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Predictive Force Models for Orthogonal Cutting Incorporating Tool Flank Wear

Ipilakyaa, Tertsegha Daniel, Tuleun, Livinus Tyovenda, Gundu, David Terfa
Department of Mechanical Engineering, University of Agriculture, P.M.B. 2373, Makurdi, Benue State, Nigeria.

ABSTRACT

In this paper, predictive force models for orthogonal metal cutting incorporating tool flank wear were developed on the basis of experimental investigations. CNC lathe machine (T6-series) was used to cut mild carbon steel *CS1030*. Cylindrical workpieces were prepared with wall thickness of 3mm and diameter of 100mm. Four levels of cut thickness (0.1, 0.17, 0.24 and 0.31mm) were tested at three levels of cutting speed (100, 150 and 200m/min) and three levels of tool rake angles $(-5, 0 \text{ } and \text{ } 5^0)$. Four levels of tool wearland sizes (0, 0.2, 0.4, 0.6mm) were selected where wearland size “0mm” represents sharp tool. The results show that wear of tool flank caused an increase in the rubbing or ploughing force on the wear land (between 802.9-2333.2N for power force and 610.9-1455.5N for thrust force). Orthogonal cutting force models are proposed which makes full use of the classical thin shear zone analysis for "sharp" tools, and may form the basis for developing the predictive force models in practical machining operations. The results also show an increase in the force components as a result of tool flank wear with indication of the thrust force exhibiting more sensitivity to cutting tool flank wear. The results may also be used for developing tool condition monitoring strategies.

Keywords: *Orthogonal Cutting; Tool Flank Wear; Machining; Cutting Force; Models*

1. INTRODUCTION

Quantitatively, estimation of the technological performance of machining operations such as tool-life, forces, power and surface finish has long been recognized and continuously 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 estimation is evident from the 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 models for predicting the technological performance quantitatively. In the empirical approach, experimentally measured machining values such as the forces and tool-life are related to the cutting conditions by regression analysis. It involves considerable testing to determine the constants in the empirical equations and the results apply only to the machining operation tested. Since there is significant and unmanageable large number of tool-work material combinations, cutting and tool variables and different practical machining operations, empirical approach is clearly unnecessary in practice. In the fundamental investigation approach, primary attention has been paid to modeling the geometrically simple orthogonal cutting process involving 2-D plastic deformation as shown in Figure 1[3-9].

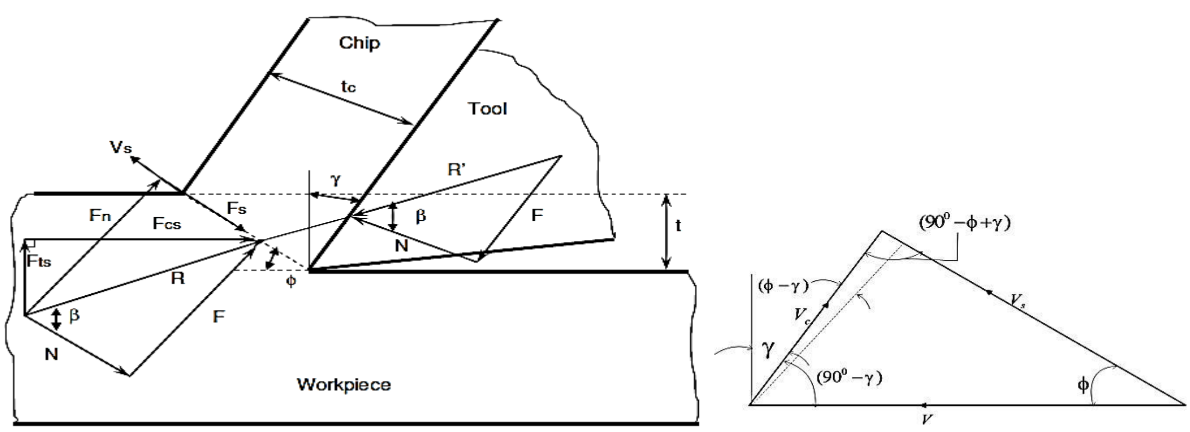

Figure 1. Model of chip formation in orthogonal cutting for a ‘sharp’ tool

Oxley *et al.* have 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 [10]. Using mechanics of cutting analysis, Armarego related the orthogonal cutting process to the oblique cutting process [11]. 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 lack 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 study, the thin shear zone orthogonal cutting analysis was reconsidered as studied by Ernst and merchant [3-4], but with a view to incorporating tool flank wear effect. The mechanics of cutting analysis for orthogonal metal cutting with tool flank wear are presented based on experimental investigations. An orthogonal cutting force model is then proposed based on the classical thin shear zone analysis.

