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The Effect of Tool Flank Wear on the Orthogonal Cutting Process and Its Practical Implications

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Abstract
A mechanics of cutting analysis for orthogonal cutting with tool flank wear is presented based on an experimental investigation. It shows that tool flank wear does not statistically affect the basic cutting quantities such as the shear angle and shear stress, both qualitatively and quantitatively, but results in an additional rubbing or ploughing force on the wearland. Based on this finding, an orthogonal cutting force model is proposed which makes full use of the classical thin shear zone analysis for "sharp" tools. This model may form the basis for developing the predictive force models in practical operations. The study also shows that tool flank wear results in a substantial increase in the force components and that the thrust force is more sensitive to tool flank wear. These may be used as a primary basis for developing tool condition monitoring strategies.

Keywords: Orthogonal cutting; Flank wear; Mechanics of cutting; Cutting forces; Machining

Nomenclature

b	width of cut
F_c	total cutting force component
F_{ce}	edge force component in the cutting direction
F_{cm}	as measured total cutting force component
F_{cs}	cutting force component required for chip formation
F_{cw}	wearland force component in the cutting direction
F_t	total thrust force component
F_{te}	edge force component in the thrust direction
F_{tm}	as measured total thrust force component
F_{ts}	thrust force component required for chip formation
F_{tw}	wearland force component in the thrust direction
k_c	intensity factor for edge force in the cutting direction
k_t	intensity factor for edge force in the thrust direction
ℓ_c, ℓ	chip length and uncut chip length = $W_c/bt\rho$
r	chip thickness ratio (t/t_c) or chip length ratio (ℓ_c/ℓ)
t, t_c	undeformed chip (or cut) thickness and chip thickness
V	resultant cutting velocity
V_c	chip flow velocity
V_s	shearing velocity
β	friction angle in the tool-chip interface
ρ	material mass density
γ	normal rake angle

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ϕ	shear angle
τ	shear stress on the shear plane

1. Introduction

The need for quantitatively estimating the technological performance of machining operations such as tool-life, forces, power and surface finish has long been recognized and re-emphasized by an international survey conducted by the International Institute of Production Research (CIRP) [1]. This performance information is required for the selection and design of machine tools and cutting tools, as well as the optimization of cutting conditions for the efficient and effective use of machining operations. The nature of this need is evident from the forecast high percentage of available production time spent on machining components in computer aided manufacturing systems (estimated at about 80% compared to about 5% for conventional manual machine tools [2]).

Both empirical and fundamental approaches may be used to establish the equations or models for quantitatively predicting the technological performance. In the empirical approach, experimentally measured machining characteristic values such as the forces and tool-life are related to the cutting conditions by regression analysis. This approach involves considerable testing to determine the constants in the empirical equations and the results apply only to the machining operation tested. Given the significantly large and unmanageable number of tool-work material combinations, cutting and tool variables and different practical machining operations, empirical approach is clearly undesirable in practice.

In the fundamental machining investigations, primary attention has been paid to modeling the geometrically simple orthogonal cutting process involving two-dimensional plastic deformation [3-9], as shown in Fig. 1. Oxley et al. [10] argued that although practical machining operations use more geometrically complex cutting tools than the wedge tools used in orthogonal cutting, the basic material removal process is always the same. Using mechanics of cutting analysis, Armarego [11] has related the orthogonal cutting process to the oblique cutting process. He then related the classical orthogonal and oblique cutting processes to each practical operation such as turning and milling [12-15] for the prediction of cutting performance. However, there seems to be a distinct dearth of the study on the cutting phenomenon and establishing cutting models for machining when tool wear occurs, although some important investigations considering tool wear effect have been reported [16-20].

In this paper, the thin shear zone orthogonal cutting analysis [3, 4] will be reconsidered with a view to incorporate the tool flank wear effect. A mechanics of cutting analysis for classical orthogonal cutting with tool flank wear is presented based on an experimental investigation. An orthogonal cutting force model will then be proposed based on the classical thin shear zone analysis. For this purpose, the orthogonal cutting analysis for "sharp" tools will be briefly reviewed first.

