ABSTRACT

ANALYSIS OF SURFACE TEXTURE PARAMETERS AND CUTTING FORCES IN MILLING OPERATIONS.

by
Preetesh U. Munshi

It has been known and understood that milling is quite a complicated process being a multi-point cutting tool operation. Each Surface texture is complex and requires different functions of forces to get the optimized Surface Texture. The challenge faced here is to devise any form of relation between the Surface Texture and the Milling Operating parameters (Spindle Speed, Feed rate, Depth of Cut), Cutting forces and the Milling Operating parameters and also between the Surface Texture and the Cutting Forces.

This Research study was conducted to determine the effect of the Operating Parameters on Surface Texture and Cutting forces and empirical relationships have been established between the Surface Texture and Operating parameters, The Cutting forces and Operating parameters and Surface Texture and Operating parameters.

Thus, the outcome of the research is to determine the optimal cutting conditions and by controlling the operating parameters, accordingly, better surface quality in milling operations can be attained.

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by
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ANALYSIS OF SURFACE TEXTURE PARAMETERS AND CUTTING FORCES IN MILLING OPERATIONS

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To my dear parents, brother and wife

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CHAPTER 1

INTRODUCTION

1.1 Background Information

It is well known that milling is quite a complicated process being a multi-point cutting tool operation. The process of cutting metals by milling operation develops stochastic cutting forces which ultimately result into variable surface roughness. In the machining industry it is of great importance to have the knowledge of Surface Texture or the Surface Finish that would be obtained by using a particular cutting operation.

Due to the stochastic nature of the cutting forces and Surface Texture it would be difficult to choose a machining operation for a particular component. This may result into unexpected and undesired tool failure which obviously needs to be avoided. In order to ensure system reliability and improve the productivity in an automated manufacturing environment it is necessary to implement sensing and corrective devices that can detect and correct the system malfunctions.

Over the last decade, researchers have put their efforts into on-line monitoring of the machining process, especially the recognition of tool breakage, because of the rapid development of computer integrated manufacturing systems and sensor based machining processes. One of the most important requirements is to obtain a relationship between the Surface Texture and Operating Parameters in the Milling operation. This would lead to developing a relationship between the cutting process parameters (spindle speed, feed rate, depth of cut) and the Surface texture parameters. These relationships are important in developing analytical models for cutting process monitoring. At the same time this research also develops a relation between the Cutting Forces and Operating parameters and thereby determine the relationship between the Surface Texture and Cutting Forces.

CHAPTER 2

LITERATURE REVIEW

In the interest of maximizing the metal removal rate and preventing tool breakage **L.K.Lauderbaugh and U.G.Ulsoy [1]** have conducted Research work on Fixed Gain Feedback Controllers which manipulate the feed rate to maintain a constant cutting force. These process controllers have resulted in substantial improvements in the metal removal rate but may have poor performance when the process parameters deviate from the design conditions. They have also presented an empirical second order model of force response for a milling system to feed rate changes along with experimental results. These results show that the parameters of the model vary significantly with cutting conditions.

In their paper by **Y Atlintas and Yelloley [4]**, the authors have shown that by force averaging over a tooth period and then differentiating twice, tool damage may be identified and normal transients may be ignored. The authors have shown that force averaging and normalized differencing form a suitable base for practical tool breakage detection algorithm.

In their paper **L.K. Lauderbaugh and A.G. Ulsoy [8]** describe the design and implementation of a model reference adaptive controller for force controlling in milling, the adaptive controller was found to be performing more effectively than the fixed gain controller but it is difficult to implement and tune because of the unmodelled dynamics or measurement noise resulting from runout on the milling cutter.

The researchers, **Ismail and F. Albestawi [7]** generated a mechanic model for Surface generation in peripheral milling that includes the effect of cutter runout and flank wear. The surface roughness parameters and characteristic features of the Surface Profile were examined by using Computer Simulation. The trend towards unattended manufacturing emphasized the need for sensing the variables in process that could affect the state of cutting force and Surface finish. The new trend brought the usage of Adaptive Control Technology and On -Line monitoring. The adaptive control denotes whereas the Numerical Control determines the proper speeds and/or the proper feed rates during the milling process as a function of , factors such as work material hardness, depth of cut, spindle speed. With increasing focus on the development of the sensing techniques many researchers demonstrated their findings by using sensing and adaptive control technology.

Bobe [10] employed a method which describes the method for determining the natural frequencies and vibration modes of milling machines. the model combined a finite element model and an asymmetric stiffness matrix system.