2. ORTHOGONAL CUTTING ANALYSIS

Orthogonal cutting is geometrically shown in Figure 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, the cutting process is represented by a plastic shearing process in a localized (i.e. thin) shear zone and a friction or secondary shearing (seizure) process at the tool-chip interface [8,9,11]. Fundamentally, all earlier thin shear zone analyses assume the following conditions: 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 [11]. This has resulted in the well-known Merchant-type model, i.e.

$$F_{cs} = \frac{\tau b t \cos(\beta - \gamma)}{\sin\phi \cos(\phi + \beta - \gamma)} \qquad (1)$$

$$F_{ts} = \frac{\tau b t \sin(\beta - \gamma)}{\sin\phi \cos(\phi + \beta - \gamma)} \qquad (2)$$

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

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

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

Where F_{cs} *and* F_{ts} are respectively power and thrust forces; β, ϕ *and* γ are respectively frictional angle, shear angle and rake angle while τ, b *and* t are the shear stress, width of cut and the cut thickness respectively. In early studies, 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 [3, 4]:

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

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 [22]. 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 edge force acting at the cutting edge. It has been suggested by many researchers 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 [9, 11, 21]. 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 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 [11]. Consequently, Equations. (3) and (5) above have been modified when evaluating β and τ, i.e.

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

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

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:

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

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

Where: C_{ce} and C_{te} (N/mm) are the edge force intensity factors, obtained from the orthogonal cutting tests.

Although analysis and models for orthogonal cutting have been well developed, no studies have been reported on the 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 ploughing 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 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 (wear land) results in a significant increase in the cutting forces that contribute to the total cutting force increase [9]. Thus the present study has considered only the flank wear effect.

3. EXPERIMENTAL SETUP

The orthogonal machining tests were carried out using a PRODIS CORP CNC lathe. The workpiece was mild carbon steel, CS1030, with chemical composition of 0.3% C, 0.6% Mn, 0.04% P and 0.05% S. The tensile strength of the material is 463.7 MPa and hardness is 126 BHN. Cylindrical workpieces were prepared with a wall thickness of 3 mm and machined from one end. The cutting tools used were grade TP20 carbide flat-top inserts with 8μm TiN coating.

A wide range of cut thickness, rake angle and cutting speed were selected for the tests. Specifically, four levels of cut thickness (0.1, 0.17, 0.24 and 0.31 mm) were tested at three levels of cutting speed (100, 150 and 200 m/min) and three levels of tool rake angle (-5, 0, 5). In addition, four levels of wear land size including 'sharp' tools were selected. These were 0, 0.2, 0.4 and 0.6 mm. The wear land 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 144 tests with 4 specially made tool holders and 16 inserts were conducted.

The wear land was artificially made on the cutting tools by a lapping process using an abrasive grinder and checked frequently under a shadowgraph projector for its size. Care was taken to ensure that the final artificial wear land 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 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 charge amplifiers. The amplified signals were then recorded for further processing by a computer through an analog-to-digital (A/D) converter card and 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, wear land sizes and rake angles, a linear regression analysis of the 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 wear land force for tools with a wear land. 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 analyzed and verified later. By comparing the intercept with that of the respective sharp tool, the wear land force component for each test (with a wear land) was evaluated for further analysis. The friction angle β and shear stress τ for each cut were finally calculated using equations (7) and (8) respectively, after the edge force (or edge and wear land force) has been removed from the measured forces. For each test, at least one chip sample was collected, and the chip length ratio and the shear angle were evaluated using equation (4).