2. Orthogonal Cutting Analysis

Orthogonal cutting is geometrically shown in Fig. 1. A single straight cutting edge with a plane face and flank is used to cut a workpiece of constant width at a constant cut thickness. The resultant cutting speed V and the chip flow speed V_c are perpendicular to the cutting edge. In the vast majority of orthogonal cutting analyses [8,9,11], the cutting process is represented by a plastic shearing process in a localized (i.e. thin) shear zone or plane (AB) and a friction or secondary shearing (seizure) process at the tool-chip interface. Essentially, all earlier thin shear zone analyses [11] assume the following apply: perfectly sharp tool with no concentrated edge force on the cutting edge, a continuous chip, plane strain, uniform shear stress distribution on the shear plane, and equilibrium of the chip under the action of equal and opposite resultant forces acting respectively at the shear zone and tool-chip interface. This has resulted in the well-known Merchant-type model, i.e.

$$F_{cs} = \frac{\tau bt \cos(\beta - \gamma)}{\sin\phi \cos(\phi + \beta - \gamma)} \quad (1)$$

$$F_{ts} = \frac{\tau bt \sin(\beta - \gamma)}{\sin\phi \cos(\phi + \beta - \gamma)} \quad (2)$$

$$\beta = \tan^{-1}\mu = \gamma + \tan^{-1}\left(\frac{F_{ts}}{F_{cs}}\right) \quad (3)$$

$$\phi = \tan^{-1}\left(\frac{r\cos\gamma}{1 - r\sin\gamma}\right) \quad (4)$$

$$\tau = \frac{(F_{cs}\cos\phi - F_{ts}\sin\phi)\sin\phi}{bt} \quad (5)$$

where the symbols are given in the Nomenclature. In early studies [3, 4], the width of cut b, cut thickness t and tool rake angle (or normal rake angle) γ are expected as given quantities for a cutting process, while the shear stress τ and the friction angle β are expected to be known from the published material data and sliding friction test data respectively, and the shear angle ϕ is found from the shear angle relation

$$\phi = \frac{\pi}{4} - \frac{1}{2}(\beta - \gamma) \quad (6)$$

However, experimental verification has found that the values of the basic cutting quantities (τ and β) are significantly different from those obtained from traditional tests [11]. For quantitative prediction purposes, the orthogonal cutting analysis can only be used when the basic cutting data (τ, β, ϕ etc.) are obtained from cutting tests.

Further development to the thin shear zone analysis is the introduction of a concentrated force (edge force) acting at the cutting edge. It has been suggested by many researchers [9, 11, 21] that since the cutting edge is not perfectly sharp, a rubbing or ploughing process could occur in the vicinity of the cutting edge resulting in an edge force in addition to the force due to the chip formation in the shear zone. This force is manifested by the positive force intercepts when the measured force versus cut thickness graphs are extrapolated to zero cut thickness, and is proportional to the engaged cutting edge length [11]. Armarego [11] has suggested the removal of the edge force from the measured force data when evaluating the basic cutting quantities using the shin shear zone model. Consequently, Eqs. (3) and (5) above have been modified when evaluating β and τ, i.e.

$$\beta = \tan^{-1}\mu = \gamma + \tan^{-1}\left(\frac{F_{tm} - F_{te}}{F_{cm} - F_{ce}}\right) \quad (7)$$

$$\tau = \frac{\left[(F_{cm} - F_{ce})\cos\phi - (F_{tm} - F_{te})\sin\phi\right]\sin\phi}{bt} \quad (8)$$

where F_{ce} and F_{te} are found from the intercepts of the measured force-cut thickness graphs. The total cutting force can be represented by

$$F_c = F_{cs} + F_{ce} = \frac{\tau bt \cos(\beta - \gamma)}{\sin\phi \cos(\phi + \beta - \gamma)} + k_c b \quad (9)$$

$$F_t = F_{ts} + F_{te} = \frac{\tau bt \sin(\beta - \gamma)}{\sin\phi \cos(\phi + \beta - \gamma)} + k_t b \quad (10)$$

The edge force intensity factors, k_c and k_t, are obtained from the orthogonal cutting tests.

It appears that the analysis and models for orthogonal cutting have been well developed. However, there have been no reported studies on the quantitative effect of tool wear on the basic cutting process in orthogonal cutting as well as the associated cutting model when tool wear is present. Whether or not the cutting analysis and model in orthogonal cutting with tool wear can be developed based on the earlier analysis for "sharp" tools need to be fully investigated. If tool wear does not affect the basic chip formation process as represented by the basic cutting quantities (shear angle, shear stress and friction angle etc.) in the shear zone and tool-chip interface, its effect on the cutting process will be an additional rubbing or ploughing forces on the worn faces of the cutting tool. In this case, the cutting model for cutting tools with wear can be developed by making full use of the "sharp" tool analysis and introducing the additional poughing or rubbing forces in a similar way to that of introducing the edge force [11]. If tool wear is found to affect the basic chip formation process, the development of cutting models considering tool wear may have to be developed from scratch. For this reason, a mechanics of cutting analysis for orthogonal cutting with tool wear will be carried out based on experimental investigation before the orthogonal cutting model is proposed. It has been reported [9] that the wear on the tool rake face (crater wear) within an acceptable size results in a slight decrease in the cutting forces, while the flank wear (wearland) results in a significant increase in the cutting forces that contribute to the total cutting force increase. Thus the present study will only consider the flank wear effect.