According to **Fussel and Srinivas [11]**, Varying machining conditions are encountered in adaptively controlled machining situations where operating conditions such as feed rate and spindle speed are adjusted continuously to achieve desired objectives. The authors have evaluated the adequacy of the models available of the milling process mechanics for many cases of varying machining conditions including the change of depth of cut and feed rate (axial and radial)They have also evaluated the significance of dynamic effects in the milling process of effects such as run out for constraint type adaptive control system.

G.Chryssolouris and M.Guillot [12] presented an approach for the selection of a set of process parameters for use in machining control. The approach is aimed at providing a range of parameters within which machining operations can be optimized. Because of the complexity and somewhat unpredictable nature of the machining process the approach combines process modeling with rule based techniques. Modeling correlates process state variables such as surface roughness or chip merit mark to process parameters such as feed rate, cutting speed and tool rake angle. The modeling techniques considered in the paper include multiple regression analysis, group method of data handling and neural network. The authors concluded that a rule based system added the flexibility necessary to treat various cases of the machining process and considered the accuracy of the model. Even though this model has been developed with a particular intelligent controller scheme it is general enough to apply as a complement to other machining controllers (e.g. adaptive control constraint or optimization) or to standard machinability databases.

S.Smith and J.Tlusty [14] claim that it has been shown for many milling operations that it is desirable to set the tooth frequency equal to the natural frequency. At this spindle speed, the development of resonant forced vibration is actually inhibited by regeneration of waviness. The authors have presented an algorithm for automatically selecting the optimum spindle speed based on the cutting force signal. It was concluded by the authors that the optimum spindle speed for a milling operation is that speed where the tooth frequency is equal to the natural frequency.

N.K.Jha [15] claims that the production planning of milling operations in an important problem. It has been observed that if discrete settings of speed and feed are taken into account, production planning becomes more complex. A procedure has been suggested in the paper for such cases. The approach suggested looks most promising for adaptive control optimization. The objective of the adaptive controller is to optimize the index of performance such as cost per piece, material removal rate by manipulating the speed or feed to maintain the measured variables at or below their constraint limit values. Especially sensors will be developed to a level at which true process performance can be measured on-line.

In conclusion a considerable amount of research has been done in the area of unattended machining, milling operations and a lot of means have been devised to get the desired cutting forces and Surface Finish on the Milled Products. During the course of the literature survey it was observed that there was no work that showed the optimal cutting conditions in which the desired cutting force and the desired Surface Texture could be obtained using typical combinations of speed, feed and depth of cut. There was hardly any work done to determine the values of spindle speed, feed rate, depth of cut using which a particular surface finish or a particular cutting force could be obtained.

Therefore, the main objective of the Research work is to improve the surface Quality of any component that is being machined on an automated Milling Machine. In order to improve the Surface quality of the machined component it would be of great benefit if the expected Surface Quality that could be obtained by the machine would be known prior to the machining operation. In an open machining system it is very difficult to improve the surface quality, and hence the need of a system which would give the feedback to the Milling machine. It is necessary to derive models that would establish empirical relations giving us the values of the expected Surface Quality. This expected value can then be compared with the actual surface quality value obtained and then depending on the need corrective measures could be incorporated to obtain the desired Surface Quality Results. As mentioned earlier in the introduction and the limitations of the literature review the interest and the focus of the research being done is to develop empirical relations between

1) Surface Texture and Operating parameters (spindle speed, feed rate and depth of cut)

2) Cutting Forces and Operating parameters (spindle speed, feed rate and depth of cut)

3) Surface Texture Parameters and Cutting Force

By establishing these results it would be possible to predict the Surface Texture or the Cutting force that would be developed by using a particular combination of spindle speed, feed rate and depth of cut. Thus, we shall have the expected value of the Cutting Force and/or Surface Texture which could serve as a reference for the actual values that would be obtained after the machining is done.

Hence, by knowing prior to machining the combination of spindle speed, feed rate and depth of cut it would be possible to set the machining system at those particular values and obtain a Surface Texture that would be desirable. in addition to that , it would also be possible to develop an Adaptive Control system which would be capable of detecting the Surface texture and the Cutting force during the process of operation and be capable of taking preventive and/or corrective measures.

This research work would greatly contribute towards improving the quality and the productivity of the components being machined using an automated milling machining and it can also be extended to other similar machining operations.

CHAPTER 3

PROPOSED METHOD AND METHODOLOGY

3.1 Methodology

In order to achieve the goals of the research Work it is necessary to conduct a number of experiments so that enough data can be collected to derive mathematical relations and models. It is necessary to conduct experiments on the milling machine so that data can be collected on the different milling operating parameters. After these experiments have been performed and data collected it would be possible to formulate mathematical models. The results obtained from these mathematical models would be then used to analyze the data collected and present the findings, give suggestions and improvements.