4. RESULTS AND DISCUSSIONS

4.1 Orthogonal cutting model with tool flank wear

The general trends of the predicted cutting forces with respect to the cut thickness are as shown in Figures 2 and 3 for power and thrust forces respectively. The predicted forces are plotted with dotted lines while the experimental forces are plotted with solid lines. The predicted forces are evaluated using equations (11) and (12), and the experimentally determined basic cutting quantity database in Table 1.

Table 1: Experimentally Determined Models for basic cutting parameters

Cutting parameter	Modeled equation
Frictional angle, β (^{0})	$\beta = 36.53 + 0.41\gamma - 0.07V$
Shear stress, τ (N/mm^2)	$\tau = 417.52 + 4.39\gamma + 0.35V$
Chip length ratio, r_l	$r_l = 0.327 + 0.004\gamma$
Edge force coefficients C_{ce} and C_{te} (N/mm)	$C_{ce} = 74.2$
	$C_{cw} = 180.6$
Wear land force coefficients C_{cw} and C_{tw} (N/mm^2)	$C_{te} = 89.3$
	$C_{tw} = 158.5$
γ *in degrees*, V *in mm/min*	

It has been observed that the forces increase linearly with the cut thickness and are in good correlation with the experimental data. It has also been found that cutting forces increase with the wear land size. Plots of cutting forces versus other variables under different conditions show that the predicted trends of the cutting forces are consistent with those reported in the literature and from the mechanics of cutting analysis [11]. Thus, the generality and plausibility of the proposed cutting force models have been amply demonstrated.

Following the analisis, it is found that there is a rubbing or ploughing force on the tool edge and tool wear land as evidenced by the existing forces when the cut thickness is zero. This rubbing forces (F_{crub} *and* F_{trub}) increase with increase in the wear land size. When a 'sharp' tool is used, this rubbing forces are in fact the so-called edge forces (F_{ce} *and* F_{te}) while the additional amount resulting from the wear land has been classified as wear land forces (F_{cw} *and* F_{tw}). For the purpose of force prediction, empirical equations for the edge force and wear land force have been established which combined with the shear forces (F_{cs} *and* F_{ts}) required for the chip formation process. These can form the model to predict the total forces in orthogonal cutting when tool flank wear is present.

Based on the above analysis, the overall force relationships and the model to predict the forces are shown in Figure 4. Mathematically, the overall cutting power (F_c) and thrust (F_t) force models have been experimentally found to be:

$$F_c = F_{cs} + F_{crub} = F_{cs} + F_{ce} + F_{cw} = \frac{\tau\cos(\beta-\gamma)}{\sin\phi\cos(\phi+\beta-\gamma)}bt + C_{ce}b + C_{cw}b.VB \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

$$F_t = F_{ts} + F_{trub} = F_{ts} + F_{te} + F_{tw} = \frac{\tau\sin(\beta-\gamma)}{\sin\phi\cos(\phi+\beta-\gamma)}bt + C_{te}b + C_{tw}b.VB \quad \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

Where C_{ce} and C_{te} are edge force intensity factors in N/mm, C_{cw} and C_{tw} are wear land force intensity factors in N/mm^2, and are determined experimentally.

It is noteworthy that the proposed cutting force models make full use of the previously developed machining theories for 'sharp' tools [11]. It is anticipated that the proposed orthogonal cutting model can be mathematically related to oblique cutting and various practical machining operations, such as turning operations, to develop predictive force models. In order to implement the proposed force model, the basic cutting quantities, such as the shear angle and friction angle, need to be determined.

4.2 Model Validation

The proposed predictive force models for orthogonal cutting with tool flank wear have been verified for their plausibility and predictive capability. The models verification is conducted by comparing both qualitatively and quantitatively the predicted forces with the corresponding experimental results.

