JOURNAL OF ENGINEERING
annals OF
FACULTY OF ENGINEERING HUNEDOARA
TOME VI (year 2008), FASCICULE 1, (ISSN 1584 – 2665)

A STUDY OF DRY MACHINING PERFORMANCE OF THE TiN, Ti(Al,N) AND Ti(C,N) COATINGS AND A M35 HSS TYPE TOOL SUBSTRATE MATERIAL ASSESSED THROUGH BASIC CUTTING QUANTITIES GENERATED WHEN ORTHOGONAL TURNING A BISALLOY 360 GRADE STEEL WORK-PIECE MATERIAL

Jaromir AUDY

SCHOOL OF ENTERPRISE AND TECHNOLOGY
EDITH COWAN UNIVERSITY, AUSTRALIA

Abstract:
This paper provides details about experimental investigations of the effects of the influence of the aforementioned three - cathodic arc evaporated - PVD coatings and one tool substrate material on the 'classical' cutting process as a whole, which is also investigated qualitatively and quantitatively, using findings obtained from orthogonal cutting tests performed on Bisalloy 360 Grade steel work piece material. The experiments looked at variations in the chip formation, the cutting force components and power, as well as the tool-chip friction. The results were then studied and compared qualitatively and quantitatively over a wide range of operation variables for the coated and uncoated HSS tools. The data on qualitative effects were analyzed by comparing the trends in the measured and derived quantities such as force components, deformation characteristics and rake face friction with changes in cutting variables to the typical trends noted in the open literature sources. For this purpose the shear angle, shear stress and friction angle, known as the basic cutting quantities, were evaluated from the chip length ratio and the measured force components using the modified thin shear zone (plane) cutting analysis for each cut taken. Various statistical methods such as regression analysis, analysis of variance and covariance, Bartlett test and Welch test were employed to compare all the qualitative trends produced by the coated and the uncoated tools employed in the orthogonal cutting tests. These statistical methods were also used for comparing the quantitative effects of the coated and the uncoated tools on the magnitudes of the forces and basic cutting quantities in the orthogonal process. The results showed that the qualitative trends for the coated and uncoated tools were similar. This means that the modified mechanics of cutting analysis applied equally for both coated and uncoated tools. It also means that the 'unified mechanics of cutting approach' to force and power prediction for drilling and other operations should apply to both coated and uncoated tools. Finally, the orthogonal tests results were used to study and compare the effects of each coating – TiN, Ti(Al, N) and Ti(C, N) - on the basic cutting quantities, chip formation, forces and power as well as the cutting process. It was found that the group of coatings was able to reduce 'on average' F_{Qt}/b (thrust force component/width of cut ratio) values by 24.9%, F_{Pt}/b (power force component/width of cut ratio) values by 14.5%, β (friction angle) values by 16.4% and ϕ (shear angle in shear zone/plane) values by 11.06%.

Keywords:
Orthogonal cutting tests, basic cutting quantities, coated high speed steel tools, dry machining performance.

1. INTRODUCTION

A literature survey has shown that some research work is concerned with the estimation of forces and power in machining by using appropriate mathematical models based on the mechanism of chip formation. In metal cutting, continuous chips are favoured in practice, and are formed by a shearing process (*i.e.* plastic deformation) in a primary deformation zone, which extends from the tool cutting edge to the junction between the surfaces of the chip and work-piece material, and a friction process at the tool-chip interface. The mechanism of chip formation has been studied and mathematically analysed by Piispanen [1], Ernst [2] and Merchant [3] in the 1930's and the 1940's and since then modified by other researchers such as Lee and Shaffer [4], Wegner [5], Albrecht [6], Zorev [7], Kececioglu [8], Nakayama [9], Christopherson, Oxley and Palmer [10], Okushima and Hitomi [11], Turkovich and Trigger [12], Bitans and Brown [13] and Armarego and Brown [14].

Through the analysis of these reports [1 to 14] it becomes evident that the theoretical chip formation models can be classified into two major categories - (1) *thin shear zone or plane models* and (2) *thick shear zone models* - according to the shape of the principal deformation zone. The thin shear zone (plane) models presume the presence of very thin plane shearing zone ahead of the cutting tool edge [1 to 11 and 14], while the thick shear zone models suppose the existence of relatively thick zone with rather complex geometrical boundaries [7 to 12]. According to the literature [14] a 'thick' shearing zone represents machining at low speeds, while a 'thin' shear zone is more advisable approximation for higher speeds. Furthermore it has also been shown that even for a 'thick' shear zone, the very high shear strain and shear rate values occur in a very narrow shear zone about a geometrical shear 'plane' [14].

Because of the geometrical complexity of the 'practical' machining operations, such as turning or drilling, some researchers preferred to use the simpler orthogonal cutting operation when studying the mechanics of cutting. The orthogonal cutting process is characterised by the relative velocity between the tool and work piece in the perpendicular direction to the 'single and straight' cutting edge (or parallel to the normal plane P_n), and the cut thickness (t) is constant through the cut. The force equilibrium ($V_w || P_n$) and deformation geometry of 'classical' orthogonal cutting during continuous chip formation is exhibited in Figure 1 below.

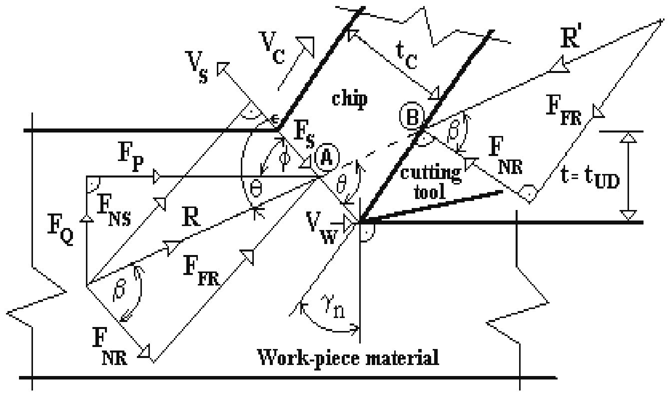

Figure 1. The force equilibrium and deformation geometry during continuous chip formation; after Armarego [14 and 15].