3. Experimental Work and Cutting Quantity Evaluation

The orthogonal machining tests were conducted on a Leadwell CNC lathe cutting a mild carbon steel, CS1020. The chemical composition of the work material is 0.2% C, 0.6% Mn, 0.06% P and 0.06% S. The tensile strength of the material is 380 MPa and hardness is 130 BHN. The workpieces were prepared in the tubular shape with a wall thickness of 3 mm and machined from an end. The cutting tools used were grade P20 carbide flat-top inserts with 8 μm TiN coating.

A wide range of cut thickness, rake angle and cutting speed have been selected for the tests. Specifically, four levels of cut thickness (0.1, 0.17, 0.24 and 0.31 mm) were tested at four levels of cutting speed (50, 100, 150 and 200 m/min) and four levels of tool rake angle (-5°, 0°, 5° and 8°). In addition, four levels of wearland size including ‘sharp’ tools were selected. These were 0, 0.2, 0.4 and 0.6 mm. The wearland sizes were selected according to ISO3685 [22] and some were higher than the recommended value in order to study the force pattern for tool condition monitoring in future investigations. Thus a total of 256 tests with 4 specially made tool holders and 16 inserts were conducted.

The wearland was artificially made on the cutting tools by a lapping process and checked frequently under a shadowgraph for its size. Care was taken to ensure that the final artificial wearland was within a tolerance of ±3% of its specified size. The specified sizes were used in the qualitative analysis but the actual sizes were used in the regression analysis for the basic cutting quantities database.

The cutting and thrust force components were measured using a Kistler type 9257A three-component piezoelectric dynamometer which was mounted on the tool post (magazine) with a specially made rest. The cutting tool was held on the top of the dynamometer. The induced cutting and thrust force signals were processed and amplified by two Kistler type 5001 charge amplifiers. The amplified signals were then recorded for further processing by a computer through an A/D converter card and an in-house developed data acquisition software. The final results were taken from the average of 20 force samples in the steady cutting stage.

For each combination of the cutting speeds, wearland sizes and rake angles, a linear regression analysis of the "as measured" cutting and thrust force components F_{cm} and F_{tm} with respect to the cut thickness t was carried out. The force intercept in the regression analysis was determined as the "edge force" component for "sharp" tools or the edge and wearland force for tools with a wearland. In doing so, it was assumed that the flank wear did not affect the forces required for chip formation in the shear zone and at the tool-chip interface. The validity of this assumption will be analysed and verified later. By comparing the intercept with that of the respective sharp tool, the wearland force component for each test (with a wearland) was evaluated for further analysis. The friction angle β and shear stress τ for each cut were finally calculated using Eqs. (7) and (8) respectively, after the edge force (or edge and wearland force) has been removed from the "as measured" forces. For each test, at least one chip sample was collected, and the chip length ratio and the shear angle were evaluated using Eq. (4).

4. Results and Discussions

4.1 Experimental trends and characteristics of the forces and basic cutting quantities

The general qualitative trends and characteristics of the basic cutting quantities (ϕ, β, τ) with changes in cut thickness, rake angle and cutting speed have been studied for both 'sharp' tools and those with flank wear. From a detailed analysis, the presence of wearland has been found to have no effect on the general trends and characteristics of the basic quantities which are essentially the same as those for sharp tools and those found in the literature [11]. While it is generally believed that tool flank wear does not change the forces acting on the shear zone and at the tool-chip interface, and therefore does not affect the shearing process and the associated cutting quantities, it is heartening that this study has proved this cutting phenomenon.

The typical trends for the basic cutting quantities and the "as measured" force components are shown in Fig. 2. It can be noticed that the force components, F_c and F_t, increase linearly with an increase in cut thickness and the rate of increase for F_t is smaller than that of F_c. Using regression analysis, the slopes and force intercepts at zero cut thickness have been found to be statistically significant. This confirms the existence of "edge force" and the secondary rubbing or ploughing force on the wearland. The latter has become evident from the fact that the intercepts for tools with flank wear are greater than those of the corresponding sharp tools.

Based on the analysis and correlation coefficient tests, the shear angle ϕ, friction angle β at the tool-chip interface and the shear stress τ in the shear plane are independent of cut thickness t, as shown in Fig. 2. An increase in rake angle γ resulted in a decrease in the two force components as well as the slopes of the force-cut thickness regression lines, as shown in Figs. 2 (a) and (b). By contrast, the shear angle ϕ and friction angle β increased with an increase in rake angle γ, while the shear stress τ has been found to be independent of rake angle. These findings have been verified by extensive regression analyses of the experimental data [23]. The regression analysis also showed that in most cases the cutting speed has no correlation with the cutting forces, as expected from previous analysis [11]. There are only a small number of cases where an increase in cutting speed resulted in a slight decrease in the cutting forces, but the evidence is not strong in the regression analysis. Similarly, the cutting speed has been found to have no significant effect on the three basic cutting quantities, ϕ, β and τ. Consequently, it appears from this qualitative analysis that tool flank wear does not the trends of the basic cutting quantities.