Quantitative comparisons between the predicted and experimental forces have been carried out to examine the adequacy of the models. The comparisons are based on the percentage deviations of the models predicted values with respect to the corresponding experimental data. It has been observed that the deviations for different wear land sizes do not exhibit any differences that can suggest the effect of wear land on the model's predictive capability, and the models give good prediction for both the power and thrust force components with the maximum percentage deviation being 2.3% for power force and 4.2% for thrust force. This percentage deviation has been confirmed statistically using independent sample t-test analysis. The statistical analyses show that, at 95% confidence, the predicted models have no significant difference since all the P-value stands at $P>0.05$ for both power and thrust forces at different wear lands. The analyses also show that, the prediction gives average percentage standard deviations of 1.43% and 4.61% for power force and thrust force models respectively. Thus, it may be concluded that the models can give adequate prediction for the cutting forces in orthogonal cutting when tool flank wear is present.

5. CONCLUSIONS

The results have shown that tool flank wear results in a substantial increase in the force components and in an additional rubbing or ploughing force on the wear land. 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.

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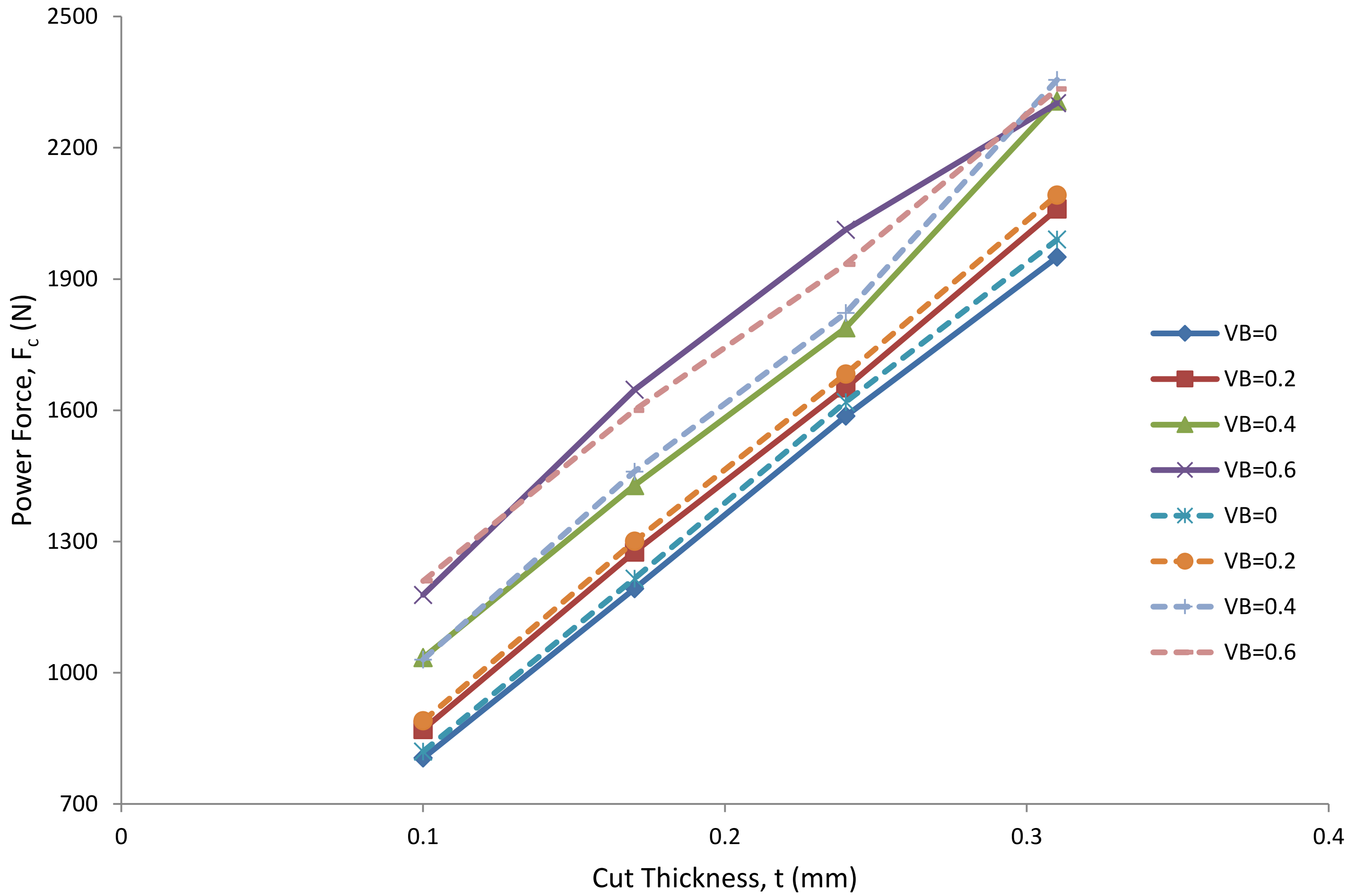