Armarego and his metal cutting group at the University of Melbourne [14 to 16] developed a mathematical analysis for the orthogonal and the three dimensional oblique cutting based on a modified Ernst and Merchant thin shear zone (or plane) model [2, 3 and 17] following extensive experimental investigations and data analyses. This modified analysis was used as a base for preparation of both experimental and statistical plans used to generate and evaluate the results from the orthogonal cutting experiments. A summary of this statistical plan is shown in the following Tables 1, 2 and 3. Qualitatively the trends in Tables 1, 2 and 3 should apply for coated and uncoated tools, Table 4.

Table 1. Qualitative effect of cut thickness (t) and width of cut (b); after Audy [18].

Quantity	Analytical assumption	Statistical Method	Expected Results
Forces $F_{P/b}$; $F_{Q/b}$	linearly related to t and b	Regression and Correlation test	Slope significant; Intercept positive and significant
Chip Length Ratio r_l Friction Angle β Shear Stress τ	independent of t and b	Regression and Correlation of r_l (β; τ) with t at given V_w and γ_n	Intercept significant; Slope non-significant; Correlation non significant

Table 2. Qualitative effect of normal rake angle γ_n.; after Audy [18].

Quantity	Analytical assumption	Statistical Method	Expected Results
Forces $F_{P/b}$; $F_{Q/b}$	Decrease(s) with the rake	Analysis of covariance (or comparison of regression lines); multiple regression for different γ_n at given V_w	Slopes not parallel and not single
Chip Length Ratio r_l Friction Angle β	Increase(s) with the rake	ANOVA or Welch	Test fails (means are not equal)
Shear Stress τ	independent of the rake	ANOVA or Welch	Test passes (means are equal)

Table 3. Quantitative effect of cutting speed V_w ; after Audy [18].

Quantity	Analytical assumption	Statistical Method	Expected Results
Forces $F_{P/b}$; $F_{Q/b}$	Force-cut thickness regression slopes not affected *i.e.* independent of width and speed	Analysis of covariance (analysis of several regression lines for different V_w at given γ_n	Slopes parallel and single (if independent to velocity)
Chip Length Ratio r_l Friction Angle β Shear Stress τ	Independent of speed	ANOVA or Welch	Analysis of variance or Welch test passes (means are equal)

Table 4. Effect of Coating (Orthogonal Cutting Tests); after Audy [18].

Quantity	Analytical assumption	Statistical Method	Expected Results
Power Force-cut thickness Thrust Force- cut thickness Friction Power- cut thickness Shear Power- cut thickness Total Power- cut thickness Shear Angle- cut thickness Friction Angle- cut thickness	Statistically different slopes of quantities between Uncoated tools and Coated tools One coating against another coating	Analysis of co-variance of several regression lines for different V_w at given γ_n	Slopes not parallel and not single Slopes not parallel and not single if the quantities are statistically different, and vice versa

2. EXPERIMENTAL DETAILS

For the orthogonal cutting tests a total of twenty-four square bars of M35 HSS have been ground to 12.5mm width, 12.5mm height, and cut to 65mm length from rods of 18mm diameter. Four sets of orthogonal cutting tools consisting of six tools of six different rake angles (-60°, -30°, 0°, 10°, 20° and 30°) have been ground.

The tools were heat-treated in the same way as usual for M35 Steel (the one used *e.g.* for twist drills). One set of six tools was left uncoated while the other three sets were coated with TiN, Ti(C,N) and Ti(Al,N) coatings by a PVD process. The eight levels of cut thickness (feed) values between 0.025mm/rev and 0.2mm/rev were run for the tools with positive rake angles. The seven different cut thickness values, in the considerable lower range, from 0.025 to 0.1mm/rev, were chosen for the tools with zero an negative rake angles. All the coated tools were examined at three cutting speeds of 4.23m/min, 12.5m/min and 30m/min. The uncoated M35 HSS tools were tested at only two speeds – one of 4.23m/min and another of 12.5m/min.

Table 5. Specification of test conditions for the 'orthogonal' (dry) cutting experiments; based on source [19]; adopted from source [18].

γ_n deg.	b mm	V_w m/min	Cut Thickness *i.e.* Feed - top row in [thou], bottom row in [mm/rev]						
			1 0.025	1.5 0.0375	2 0.05	2.5 0.0625	3 0.075	3.5 0.0875	4 0.1
-60, -30, 0	3	4.23 and 12.5	Coated and uncoated tools						
-60, -30, 0	3	30	Coated tools only						

γ_n deg.	b mm	V_w m/min	Cut Thickness *i.e.* Feed - top row in [thou], bottom row in [mm/rev]							
			1 0.025	2 0.05	3 0.075	4 0.1	5 0.125	6 0.15	7 0.175	8 0.2
10, 20, 30	3	4.23 and 12.5	Coated and uncoated tools							
10, 20, 30	3	30	Coated tools only							

Note: γ_n – rake angle, b – width of cut, V_w cutting speed

Details of the test conditions are shown in Table 5 for each coated and uncoated tool, providing also some constraints for the feed and speed values according to a data reported in the literature [19]. From this table it is evident that the study of the effects of coatings on the orthogonal cutting process, friction, forces and power required taking some 540 cuts at a wide range of cutting conditions.

Photographs in Figure 2 illustrate the general experimental arrangement used for the orthogonal cutting tests.

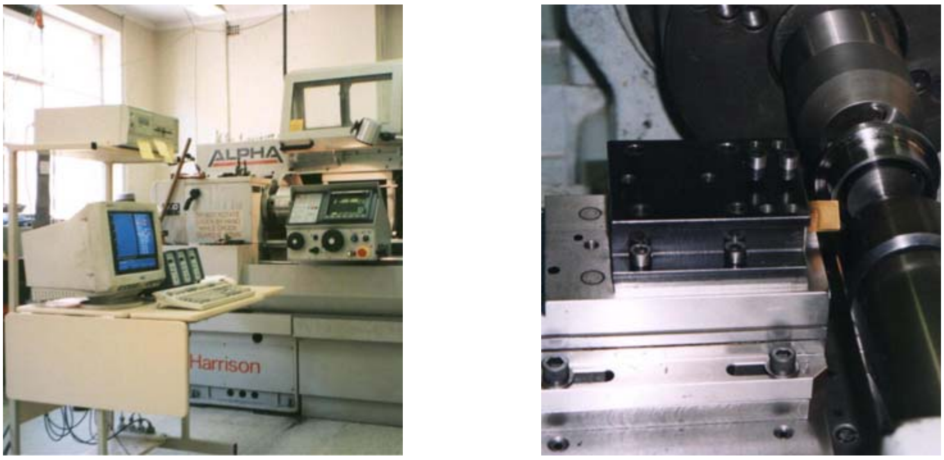

Figure 2. General experimental arrangement used for the orthogonal cutting tests; [18].

