AN ANALYTICAL MODEL FOR IN-PROCESS PREDICTION OF SURFACE ROUGHNESS IN FINISH TURNING

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submitted to the
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by

Parag Gupta

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ABSTRACT

Achieving a desired surface roughness is a requirement for finish turning whereas achieving the maximum material removal rate is the main goal in rough turning. There is no industrial technique available by which an in-process measurement of surface roughness can be made in finish turning. Previous researchers have developed models which considered the tool geometry, feed rate and cutting speed in predicting the surface roughness. However, they have not considered tool wear so that the models are unable to predict the surface roughness in the time domain as the tool wears.

An analytical model is proposed to predict the surface roughness in restricted finish turning where both the principal and auxiliary cutting edges participate. Unrestricted turning in which only the principal cutting edge is effective produces a very poor surface finish and is therefore not recommended for finish turning. The model takes into account tool wear for the first time which makes it possible to forecast the surface roughness generated by a worn tool. Tool wear itself can be predicted on-line by monitoring the change in spindle speed. Consequently, the predicted tool wear can be used with known tool dimensions, feed rate and depth of cut to predict the surface roughness in real time.

By using the new model, the feed rate could be controlled adaptively to

achieve the desired surface roughness by using a worn tool at the highest possible feed-rate. The highest possible feedrate is synonymous to the minimum possible machining time which, in turn, implies higher productivity.

The standard deviation of the feed cutting force appeared to correlate well (correlation coefficient of 0.76) with the workpiece's surface roughness. This observation suggests that the rigidity of the machine tool in the feed direction plays an important role in the surface finish.

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LIST OF SYMBOLS

h_{fp}, h_{fa} --flank wear on the principal and auxiliary cutting edge in the elevation view, respectively

r_{fp}, r_{fa} --flank wear on the principal and auxiliary cutting edge in plan view, respectively

V_p, V_a --chip velocity at the principal and auxiliary cutting edges, respectively

ϕ_p, ϕ_a --principal and auxiliary cutting edge angle of the tool, respectively

α_s, α_{s1} --side and back rake angles of the tool, respectively

τ_s, τ_{s1} --side and back relief angle of the tool, respectively

r --nose radius of the tool

R_0 --peak-to-valley distance of machined surface with a perfect tool bit

R_1 --peak-to-valley distance of machined surface due to tool wear alone

R_{max} --peak-to-valley distance of the machined surface

s --feed rate

t --depth of cut

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

The lathe, which is often called the "father of machine tools", is one of the most important and oldest machine tools. Wooden lathes were used in France as early as 1569. England adapted the machine for metal cutting during the industrial revolution in the 18th century. Given this long history, it is not surprising that extensive research has been conducted in the field of metal cutting and machine tools which has made C.N.C lathes commonplace in modern machine shops.

The major goal of the present research is to help to perform economical, unmanned and accurate machining by using an optimal speed, feed rate and depth of cut in finish turning. The objective in finish turning is to achieve a desired tolerance in order to meet the part specification. The objective of rough turning, on the other hand, is to achieve the maximum material removal rate. In addition, the surface topography of the machined part should also meet the specification which, in turn, depends upon the final function of the part [Noaker, 1991].

Modern C.N.C lathes can machine cylindrical parts within a low tolerance bandwidth by employing position feedback control strategies.

However, there is no machine tool sensor for the in-process control of surface topography [Harding, 1991] in finish turning. Therefore, the present research is geared to achieving a desired surface topography in finish turning.

1.2 SURFACE TOPOGRAPHY

The outermost layers of a machined surface have macro-geometrical as well as micro-geometrical deviations from the perfect or ideal geometrical surface. First order deviations are macro-geometrical and include errors of form. Waves are deviations of the second order and deviations of the third and higher order refer to the surface roughness.

The major elements of surfaces, as defined by Bhattacharya [Bhattacharya, 1984] and illustrated in Fig.1.1 [Noaker, 1991], are as follows.

(a)SURFACE: An object's surface is the boundary which separates that object from the atmosphere.

(b)PROFILE:The contour of a section through a surface is the profile of the section.

(c)ROUGHNESS: Roughness is due to relatively finely spaced irregularities on the surface. These irregularities are produced as a result of the tool's geometry and the feed of the machine tool. Roughness can be considered to be superimposed on a wavy surface.

(d)WAVINESS: Surface irregularities have a larger spacing than that of the

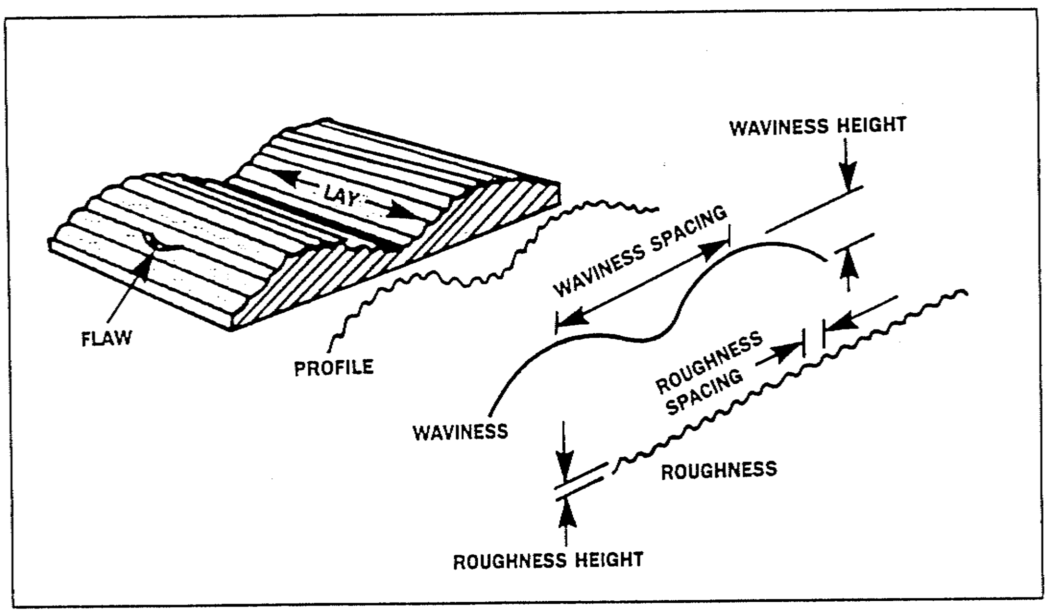


Fig.1.1 Surface Anatomy [Noaker, 1991].

roughness. Waviness on a machined surface may be due to machine and workpiece deflections or to machine tool vibrations, etc.

(e)FLAWS: Flaws are nothing but irregularities which occur at a place or at infrequent intervals on the surface. A flaw may be a ridge, a crack, scratch etc.

Surface roughness plays an important role in all areas of tribology. The surface finish of machined parts is an important design specification in machined parts subjected to fatigue loads, fastener holes, precision fits etc.[Hasegawa,1976]. If the surface finish can be controlled in finish turning, then the machining time can be reduced by using the maximum possible feed rate.

1.3 FACTORS AFFECTING SURFACE ROUGHNESS

The surface roughness (i.e the primary texture of the surface) is affected by the following factors:

(a) the rigidity of the machine tool and the condition of the spindle bearings;

(b) the 'finishability' of the work material;

(c) the type and condition of the cutting tool;

(d) the use or non-use of a cutting fluid ;

(e) the geometry of the cutting tool (principal and auxiliary cutting edges as well as the cutting angles); and

(f) cutting parameters, such as feed rate, depth of cut and cutting speed.

Surface irregularities, which have a greater spacing (waviness) than that of surface roughness, may be due to vibrations which are a result of:

(a) internal unbalance of machine elements;

(b) defects in the drive of the machine tool; and

(c) self excited vibrations.

1.4 TECHNIQUES FOR MEASURING SURFACE ROUGHNESS

Surface roughness was specified by the use of tactual standards before 1930. A set of reference specimens that had different surface roughnesses were used. The machinist would judge the finish of the machined surface by running a finger nail, first across a standard or reference tactual surface and then across the newly machined surface. If the two surfaces were felt to have the same roughness, the new workpiece was considered to have the same roughness as the reference surface.

In the early 1930's, the measurement of surface roughness became quantitative due to the emergence of stylus instruments which traversed the surface with a lightly contacting diamond stylus. These instruments employed transducers which converted the vertical and horizontal movements of the diamond into recorded traces. However, the diamond stylus can leave a permanent mark on the machined surface unless a very light stylus loading is used.

Non-contact techniques were developed around 1960. They were based on the principle of interference and the scattering of a laser beam reflected from a rough surface. However, both contacting and non-contacting methods are quite slow and require the workpiece to be stationary during the measurement. Real time measurement requires that the surface roughness of a nonstationary workpiece be measured in-process because the tool nose's profile changes with time. However, previously described methods require the process to be interrupted regularly which would increase a machine's idle time and reduce productivity.

1.5 STANDARDS FOR SURFACE ROUGHNESS

The root mean square (R.M.S) of the vertical motion (in microinches) of the diamond stylus was used in the 1930's, in the U.S.A, to specify surface roughness. The Europeans as well as the Japanese were also able to measure surface roughness quantitatively, but they employed the maximum peak-to-valley roughness (R_t) instead of the RMS value. The British used the centre line average (CLA). This is the standard which is employed now in the United States and it is also called the arithmetic average (AA) roughness. The AA or CLA roughness, usually abreviated nowadays as R_a, is an arithmetic average of the deviation of the peaks from the centre line of a trace, the centre line being the line below and above which there is an equal area between it and the surface trace. A more detailed review of previous research relating to the factors affecting surface roughness is presented next.

1.6 PREVIOUS RESEARCH

Researchers [Shaw, 1965; Allgaier,1962] have proposed equations to calculate the surface roughness. These equations assume ideal machining conditions i.e. the surface roughness is only due to the smooth geometry of the tool. The effect of tool wear as well as a change in the nose radius during machining is ignored.

Olsen [Olsen,1968] experimentally determined the combined effects of the cutting speed and the feed rate on the surface roughness. He provided nomograms for choosing an appopriate cutting speed and feed rate combination to achieve a desired surface roughness for a given nose radius. The nomograms were made for machining specified plain carbon steel. However, the influence of the tool's geometry and wear on the machined surface were ignored.

Bhattacharya et al.[Bhattacharya, 1970] proposed a generalized empirical expression which was developed by using the least square method. This expression was based on data provided by Olsen. The model considered the tool bit's nose radius, the hardness of the work piece material, feed rate as well as the tool bit's side cutting edge angle. However, it ignored tool wear again so that the model can not predict the surface roughness generated by a worn tool.