Figure 2: Predicted and experimental power cutting forces F_c, in orthogonal cutting at V=150m/min, $\gamma = 0^0$

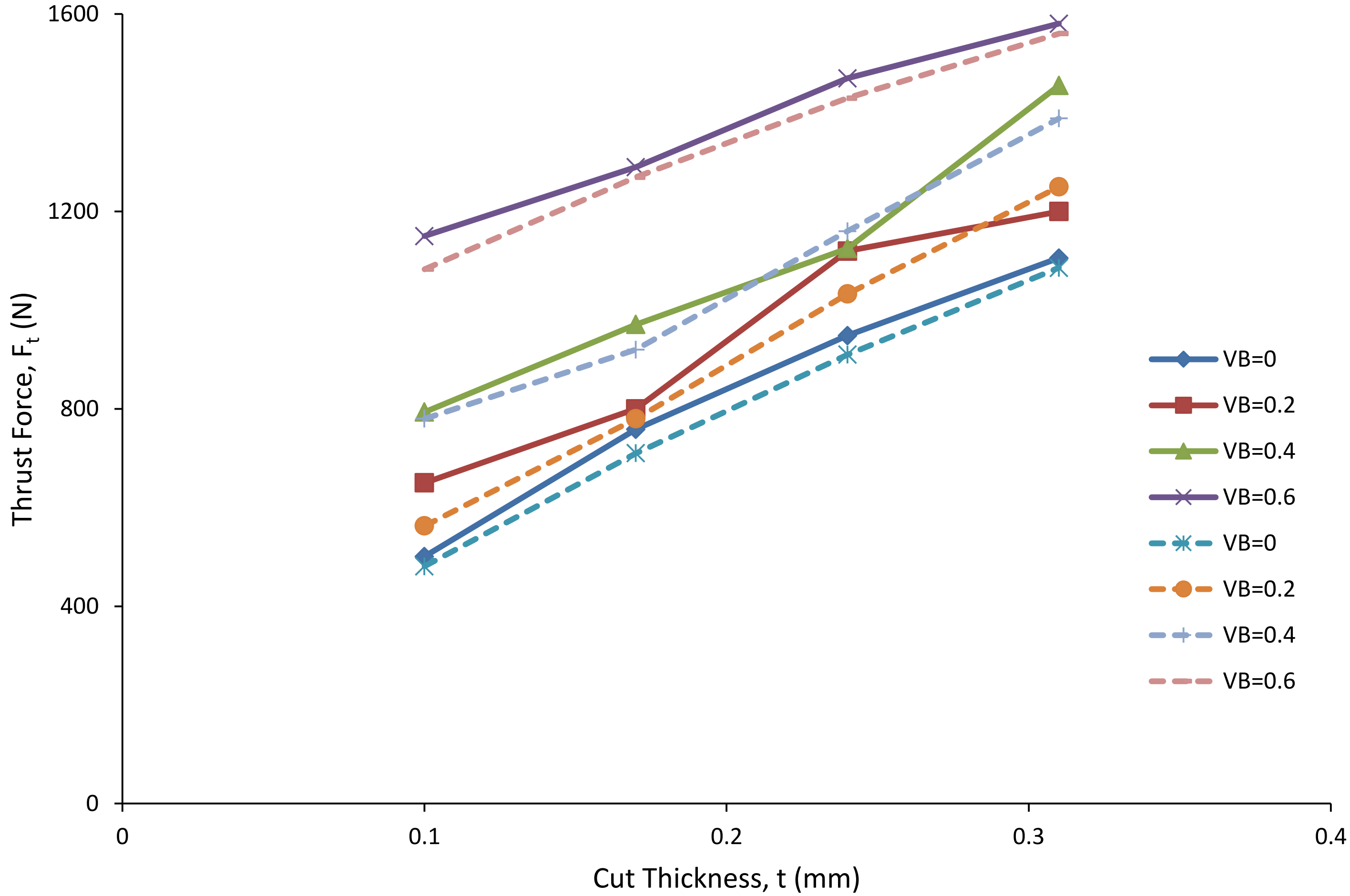

Figure 3: Predicted and experimental thrust forces F_t, in orthogonal cutting at V=150m/min, $\gamma = 0^0$