The sketch in Figure 3 (a) shows the actual position of the cutting tool and work-piece in the orthogonal cutting tests. The feed, f, corresponded to the cut thickness, t, while the actual thickness of a tubular work-piece corresponded to the width of cut, b in orthogonal cutting tests. Figure 3 (b) exhibits the tool cutting edge set 'on-centre' and oriented in the radial direction so the resultant cutting velocity, V_w, is perpendicular to the active cutting edge. The arrangement of the experimental rig is presented in Figure 3 (c).

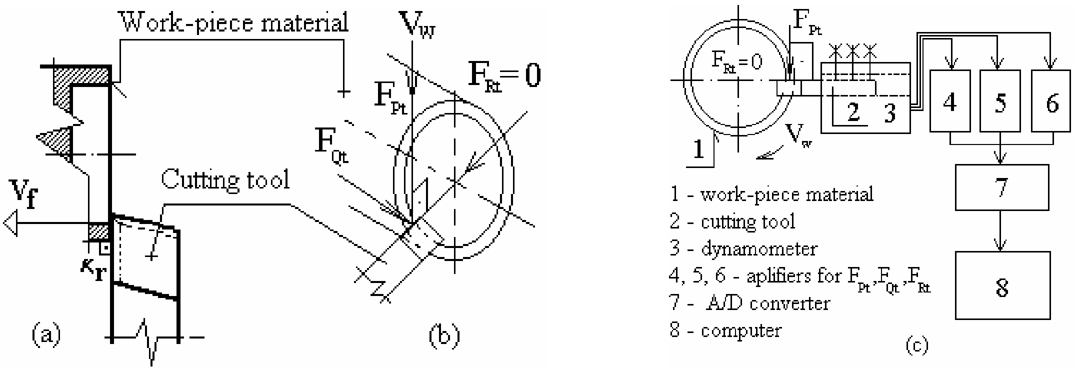

Figure 3. Orthogonal Cutting Experimental Set-up; (a) position of tool cutting edge and work piece material, (b) force components and cutting velocity in the orthogonal cutting, (c) arrangement of experimental rig; after Audy [18].

Moreover, the thickness of a tube *i.e.* the width of cut was very small (3mm) in comparison with the relatively high work-piece diameters/grooves (D_1=90mm and D_2=76mm) so that the resultant velocity can be considered constant along the active cutting edge.

A manual industrial lathe with CNC assistance (Model Alpha 400) supplied by Harisson Pty Ltd (Melbourne) has been employed to perform the orthogonal cutting tests. This large and rigid machine with a power of 7.5kW (10hp) is equipped with infinitely variable speeds ranging from 25rpm to 2500rpm and has a set of automatic feeds ranging from 0.03mm/rev (0.001in/rev) to 0.4mm/rev (0.024in/mm) [20]. The work-pieces were machined using the wedge tools mounted in a Kistler three component piezoelectric dynamometer fixed on the tool post of the lathe. The force component F_{Rt} in the radial direction was equal to zero as shown in Figure 3 (b), while the tangential and feed motion directions were coincident with the required F_{Pt} and F_{Qt} force components, respectively. The inclination angle was 0° as required for orthogonal cutting tests.

The cutting force components (F_{Pt} and F_{Qt}) were recorded, in real cutting time, using a Kistler three component piezoelectric dynamometer. A special 'highly insulated and resistant' cable was used to transfer the electric charges from the output of the dynamometer to Kistler amplifiers. The actual signal data was then manipulated/converted by A/D boards and then transferred to a custom-built software package which was fully menu driven and had provision for the data acquisition analysis and display. The force components (F_{Pt} and F_{Qt}) were acquired using ASP® (Array String Processor) Monitoring Software, and stored on a computer hard disc for further computer analysis and processing. For the recording, the computer sampling rate was fixed at 250Hz for a constant value of cutting time set up to 10 seconds (=0.166min).

The chips produced during each cut were collected and stored for chip length ratio measurement. It has been expected that the chip thickness may vary at the beginning and at the end of a cut even for continuous chips. Thus to avoid the influence of such error sources on the expected results it has been decided to take the three samples of various chip lengths from the middle part of a given chip. The corresponding chip length ratios were evaluated using the 'weight method' for each particular cut. The chips of measured lengths were weighed using a 'Sartorius' high precision chemical balance. A major focus was on the identification of the type of chip formation at the different cut thickness, rake angle and cutting speed tested in addition to the chip length ratio measurements.

3. RESULTS AND DISCUSSION

Qualitative and quantitative effects of the three different coatings and uncoated tools for the orthogonal cutting process have been examined by comparison of results relating cutting force components and derived basic cutting quantities over the range of cutting conditions tested. This approach allowed to compare the cutting performance of the three different coatings between themselves, and also against a Type M35 uncoated HSS tools.

Graphical comparison of the force values has been made for all the coated and uncoated tools examined in the orthogonal cutting tests. Some of the typical graphical patterns have been presented in the following Figures 4 (a-f) and 5 (a-f).