Taraman et al.[Taraman, 1974 (b)] utilized a response surface methodology to develop a first order as well as a second order surface roughness model based on the speed, feed and depth of cut. They used the model to generate contours which were utilized to select machining parameters to achieve maximum material removal while maintaining the surface roughness at a desired level.

Hasegawa et al.[Hasegawa, 1976] developed an empirical, second order equation to predict the surface roughness by using three primary variables i.e the speed (v), feed (s), and nose radius (r). Other variables in the second order equation were products of all possible combinations (such as v^2, r^2, s^2, rv, sr and vs) of the three primary variables. The authors conducted 12 tests for different speeds, feeds, depth of cuts and nose radiuses. The depth of cut was eliminated from the equation because experiments showed that the correlation between the depth of cut and surface finish was about 0.01 i.e the depth of cut had very little effect on the surface roughness for the range of cutting conditions used.

Rakhit et al.[Rakhit, 1976] suggested that the centre line average of the surface, R_a, was due to a combination of the mean square response of the tool,

σ_f, and the centre line average value, Ra_{th}, of the basic waveform (i.e. the theoretical or ideal surface roughness created by a perfect tool bit) of the surface. The Ra_{th} of the basic waveform depends upon the tool geometry, especially the nose radius, and the feed rate. The σ_f depends upon the response of a machine tool caused by the cutting force's fluctuations. However, unknown quantities such as the elastoplastic flow of a chip, the interface temperature distribution as well as the thermodynamic process involved is quite complex. Hence, the establishment of a relationship between the vibratory response of the tool tip and the amplitude fluctuations of the surface produced by the random fluctuations of the cutting forces is an extremely complex problem. On the other hand, Rakhit et al. proposed an empirical relationship between the cutting conditions and the expected surface roughness.

Mital et al.[Mital, 1988] studied the effect of speed, feed and tool nose radius on the surface finish of five metals (ductile cast iron, steel 10L45, steel 4130, Inconel 718 and aluminium 390). The data was analyzed by employing a parametric analysis of the variance in speed, feed rate and depth of cut. The surface roughness was used as the dependent variable. A general as well as a specific model was developed for each metal. However, both models ignore tool wear.

Jang et al. [Jang,1989] accounted for the considerable variations in surface roughness predicted by models proposed by previous authors [Olsen,1968; Sundaram, 1981; Albrecht, 1956; Chandiramani, 1970; Solaja, 1958; Ansell, 1962; Taraman, 1974 (a); Wu, 1964] by including the vibratory behaviour of the machine tool. They derived an empirical equation which considered these vibrations in addition to the cutting speed, feed rate, depth of cut and nose radius. Furthermore, Jang et al. performed a kinematic analysis and suggested that the surface roughness due purely to the dynamic movement of the tool is negligible compared to that generated due to geometry of the tool bit. This assertion holds as long as the fundamental natural frequency of the tool assembly is greater than about 150 Hz.

1.7 GOALS OF THE THESIS

The previously mentioned models [Shaw, 1965; Allgaier, 1962; Jang, 1989; Olsen, 1968; Hasegawa, 1976; Petropoulos, 1974; Mital, 1988; Rakhit, 1976; Bhattacharya, 1970; Taraman, 1974 (b)] can be categorised broadly into two types. An analytical formula was developed based on the smooth geometry of the tool [Shaw, 1965; Allgaier, 1962], or an empirical formula was determined based on the depth of cut, nose radius within a specified range of cutting speeds and feeds of the tool bit [Jang, 1989; Olsen, 1968; Hasegawa, 1976; Petropoulos, 1974; Mital, 1988; Rakhit, 1976; Bhattacharya, 1970; Taraman 1974 (b)]. However, all the models ignore the tool's dimensions which change progressively with wear. This deficiency has been noted by previous researchers, most notably by Dontamsetti [Dontamsetti, 1988], who suggested that the theoretical models fail because they do not account for changes in tool geometry caused by wear which alter the feed marks produced on the machined surface. In addition, empirical formulae are disadvantageously valid for only a small range of speeds, feed rates and workpiece materials.

An analytical model is proposed here to predict the surface roughness in restricted finish turning where the two cutting edges of a tool, the principal and auxiliary cutting edges, participate. The model takes into account tool wear for the first time. This accommodation makes it possible to forecast the surface roughness generated by a worn tool for a wider range of speeds and feed rates. The model should be valid for most materials as long as there is no built up edge formation and continuous chips are formed. Tool wear itself can be predicted in-process by monitoring the tangential and feed cutting forces, the motor current, voltage, the vibration of the tool assembly or the change in spindle speed. The spindle speed was considered for measuring the flank wear because the electronic equipment used for measuring a change in the spindle speed, unlike the force transducer, can be advantageously used because it is remote from the harsh cutting environment typical of industry. Consequently, tool wear can be used with known tool dimensions, feed and depth of cut for the in-process prediction of surface roughness. As mentioned earlier, measuring the surface roughness during turning requires regular interruption of the process which increases a machine's idle time and reduces productivity. By using the new model, an adaptive control strategy can be implemented which could signal the operator when the tool is worn completely and needs replacement or grinding to achieve the desired surface finish. In other words, it would no longer be necessary to interrupt the machining process to measure the surface roughness.

CHAPTER 2. EXPERIMENTAL SETUP AND PROCEDURE

2.1 PROCESS MONITORING

In order to investigate the possibility of using the change in spindle speed as a tool wear predictor and test the model throughout the turning process, a data acquisition system (DAS) was designed and installed on a retro-fitted Supermat 1011 lathe. A current transformer and a voltage transformer monitored the spindle motor's current and applied line voltage, respectively. A three dimensional strain gauge force dynamometer, which was fabricated by Prof.S.Balakrishnan, measured the tangential, feed and radial cutting forces. A static calibration of the dynamometer was performed by Mr. D.H.Yan who applyed a known static load in the tangential, feed and radial directions, in turn, and measured the corresponding output voltage of all three channels of the cutting forces. It was determined during the static calibration that the crosstalk between the tangential and feed force channels is much smaller (1 to 3%) than that between the radial and either of the two remaining channels (20 to 25 %). Due to this crosstalk and the previous findings of Taraman et al. [Taraman, 1974 (a)], who reported no useful relationship between the flank wear and radial force, it was decided to replace the radial force component with a radially orientated accelerometer secured to the force dynamometer. In addition, an accurate optical encoder speed sensor and custom electronics was designed [Kaye, 1990] and installed on the lathe's spindle. The electronics were interfaced to a 386 IBM compatible computer. Apart from the speed encoder which generated 1024 pulses per revolution, all sensors were sampled at 12.5Khz. and transferred to storage through a Direct Memory Access (DMA) operation. All sampling was synchronized. A schematic of the experimental setup is shown in Fig.2.1.

2.2 WORKPIECE

A 6 m (20 feet) bar of 4340 SPS steel bar was cut into twenty equally sized workpieces. The workpieces were hardened by austenitizing them for two hours at 850° C followed by ageing at 650° C for two hours. The hardness of the workpieces was determined, by using a Versitron hardness tester, to be 32 $\pm$3 on the Rockwell C scale. Workpieces of 33 $\pm$ 0.25 mm diameter were cut in succession in order to ensure a constant surface cutting velocity. A workpiece length to diameter ratio of approximately eight was also maintained throughout the cutting process in order to maintain a uniform rigidity. The load torque on the spindle depends on the radius of the workpiece as well as the force. Consequently, the same diameter was maintained to ensure that changes in the torque were due only to cutting force fluctuations.

2.3 TOOL BIT

The tool bit was disengaged after each workpiece was machined in order to take magnified (25x) photographs of the tool's flank by using a Nikon EPIPHOT-TME optical microscope. The flank wear was measured from the photographs. A scaling factor supplied with the precision lens was used to get

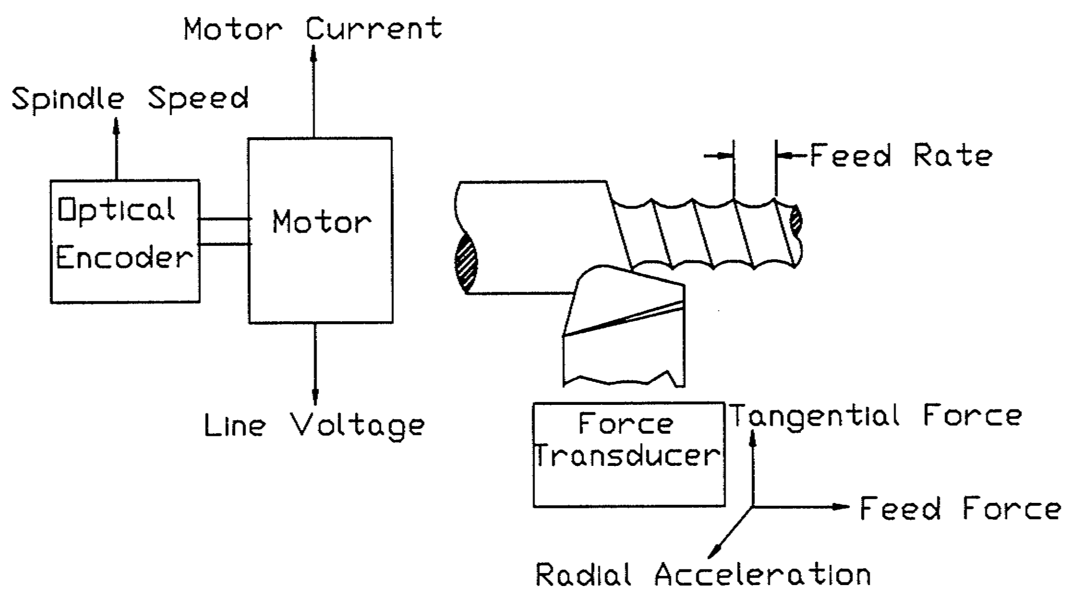


Fig.2.1 Experimental Setup.

the actual value of flank wear. Flank wear was determined at the point where the nose

radius is tangential to the principal cutting edge, as shown in Fig.2.2. A rigid tool holder along with a plasticene mould of the tool shank was used to ensure that the tool bit always had the same inclination while being photographed.

2.4 SURFACE ROUGHNESS

The surface roughness of a machined surface was measured at sixteen different points in a direction parallel to the motion of the tool by using a Mitutoyo Surftest, model 401. The sixteen points were divided longitudinally into equispaced sets of four points. The four points in any one set were equally spaced circumferentially. The cut-off length for the Surftest's stylus was 0.8mm(0.0315 in) and a total distance of 0.8x5=4mm(0.157 in) was traversed in steps of 0.8mm(0.0315 in). The instrument provided a mean value of five readings at each of the sixteen points and an arithmetical average of the sixteen means was calculated manually.