4.2 Quantitative effect of tool flank wear on the forces and basic cutting quantities

Fig. 3 shows the 'as measured' force components with respect to the cut thickness at different wearland sizes VB. It is evident that flank wear results in a substantial increase in the two force components because of the increased ploughing or rubbing action on the wearland. The analysis has also shown that in most cases the force slope in the force-cut thickness diagrams reduces slightly as the wearland size increases. However, a correlation analysis has indicted that this reduction is not statistically significant. It is believed that the increase in the force components with wearland size is a result of the secondary rubbing or ploughing process between the wearland and the workpiece as well as the possible change of the basic cutting quantities (τ, β, ϕ) due to the presence of a wearland. The former has been confirmed during the data process whereby an increased force intercept has been noticed at zero cut thickness. The latter, If a wearland changes the basic cutting quantities, will be investigated later.

Quantitative comparisons have been carried out for each combination of t, γ and V based on the percentage increase of the 'as measured' force components for cutting tools with a wearland with respect to those of 'sharp' tools. These are given in Fig. 4. It is apparent that the average deviations in the cutting force component are noticeable with about 13.7% and 23.6% for 0.4 mm and 0.6 mm wearland sizes, respectively, as compared to sharp tool cutting. The individual percentage increases range from –1.7% to 54.4% for 0.4 mm wearland and from 3.7% to 88.1% for 0.6 mm wearland. The corresponding thrust force component shows similar trends, but with increased average deviations for the two wearland sizes (18.2% and 32.6% respectively) while the maximum deviations are as high as 119.4% and 201.6% for 0.4 and 0.6 mm of wearland, respectively. This finding implies that the thrust force component is more sensitive to flank wear than the cutting force component and may be used as a primary basis in developing tool condition monitoring strategies.

Figs. 5 (a) to (c) show the quantitative effect of tool flank wear on the basic cutting quantities. It is apparent that flank wear has no effects on any of the three basic quantities. As can be seen in Fig. 5(a), the shear angle is generally independent of cut thickness and tool flank wear. An analysis of variance (ANOVA) and a correlation analysis on the mean values for each cutting speed and rake angle have validated this conclusion. The results show that more than 85% of the test cases possess equal mean ϕ values with an insignificant correlation to both flank wear and cut thickness at a 95% confidence level.

Fig. 5(b) shows the effect of wearland on the angle of friction at the tool-chip interface. From the observation of the experimental data, there are cases where the mean values of the friction angle vary with the wearland size. A correlation analysis was then carried out, which showed a strong evidence of insignificant correlation between friction angle and wearland at a 95% confidence level. A detailed analysis of the experimental data has found that the friction angle fluctuates, but there is no trend to suggest any correlation between the wearland size and friction angle.

Similarly, the ANOVA results showed that in more than a half of the test cases, the shear stresses at different wearland sizes had equal mean values, while a correlation analysis had indicated a strong evidence of insignificant correlation, suggesting that the shear stress in the shear plane is independent of flank wear. This is shown in Fig. 5(c).

It is interesting to note that a further statistical analysis has found that the wearland force components in the cutting and thrust directions extracted from the force intercept in the force-cut thickness relation are in fact the difference between the respective force components for 'sharp' and worn tools. This finding is heartening in that it further confirms that the flank wear results in only an additional ploughing or rubbing force on the wearland.

The foregoing analysis has showed that tool flank wear result in a significant increase in the total cutting force. The thrust force component is more sensitive to flank wear than the cutting force component and may be used as a primary reference for tool condition monitoring. More importantly, this analysis has proved in the first time that the flank wear of a cutting tool does not affect the basic cutting quantities both qualitatively and quantitatively, and hence does not affect the forces required for chip formation and the chip formation process in the shear zone. It has further confirmed that tool flank wear results in an additional ploughing force on the wearland and thus an increase in the overall cutting forces. The practical implications of this finding is significant in that, rather than starting from scratch, the thin shear zone analysis in early studies can still be used to determine the forces in the shear plane and at the tool-chip interface for cutting with tool flank wear with the addition of the rubbing or ploughing forces in the wearland.