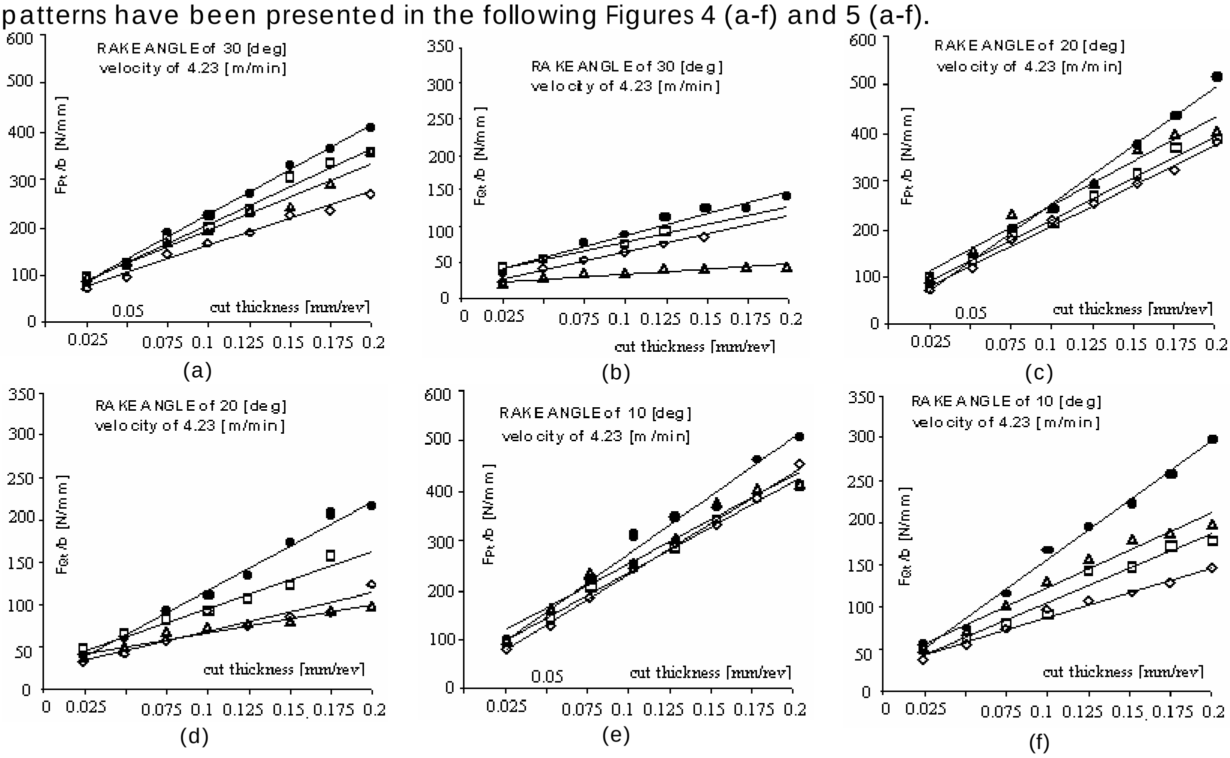

Figure 4. Comparison of force component values for the coated and uncoated tools for different tool rake angles and a cutting speed of 4.23m/min. Note: ● - uncoated tools; □ - TiN coated tools; ◇ - TiAlN coated tools; △ - TiCN coated tools; [18].

Figure 4 (a-f) shows graphically the quantitative differences in force trends between the coated and the uncoated tools. A typical comparison of trends and magnitudes of the 'as measured' cutting quantities for the force components F_{Pt}/b and F_{Qt}/b is presented for the cutting speed of 4.23m/min and positive tool rake angles of 30° in Figure 4 (a and b), 20° in Figure 4 (c and d) and 10° in Figure 4 (e and f) over eight cut thickness values ranging from 0.025mm/rev to 0.2mm/rev. The same trends between the uncoated and the coated tools have been observed for the cutting speed of 12.5m/min. Figure 4 (a-f) confirms that the linear force functions (F_{Pt}/b versus t, and F_{Qt}/b versus t) for the whole sets of coated HSS tools were shallower than those for the uncoated HSS tools resulting in lower forces for the coated tools.

Figure 5 (a-f) shows comparisons of trends and magnitudes of the 'as measured' cutting quantities F_{Pt}/b and F_{Qt}/b for the coated tools examined at a cutting speed of 30m/min, positive tool rake angles of 30° in Figure 5 (a and b), 20° in Figure 5 (c and d), and 10° in Figure 5 (e and f), and the eight cut thickness values ranging from 0.025mm/rev to 0.2mm/rev. Similar qualitative differences between the coated tools have been observed graphically for the cutting speed of 12.5m/min. The same Figure 5 (a to f) suggests that all the three coatings produced qualitatively the same force patterns and quantitatively very similar force component values.

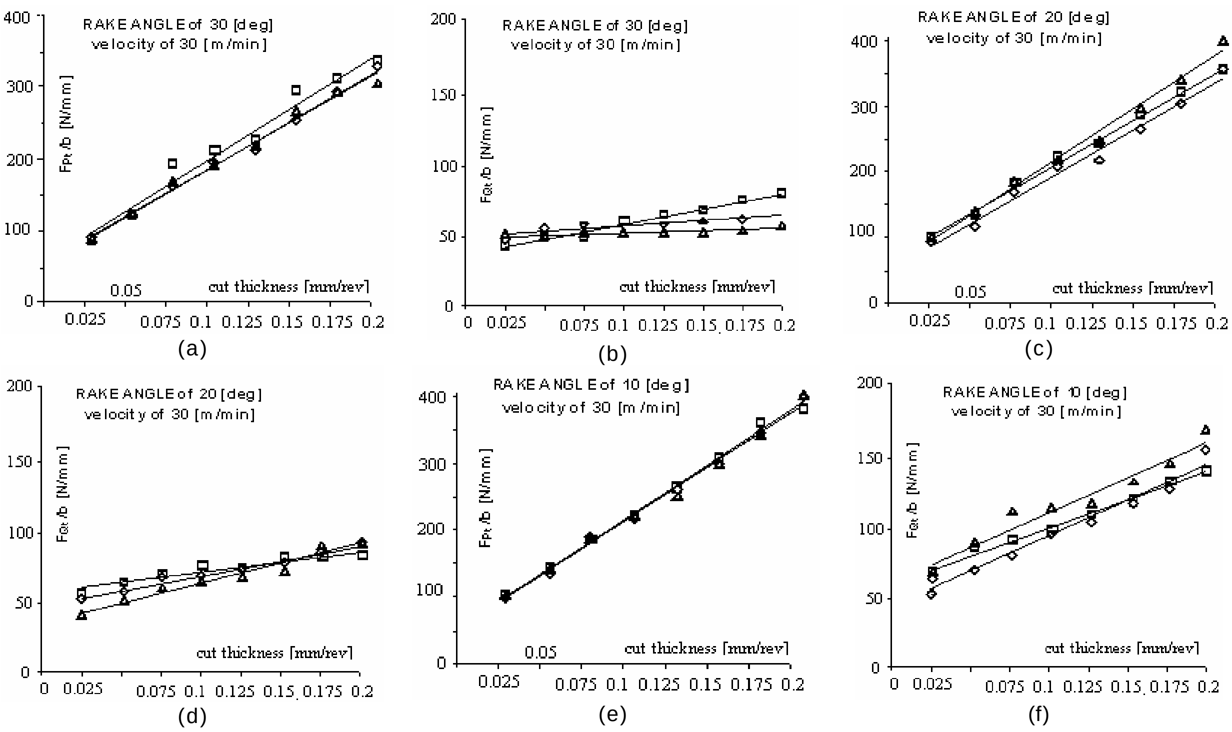

Figure 5. Comparison of force component values for the coated tools for different positive tool rake angles and a cutting speed of 30m/min. Note: □ - TiN coated tools; ◇ - TiAlN coated tools; △ - TiCN coated tools; [18].