3.2 Variations in Cutting Forces and Surface Finish

Milling is a process in which the material is cut using a multi point cutting tool, thus ,making the milling process a complicated process. This complicated process is controlled by various operating parameters like spindle speed, feed rate and depth of cut. This complicated milling process results in stochastic forces, which also result in stochastic surface finish. The milling process can generate a wide range of shapes and obtain different surface texture results. It can also give a high material removal rate. All these properties of a milling process give rise to variations in the cutting forces which ultimately vary the final surface quality result. The problems mentioned above are critical to study the behavior of the milling process. There are also many other factors that affect the cutting process. Hence, the surface finish, cutting forces and for that matter even tool wear are stochastic making it very difficult to predict the accuracy of these measures. Hence, the output of the cutting force varies from point to point and from one machine to another, even under the same operating conditions. It is of interest to examine the two applications that result from the stochastic milling process. One being, to identify the cutting conditions under different operating conditions and the other being able to examine the surface quality results due to the stochastic nature of the cutting force.

3.3 Design of Experiments

Experimental design is necessary to obtain reliable results. In this research, the validation of the models depends on the way the experiments were designed since the mathematical models of cutting force and Surface Texture will be formulated according to the experimental collected data.

In a milling process there are 3 control parameters that is the spindle speed, feed rate and depth of cut. These three variables can be selected to be the independent variables of the mathematical models of cutting force and surface roughness. A factorial design can be introduced for the formulation of the mathematical model. In a factorial design a fixed number of levels are selected for each of the number of variables and then experiments are run with all the possible combinations. If there are L1 variables for the first variable , L2 variables for the second variable , ... Lk variables for the Kth variable , the experimental run is called an L1 x L2 x .... x Lk factorial design. These designs are of importance for a number of reasons. they require relatively few runs per factor studied and although they are unable to explore fully a wide region in the factor space, they can indicate major trends and so determine a promising direction for further experimentation. these designs and the corresponding fractional designs may be used as building blocks so that the degree of the complexity of the finally constructed design can match the sophistication of the problem. The interpretation of the observations produced by the design can proceed largely by using common sense and elementary arithmetic.

LEVEL	Cutting Speed	Feed rate	Depth of cut
High	S_h	F_h	D_h
Central	S_c	F_{c1}, F_{c2}	D_c
Low	S_l	F_l	D_l

The advantages of the factorial experimentation naturally depend on the purpose that is to investigate the effects of each factor over some pre assigned range that is covered by the levels of that factors which are used in the experiment. If all the factors are independent in their effect the factorial effect will save a considerable time and material devoted to the experiment. When the factors are not independent the purpose then is to still investigate each factor over the range represented by its levels. When the factors are not independent, the simple effects of a factor vary according to the particular combination of other factors with which these are produced.

3.4 Methods, Set Up and Procedures

It is necessary to come up with a method and the procedure in which the experiments would be conducted to obtain the desirable results. Explained as follows is the proposed procedure to obtain the desired models and results. First of all an appropriate workpiece has to be selected on which the experiments could be performed. The workpiece can be placed on the load cell and fixed with the aid of a vice. The data acquisition board is kept ready and all the necessary information is entered to a proper software. After that the amplifier is set up after a warm up of a fixed amount of time. The CNC milling machine and the NC part program are kept ready. The data acquisition program is then actuated and the process is performed. If there is no overload signal the data is saved. The Surface finish of the workpiece is measured by the necessary instrument and the collected data is transferred to the Surface Finish software.

The cutting force varies due to the stochastic nature of the process at each moment of time and thereby it leads to the variation in the surface roughness every time. Thus the cutting forces were also to be recorded at the same time. In this research, a transducer was used for converting the vibrations of the cutting force to analog signals. A transducer is a device that converts one type of physical quantity such as temperature, force, velocity into another type, commonly an electrical voltage. The reason for making this conversion is that the converted signal can be used or evaluated more conveniently. Basically, there are two types of transducers, analog and digital. The analog transducers produce a continuos analog signal for e.g. an electrical voltage. in the research the transducer can be used to measure each separate component of the force at the same time. A force transducer will be used to measure the three orthogonal components of the cutting forces in arbitrary directions. The workpiece can be connected with 4 screws to the fixture and after every 4 experiments the workpiece can be changed to another one. The transducer has to be calibrated with the fixture as a perload.