4.3 Proposed orthogonal cutting model with tool flank wear

From the analysis in the previous sections, the overall cutting forces for cutting with tool flank wear may be a result of the forces required for chip formation in the shear zone and tool-chip interface, the concentrated edge forces, and the rubbing forces on the wearland. Using the thin shear zone analysis and the suggested approach to introducing the concentrated "edge force" component between the cutting edge and workpiece [11], an orthogonal cutting model for cutting tools with flank wear has been proposed, as shown in Fig. 6, by taking into account the secondary rubbing or ploughing force on the tool wearland. The mathematical equations for the cutting and thrust force components can be established based on Eqs. (9) and (10), i.e.

$$F_c = F_{cs} + F_{ce} + F_{cw} = \frac{\tau b t \cos(\beta - \gamma)}{\sin\phi \cos(\phi + \beta - \gamma)} + k_c b + F_{cw} \tag{11}$$

$$F_t = F_{ts} + F_{te} + F_{tw} = \frac{\tau b t \sin(\beta - \gamma)}{\sin\phi \cos(\phi + \beta - \gamma)} + k_t b + F_{tw} \tag{12}$$

This cutting model makes full use of the previously developed machining theories for "sharp" tools, such as the unified mechanics of cutting analysis [11]. The wearland force component can be allowed for by using a computational approach similar to that for the edge force [11], i.e. by experimentally determining the wearland force intensity as a function of the orthogonal cutting variables for a given tool-work material combination. A more comprehensive study is being carried out to mathematically model the wearland force using the slip-line theory for eventual integration into the proposed orthogonal cutting model allowing for tool flank wear. It is anticipated that this orthogonal cutting model can be mathematically related to oblique cutting and the various practical machining operations using the same approach for “sharp” tools.

5. Conclusions

A brief review of the orthogonal analyses has revealed that numerous investigations have provided an in-depth understanding of this cutting process for “sharp” tools, and that there is a need to quantitatively study the effect of tool wear on the cutting process and to develop cutting performance models allowing for tool wear effect. An analysis of the experimental data in orthogonal cutting with tool flank wear has been carried out. It has been shown that tool flank wear results in a substantial increase in the force components and needs to be incorporated into the cutting performance predictive models. The study has also shown that the thrust force component is more sensitive to tool flank wear and may be used as a primary basis for developing tool condition monitoring strategies. An extensive analysis has found that tool flank wear does not affect both qualitatively and quantitatively the basic cutting quantities (ϕ, β, τ) in orthogonal cutting, but results in an additional rubbing or ploughing force on the wearland. Thus, an orthogonal cutting model has been proposed which makes full use of the mechanics of cutting analysis for "sharp" tools. A study is being undertaken to model the wearland forces.

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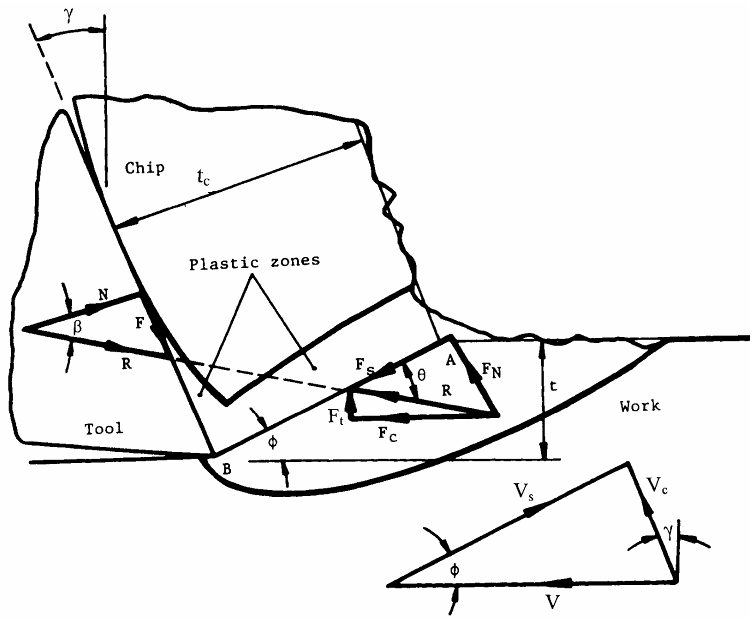


Fig. 1. Model of chip formation in orthogonal cutting [8].