Graphical comparison of r_l, β and τ values has been made for all the uncoated and the coated - Type M35 HSS - tools examined for different tool rake angles, cutting speeds and cut thickness values in the orthogonal cutting tests. Some of these graphical patterns are presented in Figure 6 below.

From Figure 6 it is evident that the uncoated tools exhibited higher mean values of chip length ratio r_l and the friction angle β than the coated tools, as expected from similar observations published in the literature [21]. By contrast the shear stress τ was not affected by the tool material or coating.

The relationship between the shear angle ϕ at the shear zone and friction β at the tool-chip interface has been considered as an important characteristic of the orthogonal cutting process and thin shear zone (plane) model. This relationship enables the shear angle ϕ to be predicted from the tool rake angle γ_n and tool chip frictionβ. The literature provides various relationships between shear angle ϕ and friction β, but, in general, it has a form, $\phi_n=C_1-C_2(\beta-\gamma_n)$ as presented by Armarego in the literature [16] and Verezub [22], where C_1 and C_2 are constants for a given tool-work piece material.

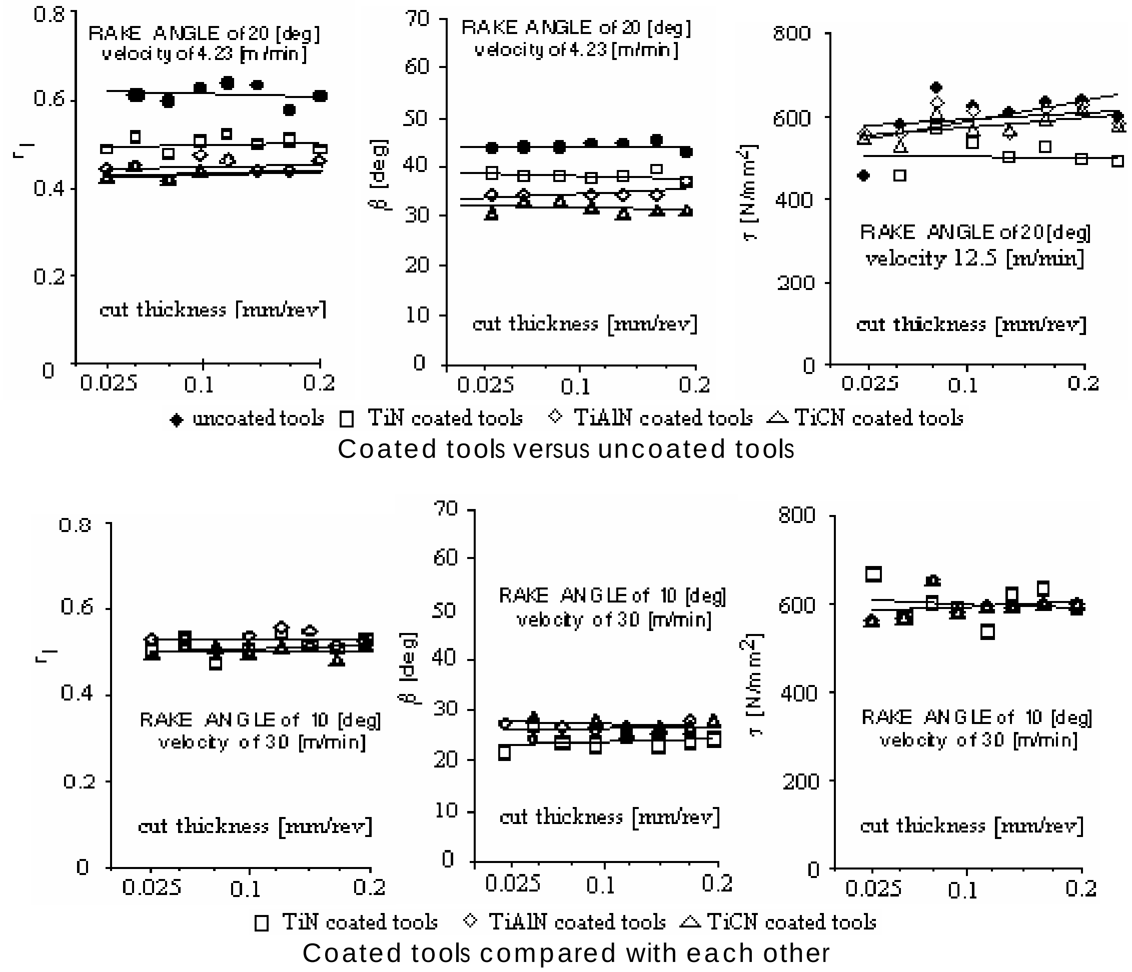

Figure 6. Comparison of the r_l, β and τ values for the uncoated and the coated Type M35 HSS tools for different tool rake angles, cutting speeds and cut thickness values; [18].

The shear angle relationships with different $\beta-\gamma_n$ for the uncoated and the coated HSS tools are plotted in Figure 7 (a) and 7 (b-d), respectively, with reference to different tool rake angles and cutting speeds as shown below.

Figure 7 (a-d) suggests; (*a*) that the shear angle ϕ decreased approximately linearly with increases in $(\beta-\gamma_n)$, and (*b*) that both variables ϕ and $(\beta-\gamma_n)$ are subjected to error and scatter. Bearing this in mind, it has been decided to employ Mandel's method as reported in the literature [22 and 23] in order to obtain the regression coefficients C_1 and C_2 of regression lines for the test data obtained from the orthogonal cutting tests. The equations of regression lines for the uncoated and three coated HSS tools are given bellow in Table 6.

Table 6. Shear angle relationships for the uncoated and coated tools and Bisalloy 360 steel work piece material; after Audy [18].

