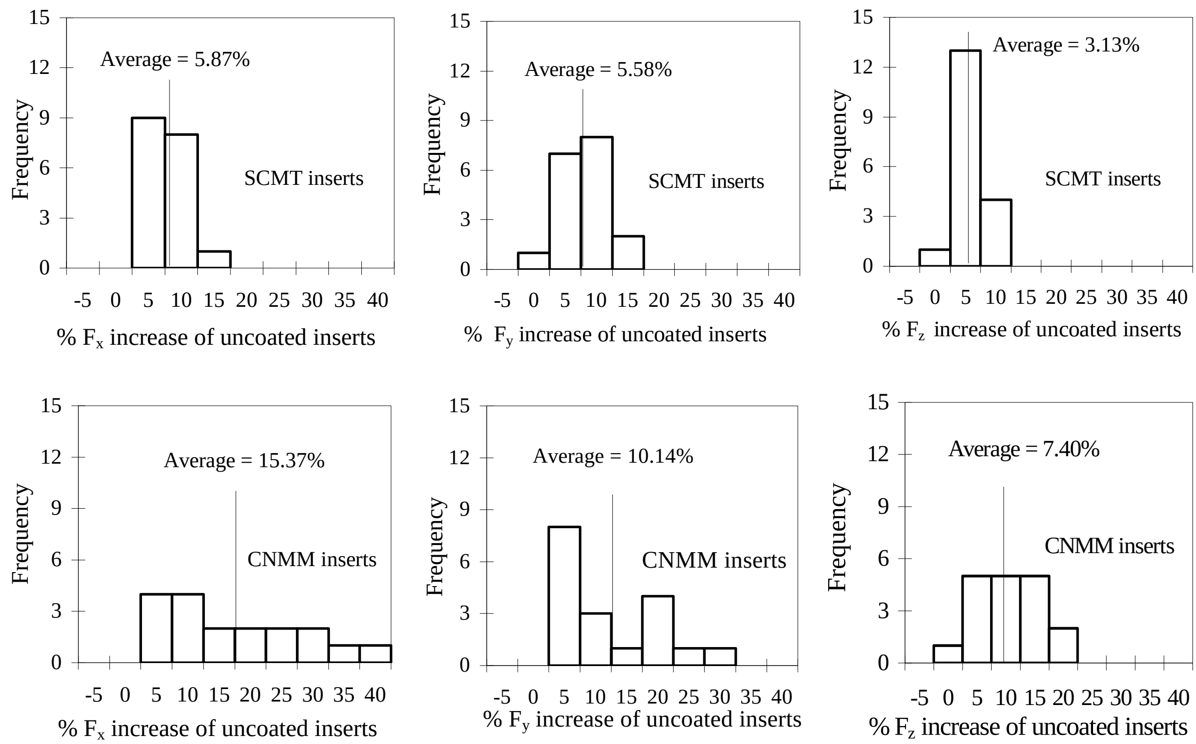
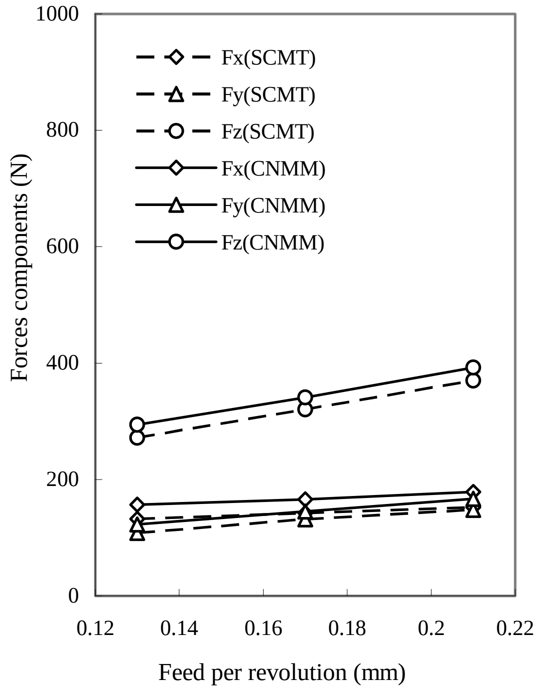
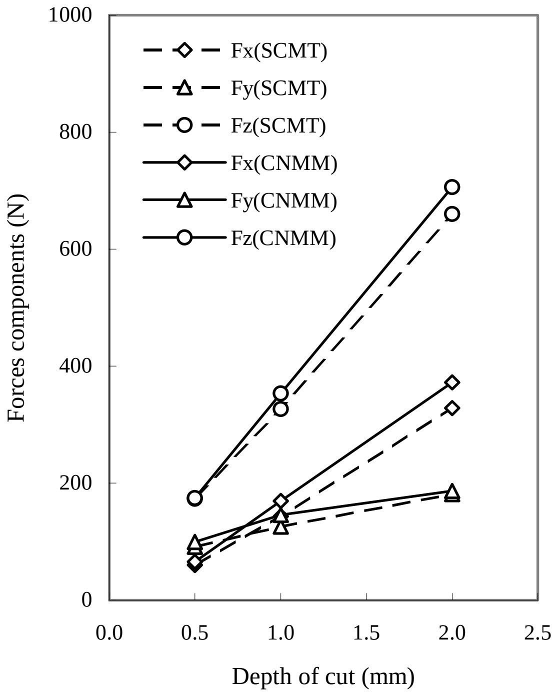