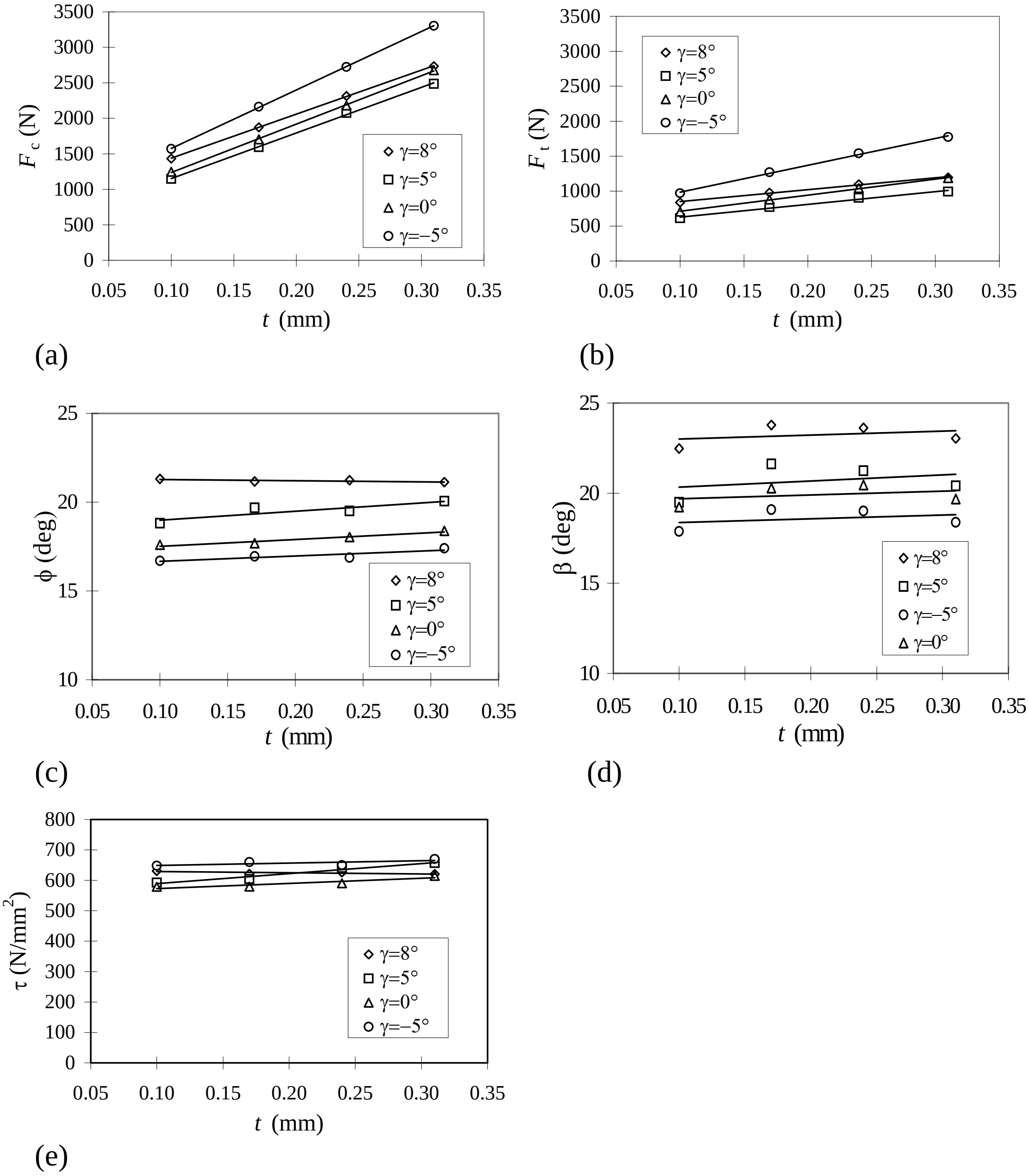


Fig. 2. Typical experimental trends and cutting characteristics in orthogonal cutting with tool wear (*V*=200 m/min, VB=0.6 mm).