2.5 CUTTING CONDITIONS

Three cutting tests were performed with identical tools and a constant depth of cut of .45mm(0.0177 in) and different speeds and feed rates to test the model for different conditions. No test was performed with different depth of cut because depth of cut does not have any effect on surface roughness as mentioned in section 1.6. Cutting was performed by using BR6C6 carbide

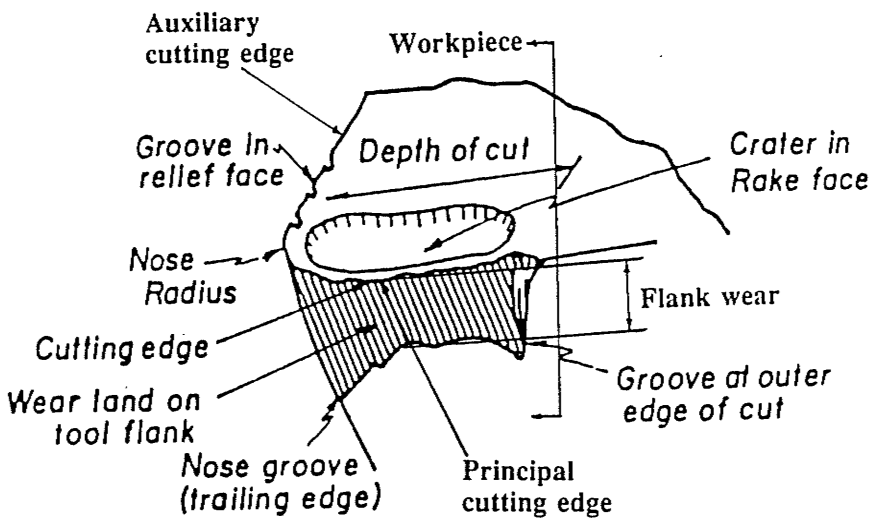


Fig.2.2 Magnified view of tool bit showing flank and crater wear [Tseng, 1979].

inserts having a tool designation 7,7,7,7,15,15,.46(0.0181 in) according to the American Standards Association [Shaw,1989]. The nominal spindle speed settings for the three tests were 115 rad/s(1160 r.p.m), 198.86 rad/s(1900 r.p.m) and 198.86 rad/s(1900 r.p.m) with feed rates set at 0.06mm/rev (0.0024in/rev), 0.06mm/rev(0.0024in/rev) and 0.091mm/rev(0.0032 in/rev), respectively, for finish turning

2.6 DATA ANALYSIS

A lathe monitoring program, which was developed by Mr. John E. Kaye, was used for the data acquisition. This program created files having 3072 samples acquired at regularly time spaced intervals. The program created four files for each workpiece and the time interval between two files was the time taken by the tool to machine 30 mm of the workpiece. Therefore, the time elapsed between the creation of two consecutive files depended upon the speed and feed rate of the machine tool. Data was not collected during the first 10 to 15 mm of a cut. This procedure allowed the cutting forces to stabilize. Four files were created for each workpiece. Each file had 3072 samples of five parameters, namely the tangential cutting force, the feed force, radial acceleration, motor current and the line voltage. A Fortran program "Stat", written by the author, read all the data points in each file and provided four statistical quantities for each of the five parameters in each file (4 x 5 = 20 statistical parameters). The four statistical quantities were the mean or root mean square, the standard deviation, skewness and kurtosis. Finally, the

"Stat" programme created a file which had an array of 20 statistical parameters of all the files created during the machining. The array of statistical parameters was increased further by the addition of the surface roughness measurements as well as that of the workpiece's hardness, flank wear, nose wear and the change in the nominal spindle speed. The final array had 25 columns and the number of rows depended on the number of workpieces machined by a tool bit until it was worn. It was desired to find parameters which correlate well and might be useful for predicting tool wear and surface roughness. However, the number of possible combinations of parameters was 300. Consequently, the programme "Corela" was written in BASIC by the author to find the correlation coefficients for all possible combinations of all the different parameters. By a visual inspection of the graphs of 40 selected combinations, it was realized that a parameter combination having a correlation coefficient modulus less than 0.7 is not well correlated. In all three tests performed, the following combinations out of all 300 combinations were found to have a correlation coefficient whose modulus was greater than 0.7.

(i) The mean tangential force, mean feed force, r.m.s motor current, speed change and flank wear were found to be correlated and their correlation coefficients are provided in Table 2.1.

(ii) The standard deviation of the tangential cutting force and the standard deviation of the feed force had a correlation coefficient of 0.93.

(iii) The standard deviation of the feed force and the surface roughness had a correlation coefficient of 0.76.

	Tangential Force	Feed force	Speed change	Motor current	Tool wear
Tangential Force	1.00	0.93	0.89	0.86	0.81
Feed force		1.00	0.90	0.88	0.80
Speed Change			1.00	0.80	0.88
Motor current				1.00	0.76
Tool wear					1.00

Table 2.1 Correlation coefficients for selected parameters.

CHAPTER 3 INTRODUCTION TO THE MODEL

3.1 A TOOL'S GEOMETRY

A turning tool, like most tools, has two edges, viz the primary or principal cutting edge and the secondary or auxiliary cutting edge. For a single point tool, the two cutting edges join at a sharp corner. However, the cutting edges for finish turning are connected, as shown in Fig.2.2, by an arc which is called the nose and the radius of this arc is termed the nose radius. Other angles required to describe the tool geometry are the rake angles, cutting edge angles and the relief angles; all of which are shown in Fig.3.1. Representative values of the rake and relief angles lie between 6° and 15°. On the other hand, typical values of the principal cutting edge angle lie between 75° and 90° and those for the auxiliary cutting angle are between 15° and 30°.

The two quantities necessary to define the inclination of the tool face relative to the tool base are the side rake angle, α_s, and the back rake angle, α_b. The recommended values of the rake angles increase as the toughness of the metal cut increases. (Toughness is defined as the energy absorbed by a material before fracture occurs and it is proportional to the area under a stress strain curve.) A reduction in the rake angles provides a greater wedge angle at the tool tip which supports a greater load. However, if very hard materials are machined or if intermittent cuts must be taken, the rake angles should be

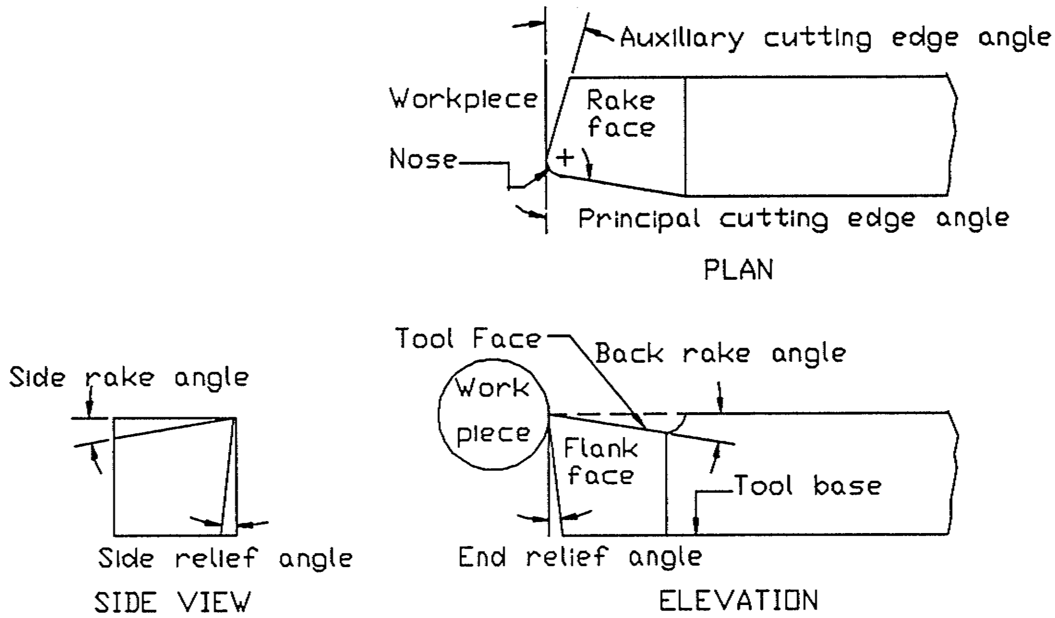


Fig.3.1 Tool geometry.

reduced to give a larger included angle in the elevation view in order to provide a greater shock absorbing capability [Shaw 1989].

A smaller principal cutting edge angle enables a cut to be made at a lower power with a tool having a larger included angle [Shaw 1989]. However the possibility of chatter increases with a reduction in the principal cutting edge's angle[Shaw 1989]. In order to avoid chatter, it is customary to have a principal cutting edge angle of 75° or higher.

The auxiliary cutting angle should be as small as possible to provide better tool strength and an improved surface finish. It normally ranges from 5° to 15°. If the machine tool is not rigid enough for high cutting forces and the auxiliary cutting edge angle is low, then an increase in the radial force could cause chatter due to the lack of an end clearance [Shaw 1989].

The relief angles shown in Fig.3.1 are provided in a tool bit to avoid rubbing of the workpiece's finished surface with the tool bit. The recommended relief angles decrease slightly as the hardness of the metal cut increases. While cutting very hard materials at a very low feed rate, a relief angle as low as 5° may be used successfully [Shaw 1989].

3.2 THE ANALYTICAL MODEL

The flank wear, which is depicted in Fig.2.2 [Tseng, 1979], is defined as the length of wear on the cutting edge, as seen in elevation, at the point where the arc of the nose radius meets the cutting edge. It generally refers to wear on the principal cutting edge rather than the auxiliary cutting edge. Flank wear spoils the surface finish [Sata,1960; Ito,1968; Takeyama,1969; Okushima, 1972; Nakayama, 1974; Mori, 1985; Okushima, 1961] because the tool bit's flank is in contact with the machined surface. The opening of a crater leads to a rapid deterioration in the finish of a machined surface [Pekalharing, 1963; Venkatesh,1968].

A tool bit's flank wear and nose radius as well as the feed rate are the major parameters which affect surface roughness. Researchers [Okushima,1961; Ansell,1963; Bhattacharya, 1984] have also reported a greater surface roughness with an increase in the feed rate and a smaller nose radius [Okushima,1961; Brierly, 1964; Olsen,1965]. However, the feed rate is the only parameter which can be adjusted on-line provided the flank wear is also known. Flank wear can be obtained on-line by measuring the tangential force, feed force, vibration of the tool assembly, motor current and spindle speed change [Gupta, 1991; Lee, 1989; Giusti, 1987; Maeda, 1987; Reif, 1986; Tseng 1979]. In addition, the analytical relationship between the flank wear, nose radius, feed rate, tool geometry and surface finish should be known. However, this analytical relationship has not been developed yet. Therefore, a model is proposed here which expresses the peak-to-valley distance of a machined surface (i.e the surface roughness) in terms of the nose radius, feed rate, tool geometry and flank wear. The model predicts the peak-to-valley distance of a machined surface rather than the CLA or Ra which are defined in section 1.5. The Ra or CLA and peak-to-valley distance are not exactly identical but they appear to be highly correlated [Bhattacharya, 1984]. By using the new model, the feed rate can be controlled adaptively to achieve the desired surface roughness by using a worn tool at the highest possible feed-rate. The highest possible feedrate is synonymous to the minimum possible machining time which, in turn, implies higher productivity.