ϕ (uncoated tools) = 60.60 - 1.07 $(\beta-\gamma_n)$	ϕ (TiN coated tools) = 40.75 - 0.57 $(\beta-\gamma_n)$
ϕ (TiAlN coated tools) = 41.36 - 0.61 $(\beta-\gamma_n)$	ϕ (TiCN coated tools) = 36.95 - 0.51 $(\beta-\gamma_n)$

The aforementioned equations suggest that the slope, represented by C_2 values, was negative for the whole test conditions, and the shear angle relation appeared to be linear for both the coated and the uncoated tools tested. Furthermore, the coefficients (intercepts and slopes) were different for the coated and the uncoated tools suggesting that the different equations will apply for the coated and the uncoated tool-work piece material combination. Surprisingly, the group of coated tools showed very similar intercepts (40.75, 41.36, 36.95) as well as the slopes (-0.57, -0.61, -0.51) indicating that the same equations may apply for all the three coatings treated as the one 'combined' group, if statistical analysis confirm this observation.

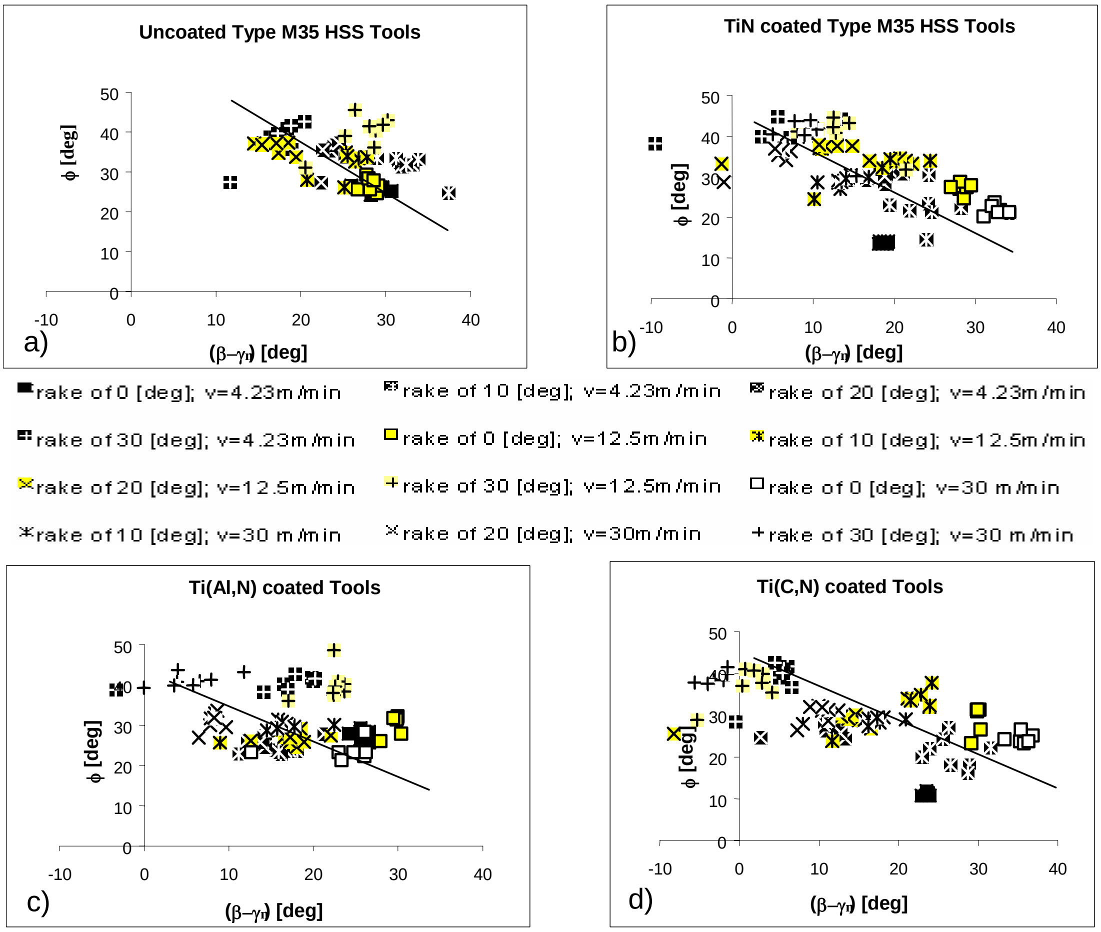

Figure 7. Shear angle relationship for the uncoated and the coated HSS tools examined in the orthogonal cutting tests; after Audy [18].

The regression lines for the shear angle relationship for the coated and the uncoated Type M35 HSS tools, at the whole set of cutting conditions, have been presented for the clarity and illustration, as shown in Figure 8. The regression lines of ϕ on $\beta-\gamma_n$ have been determined by using Mandel's method.

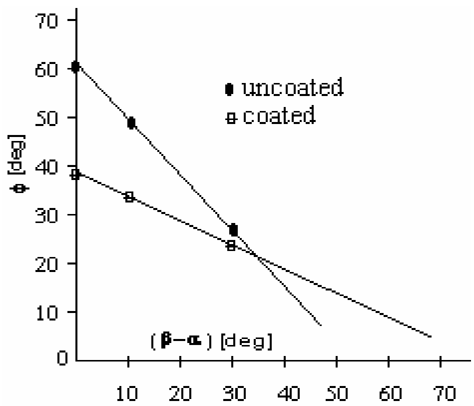

Figure 8. Comparison of Shear Angle Relationship for the Coated and the Uncoated M35 HSS tools; [18].

Figure 8 shows clearly that the uncoated tools produced a higher shear angle relation intercepts than the coated tools, while for the group of the coated tools the shear angle was similar in terms of the slopes and intercepts for all the three coatings investigated.