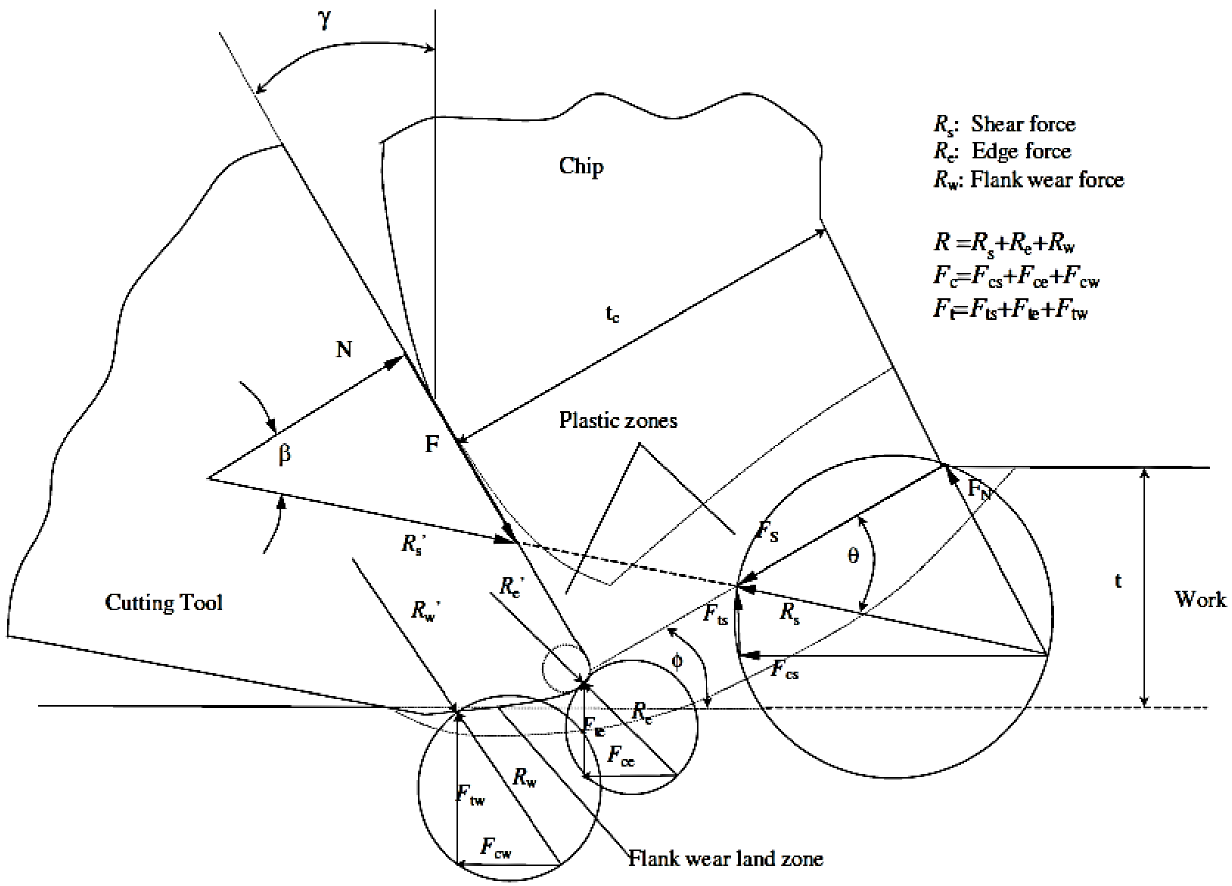

Figure 4: Orthogonal cutting model allowing for the effect of tool flank wear