The proposed model is suitable for restricted cutting in which both the primary and auxiliary cutting edges participate. Unlike unrestricted cutting, in which only the principal cutting edge is in contact with the workpiece, there is no built up edge formation above a critical speed in restricted cutting [Shaw,1965]. The critical speed at which a built up edge disappears reduces with an increase in the rake angle of the tool, greater hardness of the workpiece as well as with a higher feed rate of the machine tool [Sata; Loladze,1958; Higginbotham, 1961]. Tool material and depth of cut have little effect on the critical speed [Sata]. Furthermore, if there is no built up edge in restricted cutting, the surface roughness reaches a constant value because the roughness is only due then to feed marks [Shaw,1956; Sata]. The assumption that there is no built up edge formation and that the surface roughness is due to feed marks alone is based most notably upon the research of Mori et al. [Mori,1985]. They suggested that the nose wear land profile is reproduced with high fidelity on the machined surface.

The change in nose profile due to tool wear can be predicted. However, the nose profile is unpredictable after tool breakage, chippage or opening of a crater because of the complexity of these processes. Therefore the model is valid as long as there is no tool chippage, breakage or opening of crater wear. Tool chippage as well as breakage can be predicted on-line by using the cutting forces and acoustic emission [Moriwaki,1983; Moriwaki,1984;Takata, 1985; Emel,1988]. The opening of crater wear, on the other hand, has to be avoided by selecting an appropriate tool life [Bhattacharya, 1984]. The model also assumes that the surface roughness due to the dynamic movement of a tool is negligible compared to that generated by the geometry of the tool. This assumption is based on the theoretical research of Jang et al. [Jang, 1989] who performed a kinematic analysis and showed that the dynamic effect is negligible compared to the geometric effect if the natural fundamental frequency of the tool assembly is greater than 150 Hz. This assumption is reasonable because the first natural frequency of the tool assembly employed in the present work was found to be 3200 Hz.

CHAPTER 4. THEORY

The maximum peak-to-valley distance of a machined surface generated by a worn tool, R_{max}, depends on the ideal peak-to-valley distance due to the geometry of the tool, R_0, and that due to flank wear, R_1. Industries use R_{max} rather than R_0 or R_1 to specify the surface finish of a part. As mentioned earlier, the in-process prediction of surface roughness in finish turning requires an analytical relationship which expresses R_{max} in terms of the tool bit's geometry and flank wear as well as the feed rate. This analytical relationship is derived here for the first time.

Fig.4.1(a) shows a plan view of an ideal turning operation and the characteristic ridges or feed marks which remain after machining with a new tool. The ridges depend upon the geometry of the tool bit's nose but they have a pitch equal to the axial feed rate. The ideal peak-to-valley distance of the (identical) ridges, R_0, can be computed readily [Shaw,1965] from the characteristics of a perfect (i.e new) tool bit and the feed rate.

Fig.4.1(b) presents an enlarged view of the tool tip which has a nose radius "r", within the indicated arc LCM having its center at point O, together with the principal and auxiliary cutting edge angles, ϕ_p, and ϕ_a, respectively. These angles are defined as the included angles between line JK, which is parallel to the longitudinal axis of the workpiece, and the straight portion of the cutting edges. In other words, ϕ_p is the included angle between lines LE and JK whereas ϕ_a is the included angle between lines MX and JK. Fig.4.1(c)

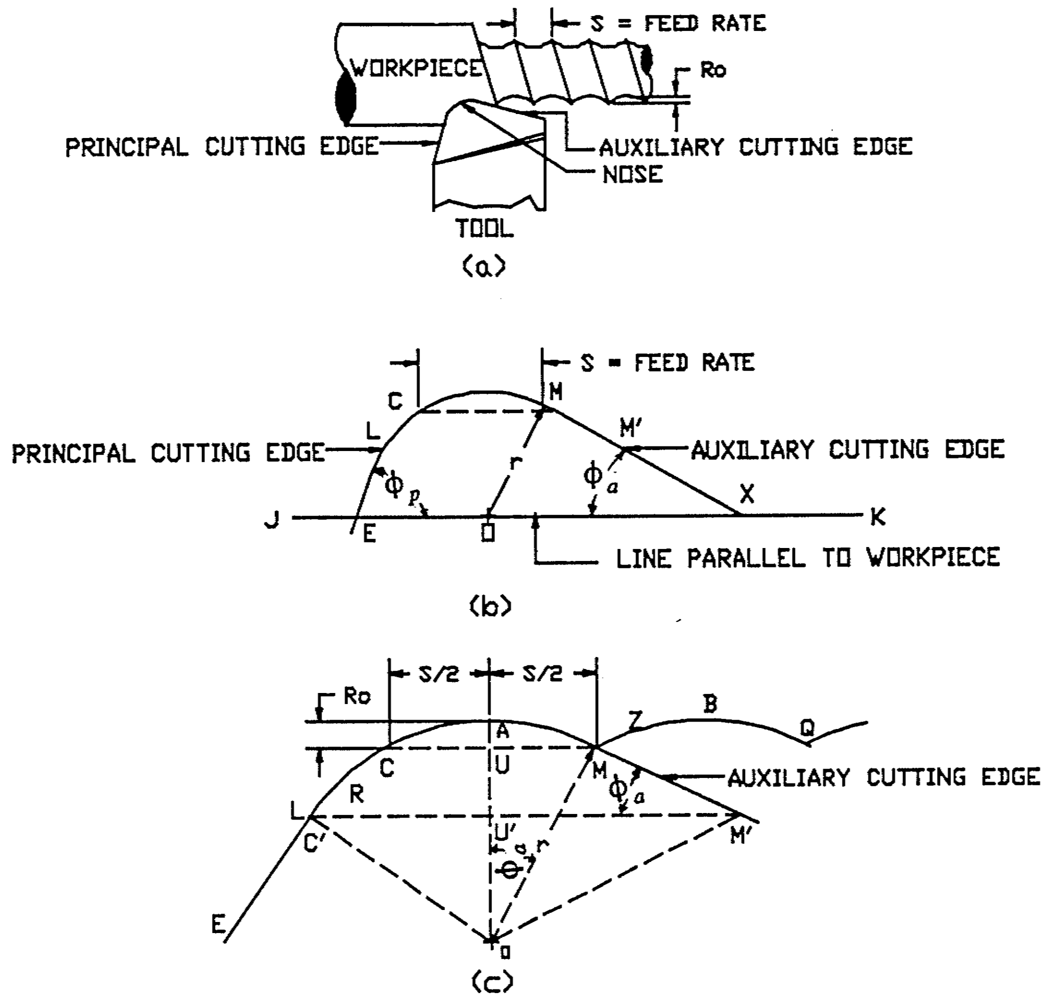


Fig.4.1 Showing (a) the characteristic ridges formed by a tool bit; (b) a magnified tool nose and (c) its effect on the ridges.

gives a further enlargement of Fig.4.1(b). The tool bit in Fig.4.1(c) is shown at two positions which are separated by a distance equivalent to the distance moved by the tool in the feed direction during one revolution of the spindle. In other words, arcs CAM and MZBQ correspond to two magnified consecutive ridges formed by the tool in Fig.4.1(a). Points E, L, C, M, M' and O in Figs.4.1(b) and 4.1(c) correspond.

In finish turning the feed rate as well as the depth of cut is smaller than that in rough turning and the curved nose as well as a portion of the principal cutting edge are in contact with the workpiece [Bhattacharya, 1984]. It can be shown straightforwardly from the geometry presented in Fig.4.1(c) and Pythagorus's theorem that the peak-to-valley distance of the characteristic ridges formed in finish turning is given by

$$R_0 = OA - OU = r - [r^2 - (s/2)^2]^{1/2}. \qquad (1)$$

Now point M is defined in Fig.4.1(c) as the point at which two consecutive valleys in the machined profile intersect so that equation (1) is valid as long as UC=UM=s/2. However, arc CAM in Fig.4.1(c) is the only section of C'CAMM' which is symmetrical about point A because MM', unlike the curve C'C, is a line. Therefore, the relationship UC=UM requires that point M be on the arc LCAM. This condition implies, in turn, that UM must be less than $r\sin\phi_a$ or, in other words, $s<2r\sin\phi_a$. The maximum recommended value of ϕ_a

is 30° so that $s/r<2\sin 30°$ i.e $s/r<1$ [Shaw, 1965]. Shaw developed a more practically orientated but complex formula than equation (1) for R_0. However, differences between the two are insignificant, from a practical viewpoint, providing the feed rate, s, is restricted by

$$s < 4r\sin\phi_a . \quad (2)$$

Inequality (2) provides a sufficiently wide range of feed rates for finish turning [Shaw, 1965] and the simpler equation (1) is preferred to the complex formula.

Considering that the tool tip is an arc of a circle and the depth of cut is less than the nose radius in finish turning , then the feedrate, which is a chord of that circle, should be less than twice the nose radius. If the feed rate is greater than twice the nose radius then thread cutting would be performed rather than finish turning. The same requirement can be obtained from relation (2) when the maximum recommended value of ϕ_a i.e 30° is substituted in that relation.