The shear angle relationship for the uncoated tools and coated tools are presented below:

Coated tools: $\phi=60.6-1.07(\beta-\gamma_n)$

Uncoated tools: $\phi=39.7-0.56(\beta-\gamma_n)$

3.1. A BRIEF SUMMARY OF QUALITATIVE TRENDS

The qualitative trends for the directly measured and derived basic cutting quantities for the uncoated and the coated HSS tools and Bisalloy 360 steel work piece material have been established with respect to the cut thickness, rake angle and cutting speed. All the trends from the orthogonal cutting tests have been found to be similar and matching to the general single edge 'classical' orthogonal test trends presented, for example, by Armarego in the literature [15] for a number of common work-piece materials. The qualitative evaluation of the effect of all the three coatings, namely TiN, Ti(Al,N) and Ti(C,N), has generally confirmed an anticipated outcome, that the coatings themselves may not have major effects on the qualitative behavior of the directly measured and derived cutting quantities with respect to the cut thickness, rake angle and cutting velocity, and hence on the orthogonal process as whole and the modified mechanics of cutting mathematical analysis. In summary, both cutting force components increased with cut thickness, and had the positive force intercepts that represented the 'edge' force components. The chip length ratio and the derived basic cutting quantities have been shown to be independent of cut thickness values. Decreases in the rake angle increased the forces and decreased the chip length ratio and the friction angle. Since no significant pattern was observed in the shear stress at different rake angles it has been concluded that the τ values were probably affected by some scatter from the chip length ratio measurements. Changes in speed appeared to affect the forces and slopes for both the coated and the uncoated tool materials. In general it appeared that the mean values of the chip length ratio increased, and the friction angle decreased, slightly with speed rises. A linear shear angle relationship was established for both the uncoated and the coated tools suggesting that the slopes, C_2, and the intercepts, C_1, are different, and hence, are not only work-material dependant, but also dependent on the tool coating examined.

From the aforementioned it is evident that the qualitative trends for the 'as measured' and for the basic cutting quantities of both the uncoated and the coated tools have been successfully established. It should be noted that although the trends for different tool materials are comparable qualitatively, it is expected that quantitative differences between the corresponding 'as measured' and derived quantities may occur. Thus, the quantitative effects of the coated and uncoated HSS tools were studied in detail and the most important findings are presented in the next section below.

3.2. A BRIEF SUMMARY OF QUANTITATIVE TRENDS

Analysis of covariance was employed to determine statistical differences, if any, in the effect of tool-coatings-material on the force-cut thickness (F_{Pt}-t and F_{Qt}-t) trends in the orthogonal cutting tests. The differences in the force functions were estimated by comparing the corresponding regression lines for the F_{Pt}/b force component and for the F_{Qt}/b force component. A similar statistical analysis has been carried out to determine the quantitative differences, if any, between the three different coatings *i.e.* TiN, Ti(Al,N) and Ti(C,N). Anova or Welch tests were employed to examine r_l, β and τ in relation to different cut thickness values.

The comparison of quantitative differences between TiN, Ti(Al,N) and Ti(C,N) coatings showed that Ti(Al,N) coating appeared to produce the smallest force components and 'edge' forces of all the three coatings, however, the statistical comparison of the respective pairs of the force-cut thickness regression lines have shown that in the majority of cases the lines could be considered parallel and single at 95% confidence level so all the three coatings produced statistically 'equal' forces and basic cutting quantities when cutting a Type 360 Bisalloy steel work-material. The quantitative differences between the three different coatings have been assessed and statistically analysed. The results obtained in this way showed no statistically significant difference in the forces and the derived basic cutting quantities r_l, β and τ produced by the three different coatings used to cut a Type 360 Bisalloy steel work-material.

Quantitative evaluation of the three different coatings against a Type M35 uncoated HSS tools showed that all the quantities – forces (F_{Pt}/b, F_{Qt}/b), friction angle (β), the shear angle (ϕ) and machining power (P) - for the three coatings were statistically lower than those for the uncoated tools at 95% confidence level, while the shear stress τ was not affected by the tool substrate material and coatings.

The quantitative reductions in the two force components, F_{Pt} and F_{Qt}, the friction angle, β, and the shear angle, ϕ, due to the tool coatings were estimated in terms of the percentage deviation to show quantitative improvement of the coated tools against the uncoated tools.
% deviation = (value for a particular coating - value for the uncoated tool) divided by value for the uncoated tool multiplied by 100.

For the purpose of comparison of the cutting efficiency of the coated and the uncoated tools it has been decided to treat the coated tools as one group since it has been statistically proved that there were no significant differences between the coatings themselves.

The resulting grand average and the distribution are shown, in Figure 9, in the form of histograms, individually for F_{Pt}/b, F_{Qt}/b, β, and ϕ.

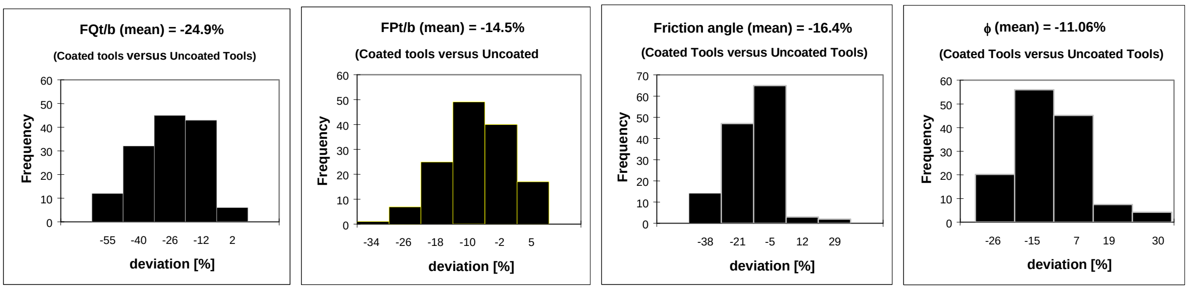

Figure 9. Histograms of percentage deviations between the quantities for the coated and uncoated tools for each individual cut, with negative values indicating lower levels for the coated tools; after Audy [18].

From Figure 9 it is evident that the group of coatings was able to reduce 'on average' F_{Qt}/b values by 24.9%, F_{Pt}/b values by 14.5%, β values by 16.4% and ϕ values by 11.06%.