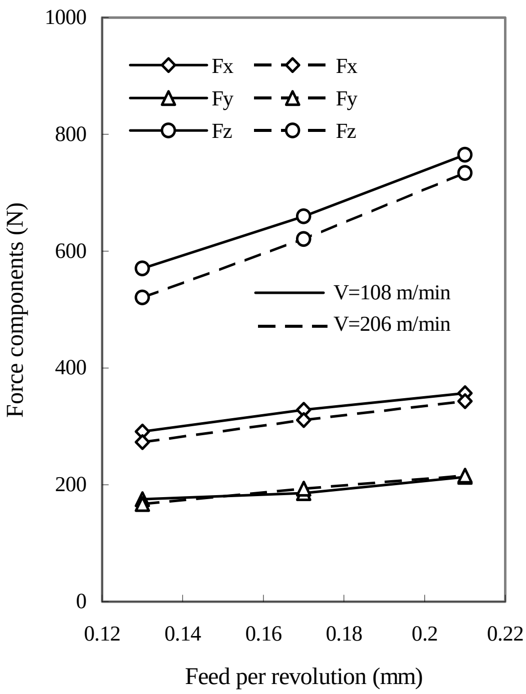
Fig. 1. Histograms for percentage deviations of coated and uncoated tool cutting forces.



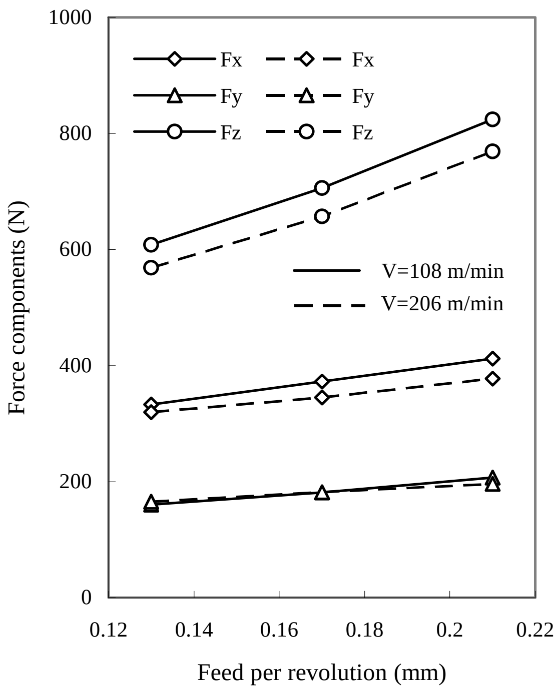
(a) Cutting forces vs. feed per revolution *f* when *d*=1 mm and *V*=206 m/min.



(b) Cutting forces vs. depth of cut *d* when *f*=0.17 mm/rev. and *V*=108 m/min.



(c) Cutting forces vs. feed per revolution *f* when *d*=2 mm and using SCMT type inserts.



(d) Cutting forces vs. feed per revolution *f* when *d*=2 mm and using CNMM type inserts.

Fig. 2. Effect of cutting conditions on the cutting force components when turning with surface coated inserts.