The peak-to-valley distance, R_0, of a surface machined by a new tool is illustrated in Fig.4.1(c) and it is reproduced in Fig.4.2(a) together with the total peak-to-valley distance produced by a worn tool (known conventionally as R_{max}). Points L, C, A, M, Z, B and Q in Fig.4.1(c) and 4.2(a) correspond. The dotted arcs NGJ and JFP shown in Fig.4.2(a), which represent a profile originating from a worn tool, are assumed to be merely off-set from the solid

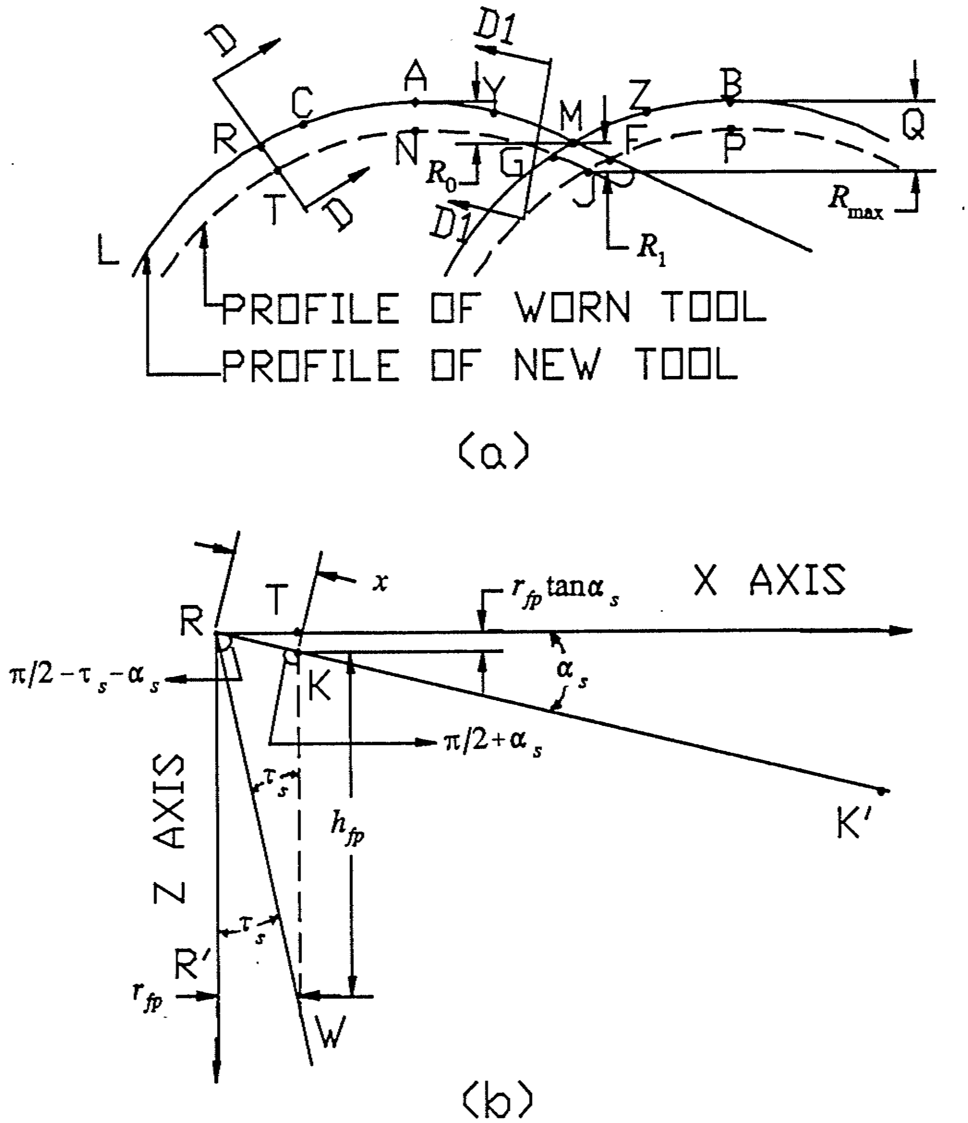


Fig.4.2 Illustrating (a) new and worn tool profiles, and (b) the elevation view of the flank wear at section DD shown in (a).

arcs AMF and GMB which indicate the profile which would have been produced by a new tool. As the tool wear grows, the new and worn tool profiles simply separate further. This enlarged separation causes an increase in the distance between points M and J which is synonymous to a growth in the peak-to-valley distance due to tool wear, R_1. Hence, more tool wear enhances the peak-to-valley distance due to tool wear, R_1, but machined profiles are always assumed to remain parallel.

The effect of change in the nose radius on the maximum peak-to-valley distance is incorporated in R_1 so that R_0 can be reasonably assumed to remain constant with progressive tool wear. On the other hand, the surface roughness also increases with tool wear i.e the maximum peak-to-valley distance, R_{max}, grows [Mori, 1985].

The R_{max} could be expressed, intuitively, as a product or sum of R_0 and R_1. If R_{max} takes the form $(R_0)^x(R_1)^y$ then the sum of the exponents, x+y, must be unity for dimensional consistency. Moreover, x and y must both be positive because R_{max} increases with larger R_0 and greater R_1. However, R_1 is zero for a (new) tool having no flank wear so that the assumption of a product would lead to a zero R_{max}. This conclusion can not be true because R_{max} must have a value at least equal to the non-zero R_0 provided by a new tool. To avoid this contradiction, the simplest form of R_{max} must correspond to the sum of R_0 and

R_1, i.e

$$R_{max}=R_0+R_1. \quad (3)$$

The detailed geometrical derivation of R_1 is given in the Appendix in terms of the tool's geometry and wear by using the following assumptions.

(i) The worn nose profile is assumed to be parallel, in plan view, to the original profile.

(ii) The arcs in a fresh and a worn tool nose profile which join the cutting edges to the tool tip are assumed to be straight lines i.e. arcs AMF, GMB, NGJ and JFP shown in Fig.4.2(a) are each idealized as a line.

Both assumptions are reasonable because all the arcs AMF, GMB, NGJ and JFP are less than a fraction of a millimetre and will cause an insignificant error in the calculation of R_1. The first assumption, however, requires that there should be no tool chippage, breakage or opening of crater wear which may dramatically change the tool nose's profile.

The major result derived in the Appendix for R_1 is that

$$R_1=r_{fp}\sin\phi_p+r_{fa}\sin\phi_a \quad (4)$$

where r_{fp} and r_{fa} are the wear, in the plan view, on the principal and auxiliary cutting edges, respectively. In addition, the total peak-to-valley distance of the machined surface, which is obtained by combining equations (1), (3) and (4), is given by

$$R_{max}=r-(r^2-(s/2)^2)^{1/2}+r_{fp}\sin\phi_a+r_{fa}\sin\phi_p. \tag{5}$$

The above equation can be simplified if the wear in the plan view of the auxiliary cutting edge, r_{fa}, is expressed in terms of the wear on the principal cutting edge, r_{fp}. The r_{fp} can be computed once the flank wear, h_{fp}, is measured in the elevation view. The flank wear can be shown to depend upon the chip velocity which, in turn, is a function of the feed rate, s, depth of cut, d, and principal cutting edge angle, ϕ_p. The chip velocity is defined as the relative velocity between the chips and the rake face of the tool.

Previous researchers [Rozenberg,1956] have reasonably assumed that the ratio of the chip velocity at the auxiliary cutting edge, V_a, to that at the principal cutting edge, V_p, is given, in restricted cutting, by

$$\frac{V_a}{V_p}=\frac{s\sin\phi_p}{2d}. \tag{6}$$

If it is assumed that continuous chips are formed, then it is reasonable to assume that the chip's velocity is proportional to the cutting velocity. Moreover, the length of the flank wear in the elevation view of the principal cutting edge, h_{fp}, is also proportional to the cutting velocity [Davies,1957]. Consequently, the wear on the flank of the cutting edge, in elevation, is proportional to the chip velocity on that edge. Hence the ratio of the flank wear on the auxiliary cutting edge to that on the principal cutting edge, h_{fa}/h_{fp}, is equivalent to the ratio of the chip velocities, V_a/V_p, at the two cutting edges. Therefore

$$\frac{h_{fa}}{h_{fp}} = \frac{s \sin\phi_p}{2d}. \tag{7}$$

The ratio of the wear on the two cutting edges in plan view, r_{fa}/r_{fp}, can be expressed in terms of the ratio of the height of the flank wear, h_{fa}/h_{fp}, and the tool bit's geometry. Hence r_{fa} can be found in terms of r_{fp} and known parameters and the resulting expression would simplify equation (5).

The wear in the plan view of the principal cutting edge, r_{fp}, has been shown to be related geometrically to the height of the flank wear, h_{fp}, and the tool bit's geometry [Bhattacharya,1984]. A similar relationship can be developed between h_{fa} and r_{fa} which allows h_{fa}/h_{fp} to be expressed in terms of r_{fa}/r_{fp}. The relationship between the flank wear on the principal cutting edge in the elevation view, h_{fp}, and that in the plan view, r_{fp}, will be derived by using Fig.4.2(b). Fig.4.2(b) depicts the cross section DD at the principal cutting edge of the tool shown in Fig.4.2(a). Points R and T in Figs.4.2(a) and 4.2(b) correspond. If the X axis is aligned towards the center of the arc RCAYM of the nose illustrated in Fig.4.2(a) and the Z axis points into the paper, then WRK and WKK' in Fig.4.2(b) represent a new and a worn tool's profile shown in elevation. In other words, triangle RKW in Fig.4.2(b) is the sectional representation of the wear on the principal cutting edge. The line RT, conversely, corresponds to the wear on the principal cutting edge in plan view, i.e r_{fp}. Line KW, which represents the front end of a worn tool, is parallel to the Z axis. This implies that angle RWK equals angle R'RW which is the side relief angle, τ_s, and that angle TRK equals the side rake angle, α_s. (To obtain a clearer perspective, refer to the side relief angle and the side rake angle in the side view of the tool depicted in Fig.3.1.) Angle R'RT in Fig.4.2(b) equals $\pi/2$, so that angle WRK equals $\pi/2-\alpha_s -\tau_s$. By using the fact that the sum of three angles in a triangle is equal to π, it is evident that angle RKW is $\pi/2 + \alpha_s$ because the sum of other two angles WRK and RKW is $\pi/2 - \alpha_s$. Let x be the distance between points R and K in Fig.4.2(b), so that, by applying the sine rule to triangle RKW, it can be seen that

$$\frac{h_{fp}}{\sin(90-\alpha_s-\tau_s)}=\frac{x}{\sin\tau_s} \tag{8}$$

and

$$r_{fp}=x\cos\alpha_s. \tag{9}$$

By eliminating x from the last two equations, r_{fp} can be found to be

$$r_{fp}=\frac{h_{fp}\tan\tau_s}{[1-\tan\tau_s\tan\alpha_s]}. \tag{10}$$

Similarly, the wear of the auxiliary cutting edge in the plan view, r_{fa}, can be expressed in terms of the wear in the elevation view, h_{fa}, by taking a cross section across the auxiliary cutting edge along the line D1D1 shown in Fig.4.2(a). This cross section corresponds to the elevation view of the tool in Fig.3.1 whereas section DD corresponded to side view of the tool in Fig 3.1. In other words the cross sections at DD and D1D1 would look alike except that the side rake angle, α_s, and the side relief angle, τ_s, in section DD would become the back rake angle, α_{s1}, and the end relief angle, τ_{s1}, in section D1D1, respectively. Therefore, to establish the relationship between r_{fa} and h_{fa}, the angles α_s and τ_s in the above equation can be replaced by α_{s1} and τ_s. Hence

$$r_{fa} = \frac{h_{fa} \tan\tau_{s1}}{[1 - \tan\tau_{s1}\tan\alpha_{s1}]}. \tag{11}$$