4. CONCLUSIONS

Increasing demand for PVD coated cutting tools, such as drills, has resulted in development of many coatings with both complex chemical compositions and structures such as single layers, multi-layers and nano-composites. Such coatings are claimed to reduce forces and power at the tool chip interface via reduced tool-chip friction; increase tool-life through reduced degradation of cutting tool substrate material from high heat generated during machining and improve tool wear; and reduce machined surface roughness due to reduction in tool-chip friction and-built-up-edge-formation. However, it is difficult to quantify such improvements because research studies have shown that there are very few papers on the effect of hard coatings on the forces and power none of which have quantified reductions in forces and power nor estimated the tool-chip friction. Furthermore, only very recently some attempts have been made to study the effect of hard coatings on the cutting process as a whole through the 'classical' orthogonal and oblique cutting operations, to estimate reductions in forces, power and tool-chip contact friction. Fortunately, relatively recently the effect of tool surface coatings on the chip formation process and mechanics of cutting mathematical analyses for 'classical' orthogonal and oblique cutting operations as well as many practical machining operations, such as drilling, have been studied by different researchers, and when reviewed for the purpose of this study it showed that the 'Unified Mechanics of Cutting Approach' to force and power prediction initially developed for the uncoated tools by Armarego and his group members should also be applicable to coated tools.

The present study investigated and compared the performance of TiN, Ti(C, N) and Ti(Al, N) coatings via analysis of the chip formation, basic cutting quantities, forces and power in orthogonal machining of Bisalloy 360 steel for the three coatings and one M35 tool substrate material used in drill production. The major findings indicated that:

- Pattern of forces and basic cutting quantities produced by the uncoated and the coated tools tested showed qualitative agreement and quantitative differences at 95% C. L.
- When comparing the effect of different coatings, one with another, the quantitative differences in various performance measures namely forces, power, friction angle, shear angle, shear stress and chip length ratio values were statistically equal at 95% C. L, *i.e.* there were no qualitative or quantitative differences between the three coatings.
- The group of coated tools reduced F_{pt} by 14.5%, F_{qt} by 24.9%, β by 16.4%, ϕ by 11% and P (power) by 14.5% in comparison with the uncoated tools. The highest reduction was in the thrust force F_{qt} not in the power force F_{pt}.

The above knowledge can be used directly, for example, in development of databases for the force predictive models in practical machining operations such as drilling, tapping, milling and turning, for prediction purposes when incorporated into adequate force predictive models.

Acknowledgement

The above project was sponsored by the AECM Postgraduate Scholarship. The research work was carried out at the University of Melbourne under supervision of Professor E.J.A. Armarego.

REFERENCES

[1.] Piispanen V.: "Theory of Formation of Metal Chips", J. Appl. Phys., Vol. 19 (1948), pp. 876.
[2.] Ernst H.: "Machining of Metals", The American Society for Metals, 1938.
[3.] Merchant M.E.: "Mechanics of Metal Cutting and Type 2 Chip", J. Applied Physics, 16 (1945), p. 267-275.
[4.] Lee E.H., Shaffer B.W.: "The Theory of Plasticity Applied to a Problem of Machining", J. Appl. Mech., Vol. 18 (1951), pp. 405-413.
[5.] Wegner U.: "Theorie des Fliess-Spans", Zeit. Ang. Mat. Mech., Vol. 38 (1958), pp. 200-206.
[6.] Albrecht P.: "New Developments in the Theory of the Metall Cutting process", Trans. ASME, J. Engineering for Industry, Vol. 38 (1961) B, p. 557.
[7.] Zorev N.N.: "Voprosi Mehaniki Processa Reznia Metalov", "Metal Cutting Mechanics", Maschgiz, Moscow, 1956.
[8.] Kececioglu D.: "Shear Zone Size, Compressive Stress and Shear Strain in Metal Cutting and Their Effects on Mean Shear-Flow Stress", Trans. ASME, J. Eng. for Industry, Vol. 82 (1960) B, p. 79.
[9.] Nakayama K.: "Studies on the Mechanism of Metal Cutting", Bull. of Fac. Eng. Yokohama National Univ., Japan, Vol. 7 (1958), pp. 1-26.
[10.] Christopherson D.G., Oxley P.L.B., Palmer W.B.: "Orthogonal Cutting of Work-Hardening Material", Engineering , Vol. 186 (1958) pp. 113-116.
[11.] Okushima K., Hitomi K.: "An Analysis of the Mechanism of Orthogonal Cutting and its Application to Discontunious Chip Formation", Trans. Amer. Soc. Mech. Engrs., Series B., J. of Eng. for Ind., 83 (1961), p. 545.
[12.] Turkovich B.F., Trigger K.J.: "Theoretical Aspects of High Speed Shear in Face Centered Cubic Metals", ASME Paper No. 62-WA-125, Winter Annual Meeting, New York, 1962.
[13.] Bitans K.J., Brown R.H.: "An Investigation of the deformation in Orthogonal Cutting", Int. J. Mat. Tool. Des. Res., 5 (1965), p. 155.
[14.] Armarego E.J.A., Brown R.H.: "The Machining of Metals", Prentice-Hall, New Jersey, 1967 or the second edition 1969.
[15.] Armarego E.J.A.: "Material Removal Process - An Intermediate Course", Manufacturing Science Group, Department of Mechanical and Manufacturing Engineering, The University of Melbourne, ISBNO64615426 5, 1994, pp. 5-16.

[16.] Armarego E.J.A.: "Economics of Machining Criteria, Constraints and Selection of Optimum Cutting Conditions", Proc. of the UNESCO-CIRP, Seminar on Manufacturing Technology, Singapore, 1982, pp. 86-100.
[17.] Merchant M.E.: "Industry-Research Integration in Computer Aided Manufacturing", Int. Conf. on Prod. Tech., I.E.Aust., Melbourne, 1974, pp. 21-29.
[18.] 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, June 2002.
[19.] Bisalloy Steels Pty, Ltd: "Bisplate - Quenched and Tempered Steel Plate", Brochure, 1978, pp. A8-A9, D1-D2, E4-E7.
[20.] A manual industrial lathe with CNC assistance (Model Alpha 400) supplied by Harisson Pty Ltd (Melbourne)
[21.] Armarego E.J.A., Verezub S. and Samaranayake P.: "The Effect of Coatings on the Cutting Process, Friction Forces and Predictive Cutting Models in Machining Operations" Proc. Inst. Mech. Engrs. Vol. 216 Part B: J Engineering Manufacture, 2002, pp. 347-356.
[22.] Verezub S.: "A Study of the Effect of TiN Coating and Substrate on the Orthogonal Cutting Process", M. Eng. Sc. Thesis, The University of Melbourne, May 1996, pp. 57, 86.
[23.] Herat A.: "Computer Aided Predictive Models for Forces and Power in Machining with Single edge and Form Tools", Ph.D. Thesis, The University of Melbourne, 1999