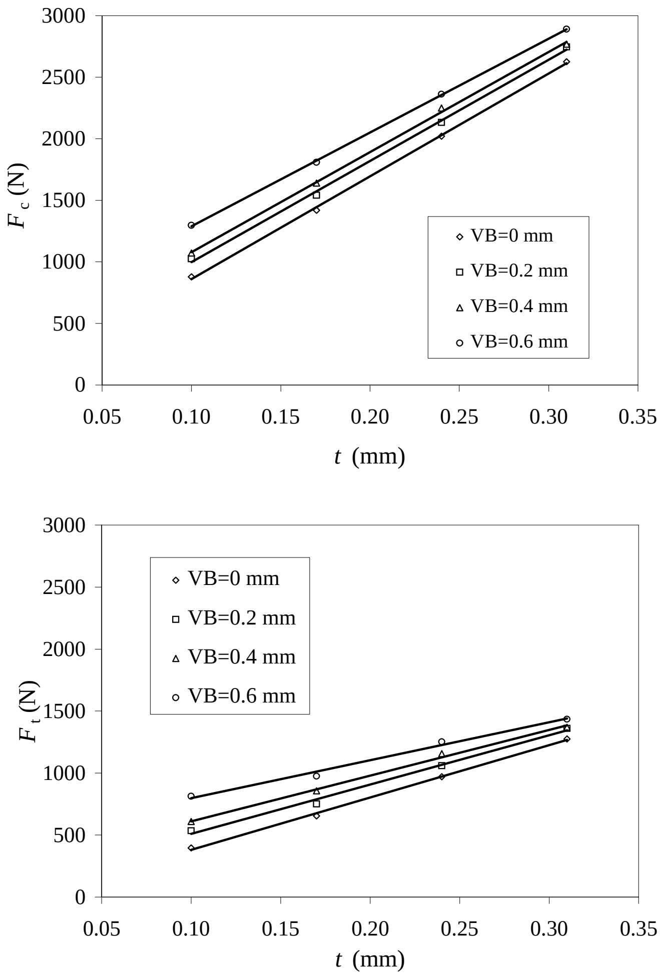
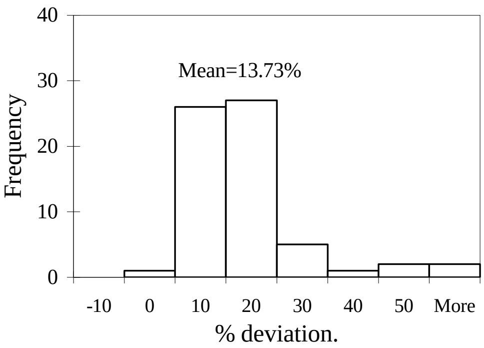
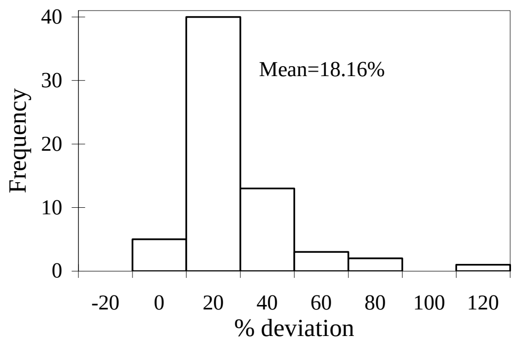


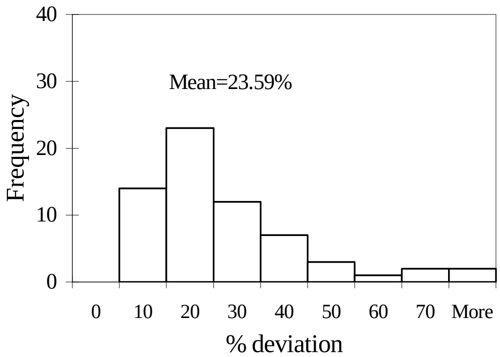
Fig. 3. Effect of tool flank wear on the force components (V=100 m/min, α=5°).



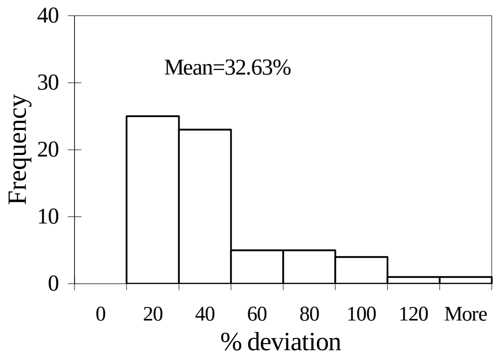
(a) F_c component when VB=0.4 mm.



(b) F_t component when VB=0.4 mm.



(c) F_c component when VB=0.6 mm.



(d) F_t component when VB=0.6 mm.

Fig. 4. Deviation of cutting forces between sharp and worn tools.