By dividing equation (11) by equation (10), the ratio r_{fa}/r_{fp} can be determined to be

$$\frac{r_{fa}}{r_{fp}} = \frac{h_{fa}\tan\tau_{s1}[1 - \tan\tau_s\tan\alpha_s]}{h_{fp}\tan\tau_s[1 - \tan\tau_{s1}\tan\alpha_{s1}]}. \tag{12}$$

Now equations (7) and (12) can be employed to express r_{fa} in terms of r_{fp}, or

$$r_{fa} = \frac{s\, r_{fp}\, k \sin\phi_p}{2d} \tag{13}$$

where

$$k = \frac{\tan\tau_{s1}[1 - \tan\tau_s \tan\alpha_s]}{\tan\tau_s[1 - \tan\tau_{s1}\tan\alpha_{s1}]} . \tag{14}$$

By using equations (13) and (14) to eliminate r_{fa} from equation(5), R_{max} can be shown to be

$$R_{max} = r - [r^2 - (s/2)^2]^{1/2} + r_{fp}[\frac{sk\sin^2\phi_p}{2d} + \sin\phi_a]. \tag{15}$$

Substituting r_{fp} and k obtained from equations (10) and (14), respectively, into equation (15) and simplifying produces

$$R_{max} = r - [r^2 - (s/2)^2]^{1/2} + h_{fp}[\frac{s\tan\tau_{s1}\sin^2\phi_p}{2d[1 - \tan\tau_{s1}\tan\alpha_{s1}]} + \frac{\sin\phi_a \tan\tau_s}{[1 - \tan\tau_s \tan\alpha_s]}]. \tag{16}$$

Equation (16) gives the total peak-to-valley distance of a machined surface which is expressed in terms of the known tool geometry, nose radius and feed rate as well as the predictable flank wear. In the case of no tool wear, h_{fp} equals zero and equation (16) degenerates to equation (1) in which tool wear is neglected.

CHAPTER 5. RESULTS AND DISCUSSIONS

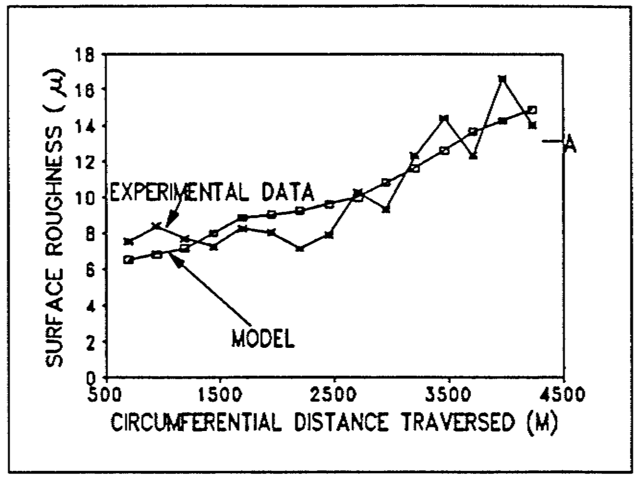
A tool bit's flank wear on its principal cutting edge was obtained from the magnified photographs. The flank wear, tool geometry, depth of cut and feed rate were used in equation (16) to obtain the surface roughness for all the three cutting tests mentioned in section 2.5. The predicted surface roughnesses correlate quite well with the experimental data shown in Fig.5.1. The model tends to underestimate the experimental roughness due to the presence of inherent microcracks in the workpiece which could have been formed in the heat treatment. Moreover, the continuous chips created during turning also spoil the surface finish when they come into contact with the finished surface. However, this contact can be avoided by using a chip breaker, but chip breaker was not used in the experiments performed. The model underestimates surface roughness for the second cutting test as shown in Fig.5.1 (b). The reason for this behaviour is unknown, However, by performing further tests at different conditions the cause of the behaviour, if any, could be known. For the sake of comparison, the surface roughness predicted by the two most accurate previous models [Jang,1989; Hasegawa,1976] are just horizontal lines through point A in Fig.5.1. Such lines correlate poorly with the experimental data.

Tool breakage is a brittle fracture occurring at the rake face at a distance from the tool tip where the temperature is lower than at the tool tip [Tlusty, 1978]. Due to tool breakage, the tip of the tool becomes effectively flat.

(a) First Cutting Test

Cutting Velocity 114 m/min

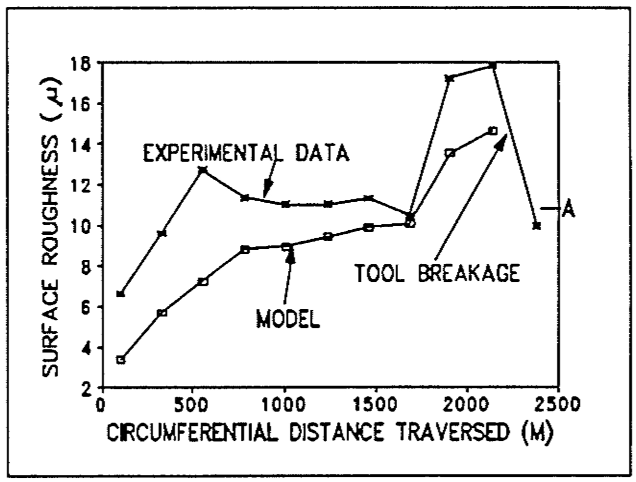
Feed rate 0.06 mm/rev



(b) Second Cutting Test

Cutting Velocity 175 m/min

Feed rate 0.06 mm/rev



(c) Third Cutting Test

Cutting Velocity 175 m/min

Feed rate 0.09 mm/rev

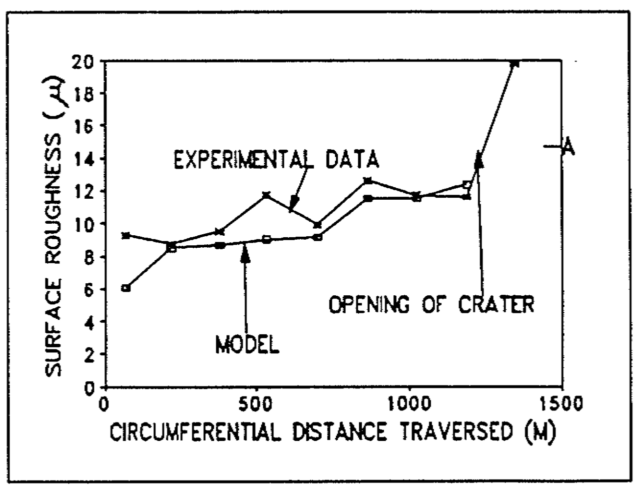


Fig.5.1 Experimental and predicted surface roughness.

Consequently the cutting edge angles, ϕ_p and ϕ_a, as well as the clearance angles, τ_s and τ_{s1}, become almost zero. This change has the effect of drastically reducing the second term in equation (16) which implies, in turn, that there would be an improvement in the surface finish after tool breakage. Indeed, Fig.5.1(b) shows that the surface finish did improve after tool breakage. Furthermore, it can be observed from Fig.5.1(c) that the opening of a crater at a circumferential distance of about 1200 m led to a rapid deterioration of the machined surface similar to that reported by Pekalharing [Pekalharing, 1963].

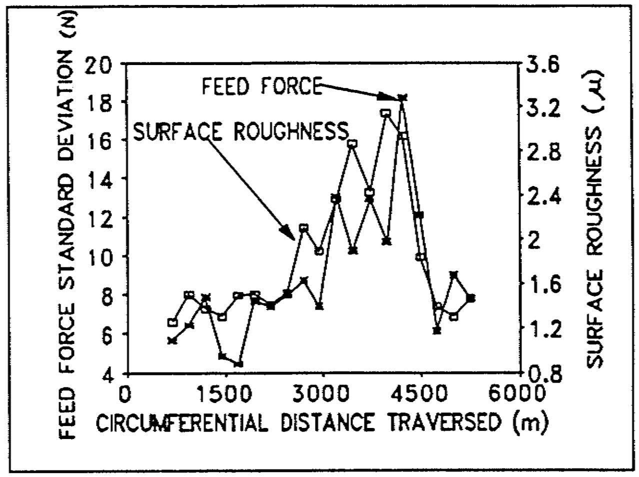
Fig 5.2 suggests that the standard deviation of the feed force appears to correlate well (correlation coefficient of 0.76) with the workpiece's surface roughness. Higher fluctuations in the feed force seem to lead to a tool's greater displacement in the feed direction. This dynamic displacement produces wider feed marks on the workpiece which give a higher surface roughness. This observation suggests that the rigidity of the machine tool in the feed direction plays an important role in the surface finish.

Figs 5.3, 5.4, 5.5 and 5.6 show a slowly increasing tangential force, feed force, motor current, spindle speed change and flank wear. This common trend, as well as the correlation coefficients presented in Table 2.1, suggests that the tangential force, feed force, motor current and spindle speed change could be useful indicators of tool wear. The effect of tool wear on the cutting force and

(a) First Cutting Test

Cutting Velocity 114 m/min

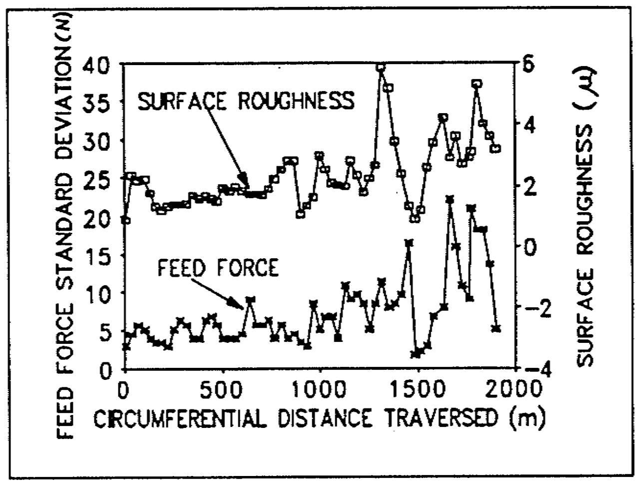
Feed rate 0.06 mm/rev



(b) Second Cutting Test

Cutting Velocity 175 m/min

Feed rate 0.06 mm/rev



(c) Third Cutting Test

Cutting Velocity 175 m/min

Feed rate 0.09 mm/rev

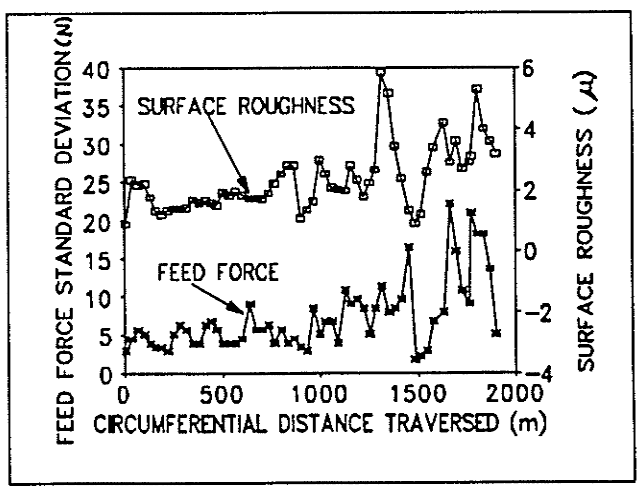
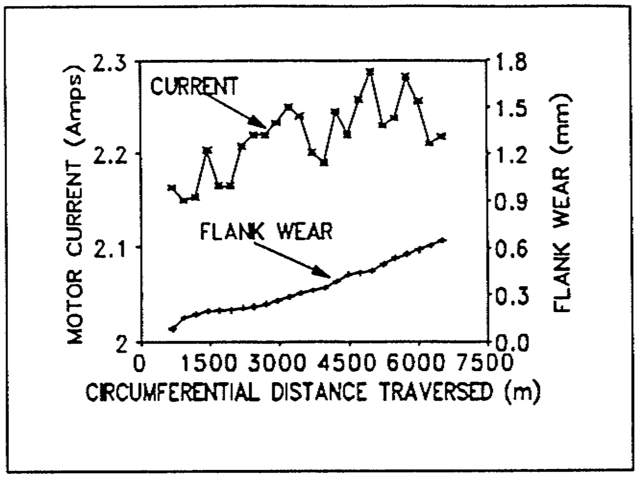


Fig.5.2 Standard deviation of feed force and surface roughness.

(a) First Cutting Test

Cutting Velocity 114 m/min

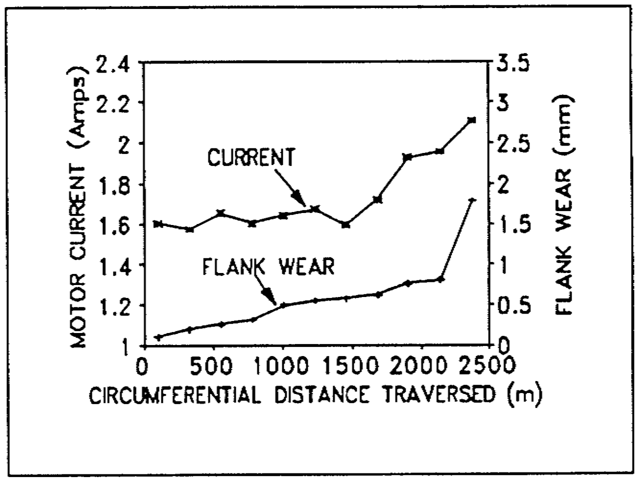
Feed rate 0.06 mm/rev



(b) Second Cutting Test

Cutting Velocity 175 m/min

Feed rate 0.06 mm/rev



(c) Third Cutting Test

Cutting Velocity 175 m/min

Feed rate 0.09 mm/rev

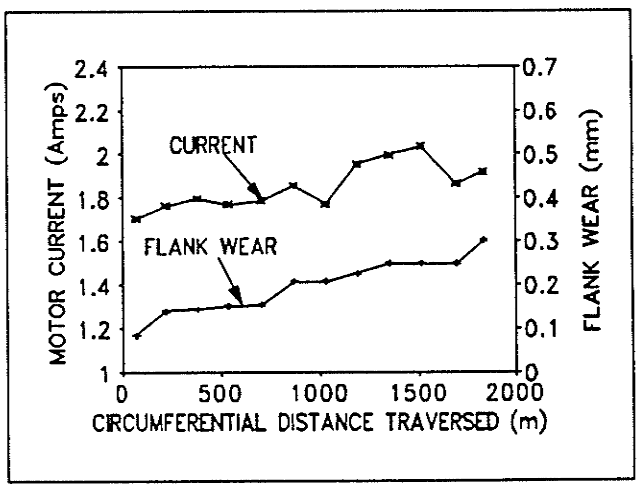
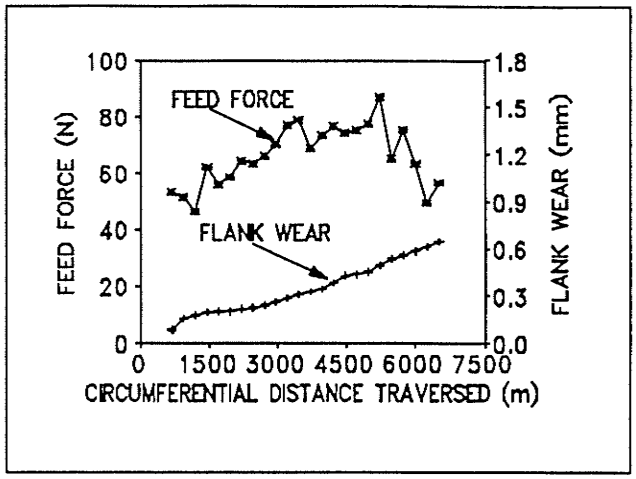


Fig.5.3 Motor current and flank wear.

(a) First Cutting Test

Cutting Velocity 114 m/min

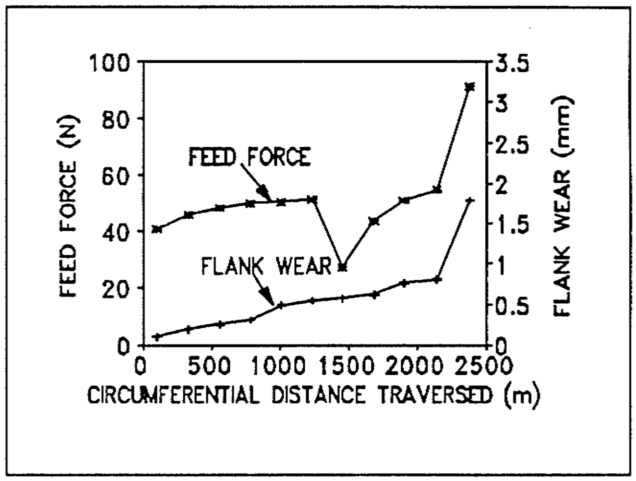
Feed rate 0.06 mm/rev



(b) Second Cutting Test

Cutting Velocity 175 m/min

Feed rate 0.06 mm/rev



(c) Third Cutting Test

Cutting Velocity 175 m/min

Feed rate 0.09 mm/rev

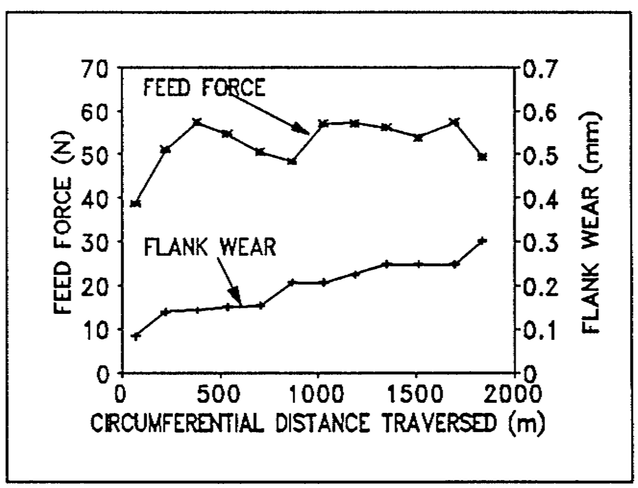
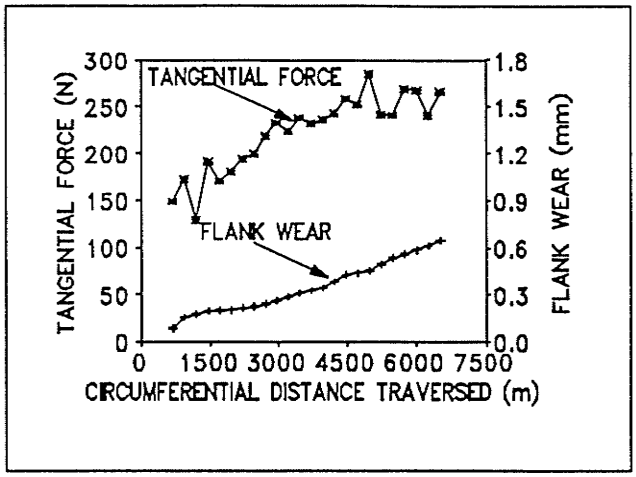


Fig.5.4 Feed force and flank wear.

(a) First Cutting Test

Cutting Velocity 114 m/min

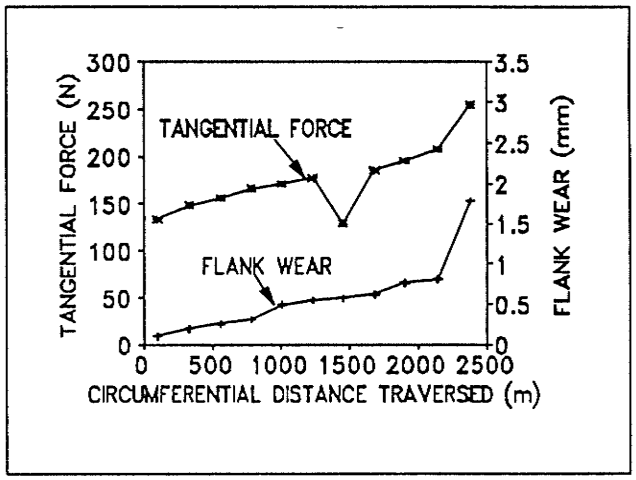
Feed rate 0.06 mm/rev



(b) Second Cutting Test

Cutting Velocity 175 m/min

Feed rate 0.06 mm/rev



(c) Third Cutting Test

Cutting Velocity 175 m/min

Feed rate 0.09 mm/rev

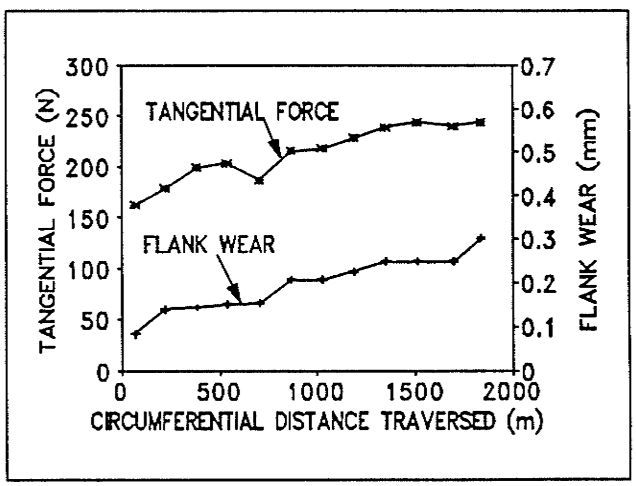
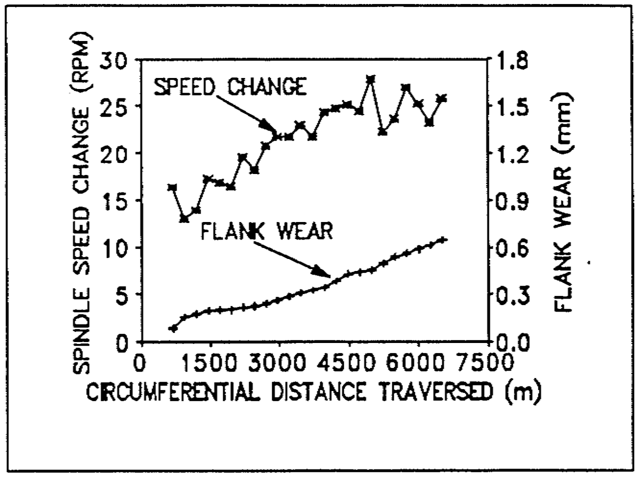


Fig.5.5 Tangential force and flank wear.