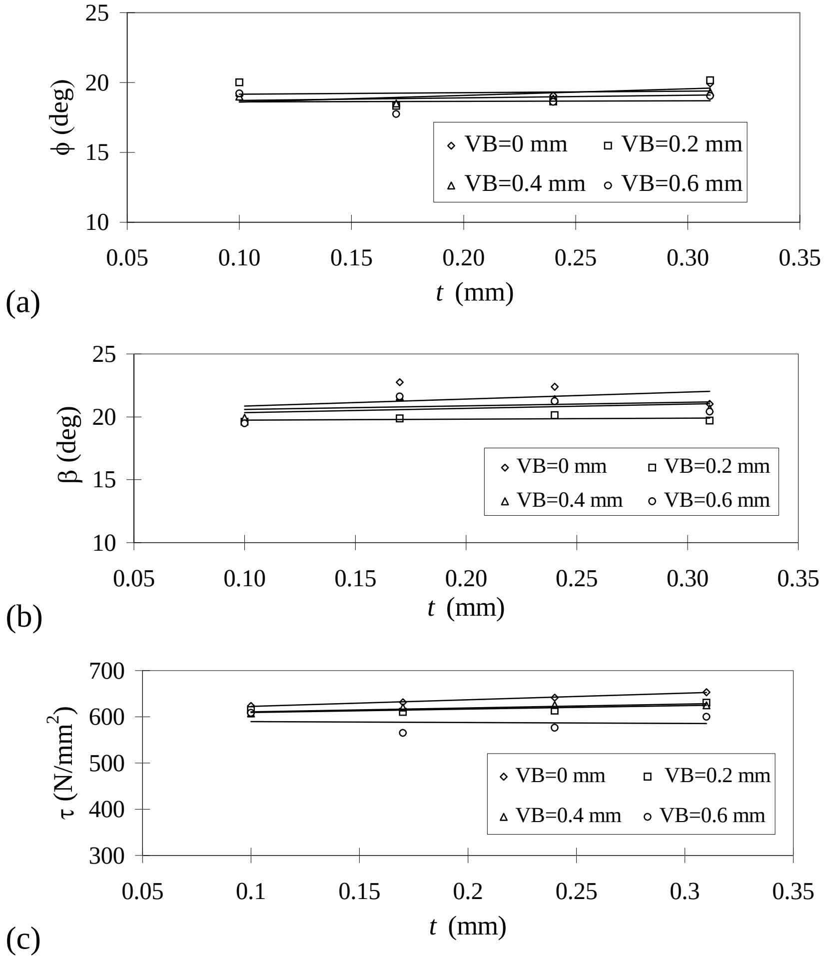


Fig. 5. Effect of tool flank wear on the basic cutting quantities (*V*=150 m/min, α=5°).

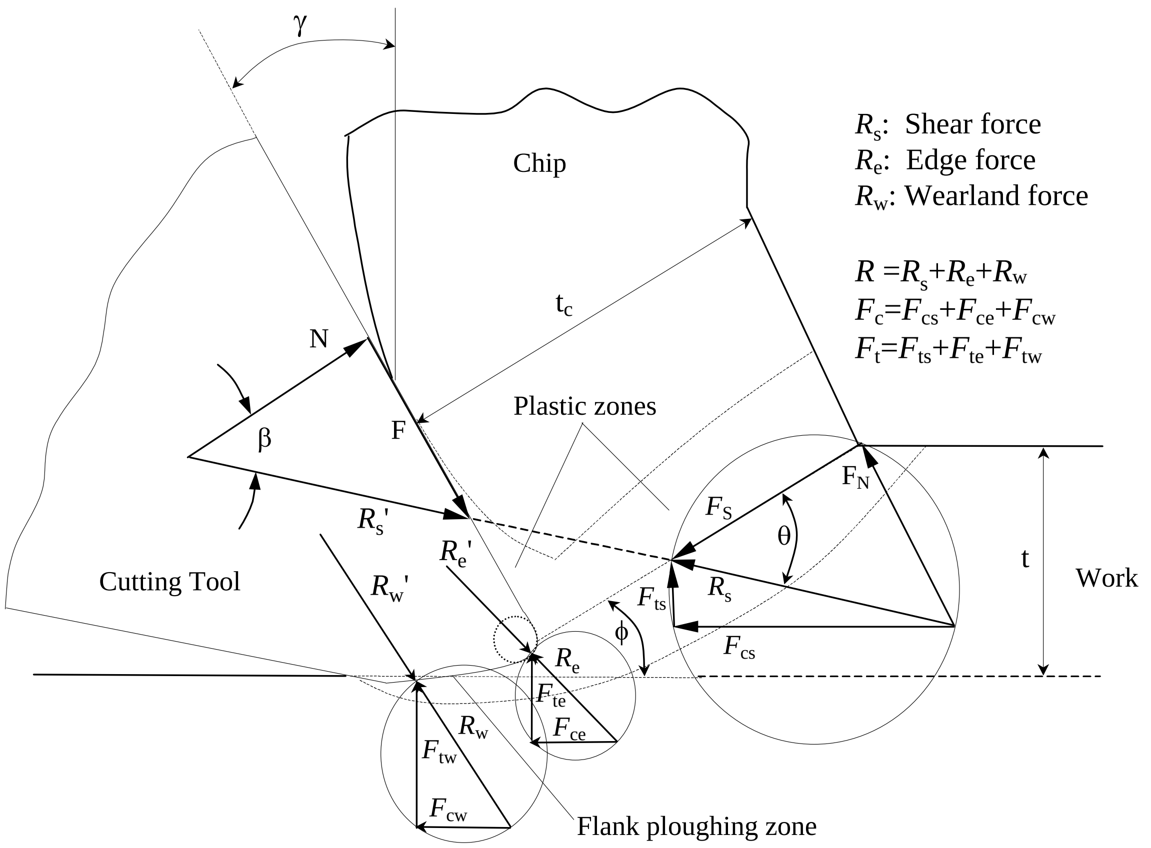


Fig. 6. Orthogonal cutting model allowing for tool flank wear effect.