(a) First Cutting Test

Cutting Velocity 114 m/min

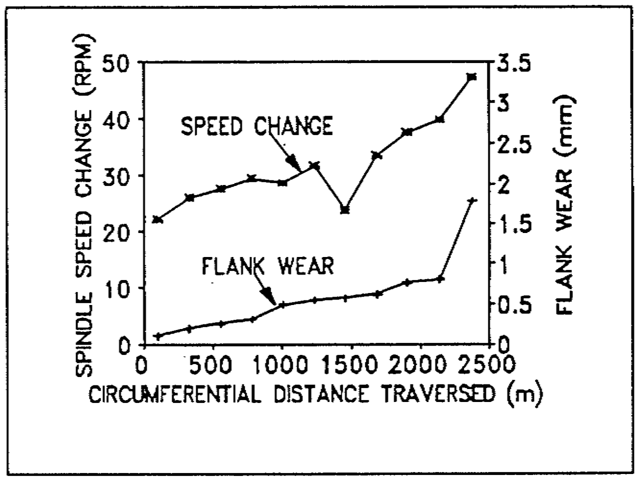
Feed rate 0.06 mm/rev



(b) Second Cutting Test

Cutting Velocity 175 m/min

Feed rate 0.06 mm/rev



(c) Third Cutting Test

Cutting Velocity 175 m/min

Feed rate 0.09 mm/rev

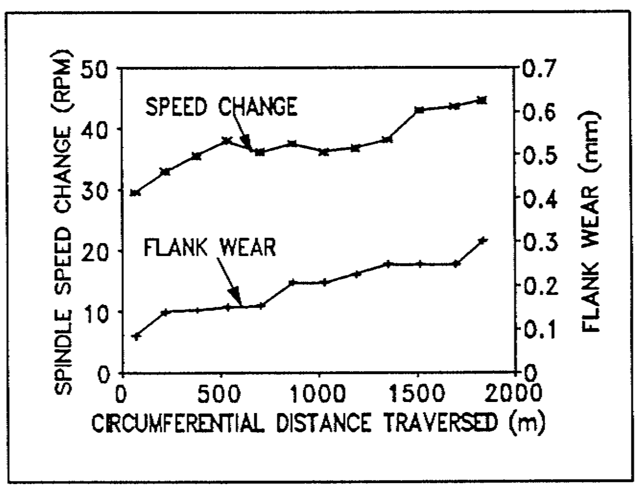


Fig.5.6 Change in spindle speed and flank wear.

the motor current has been reported previously [Lee, 1989; Giusti, 1987; Maeda, 1987; Reif, 1986; Tseng 1979]. However, the motor current is relatively insensitive to tool wear compared to the cutting force components and the change in spindle speed. On the other hand, the measurement of the cutting forces requires an expensive force dynamometer whose use is inconvenient in industrial applications. A change in the spindle speed, conversely, can be found by using a cheap precision optical encoder and custom designed electronics. Such a device is located away from the cutting process so that it is potentially much more useful.

CHAPTER 6. CONCLUSIONS

A predictive model of surface roughness has been developed based on a tool's geometry, and nose radius, as well as the feed rate and flank wear. Its predictions show good correlation with actual roughness measurements. The model requires that there should be no built up edge formation which is appropriate to finish turning. In addition, it assumes that continuous chips should be formed which requires the workpiece's material to be ductile. An on-line algorithm, which utilizes the model, can be implemented to quickly predict the surface roughness. By employing an adaptive control strategy, the model can also be used to adjust the feed rate on-line to achieve a desired surface roughness with a worn tool at the highest possible feed rate or minimum time. The good correlation observed between the flank wear and spindle speed changes suggests that these changes can be used on-line for predicting the tool wear.

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APPENDIX

The objective of this Appendix is to find the total peak-to-valley distance of a machined surface, R_{max}, in terms of known parameters. According to equation (3) of the main text, R_{max} is simply the sum of R_0 and R_1 where R_0 is given by equation (1). Hence only R_1, the peak-to-valley distance caused by the tool wear alone, needs to be determined here.

Fig.A.1 depicts the offset arcs AMF, GMB, NGJ and JFP of Fig.4.2(a) as parallel lines. It can be seen from this figure that R_1 =IH =IF + FH. Now the MF and MG also shown in Fig.A.1 are the wear on the principal and auxiliary cutting edges in plan view, r_{fp}, and r_{fa}. Lines GJ and MG are parallel to MF and JF, respectively. Therefore, MGJF is a parallelogram so that MG equals JF. Moreover, lines GB and M_2M_1 are parallel to lines JP and IK and, hence, $\angle M_2MG=\angle JFI=\pi/2-\phi_p$. From Fig.A.1, $IF=JF\cos(\pi/2-\phi_p)=JF\sin\phi_p=MG\sin\phi_p$ and $FH=MF\sin\phi_a$. Consequently, the peak-to-valley distance due to tool wear, R_1, is simply equal to $IH=IF+FH=MG\sin\phi_p + MF\sin\phi_a$. However, it can be seen from the figure that the wear on the auxiliary cutting edge, in plan view, is the distance between the new and worn auxiliary cutting edges (i.e MG which equals r_{fa}). Similarly, the wear on the principal cutting edge is the distance between the new and worn principal cutting edges (i.e MF which equals r_{fp}). Hence,

$$R_1= r_{fp}\sin\phi_p + r_{fa}\sin\phi_a$$

which corresponds to equation (4) of the main text.

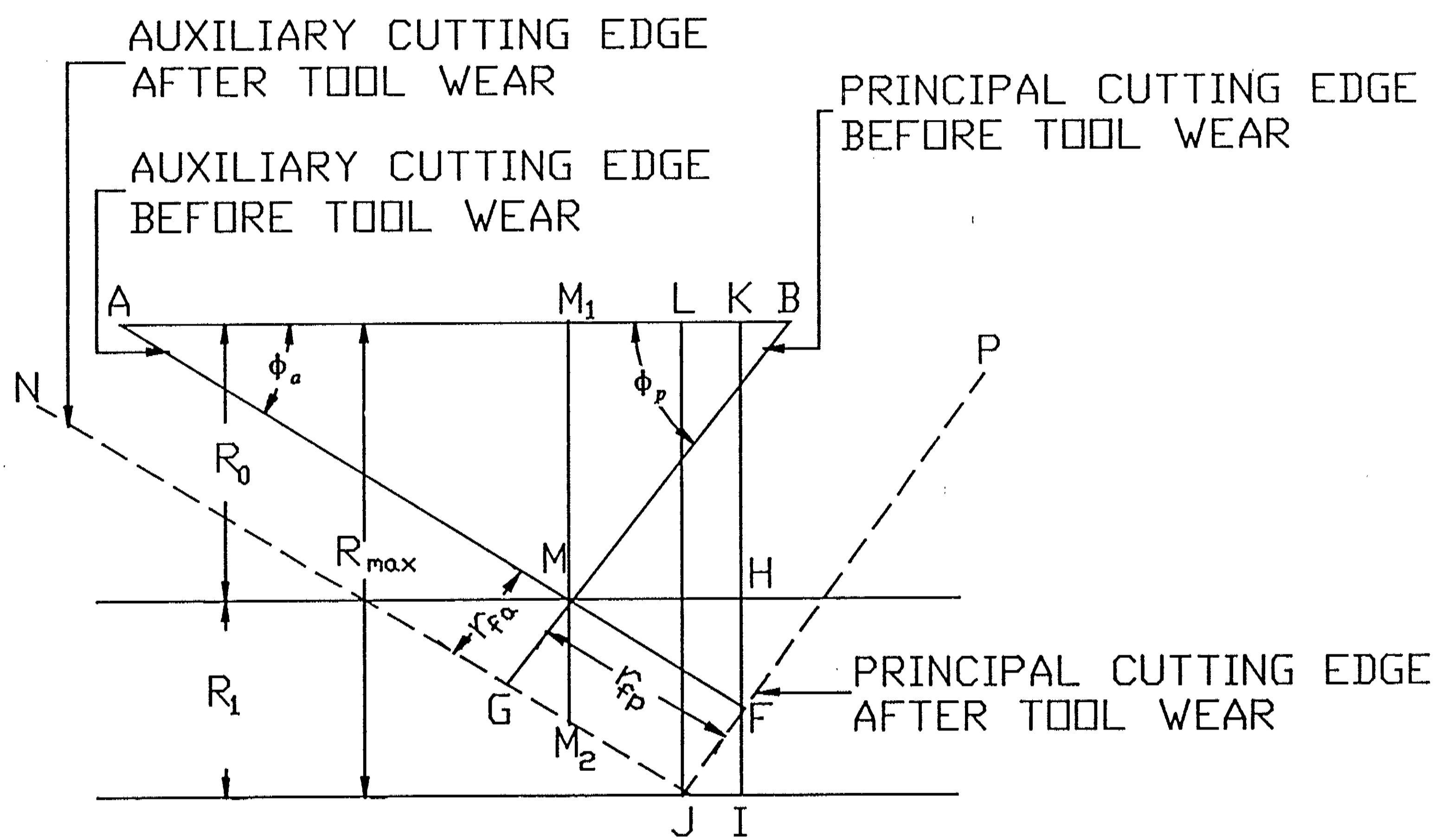

Fig.A.1 Geometrical representation of the peak-to-valley distance due to tool wear.