A CNC machine can be used to perform the milling process. The machine that would be selected should have the three X, Y and Z axes and should be able to rotate in both the directions of rotation. A high speed processor would be required to increase the machine capability to use faster feedrates. These higher feedrates may be attained without emptying the machine buffer. There are also additional G and M code capabilities. The macro capabilities provides a programmer with full mathematical calculations within a program.

A mill can be used to perform the cutting operation. The cutters used should be constructed from a high speed steel matr. (HSS). First, the roughing operation is performed and then the finishing operation and the data has to be collected. For these experiments appropriate material of the workpiece should be selected so that it can be cut by the HSS cutter. Each experiment would consist of cutting in different directions. The total time for cutting should also be recorded for different combinations of the operating parameters which would help towards the analysis of all the data collected.

3.5 Data Collection

The most important part of the research work was the data collection. The data collection was divided into two parts. The first was the data collected for the different surface quality parameters and the second part was the data collected for the cutting forces.

The data that was collected for the Surface Quality had five different parameters: Rku, Ra, Rq, Rp and Rt. Fig. 3.1 shows the rough sketch of the profile of the Surface Quality parameters. The explanation of those parameters is as given below.

1) Rku - Kurtois provides a measure of the sharpness of the Surface Profile, a spiky surface has a high Rku and a bumpy surface has a low Rku value. Rsk which is the skew value cannot detect if the spikes on the profile are evenly distributed or not where as the Kurtois can, hence the Kurtois value is to be used.

Std K - The standard deviation of the sharpness of the surface profile.

S/N Rku - This is the Signal to noise ratio for the Rku value.

2) Ra - Ra is the parameter for roughness. It is the arithmetic mean of the departures of the roughness profile from the mean line.

3) Rq - Rq is the RMS parameter corresponding to Ra.

4) Rp - Rp is the maximum height of the profile above the mean line within the assessment length.

5) Rt - Rt is the maximum peak to valley height of the profile in the assessment length.

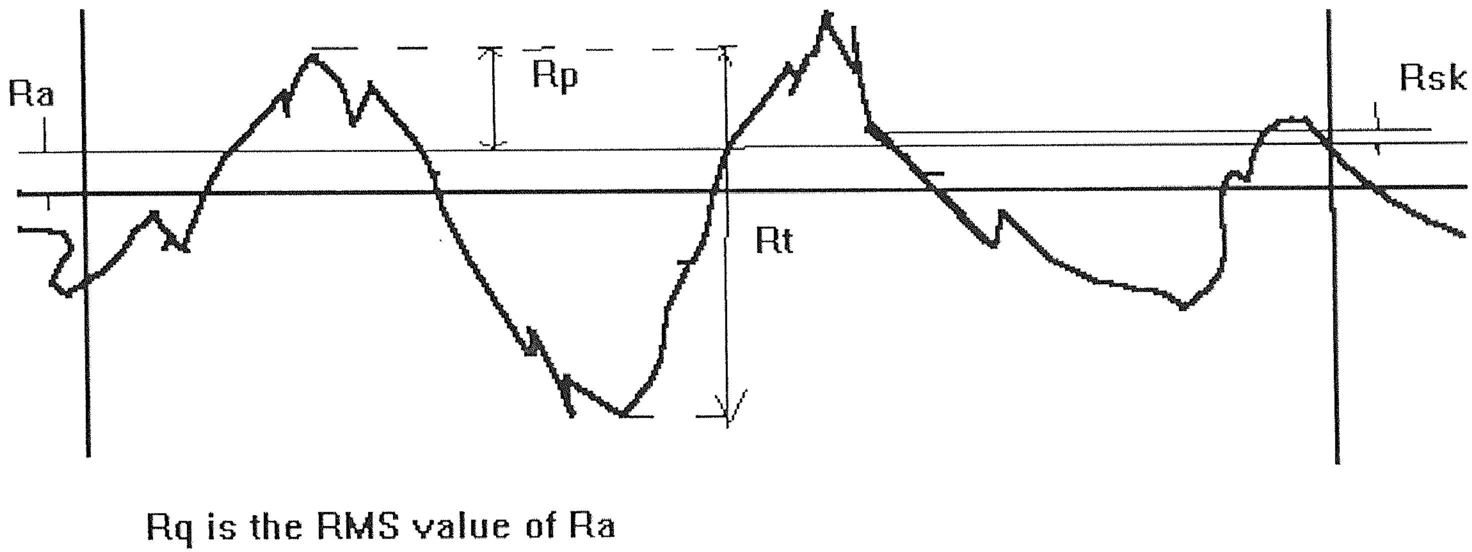


Fig 3.1 Profile of the Surface Quality Parameters

Each of the above parameters have their standard deviations and Signal to Noise Ratios.

The second part that is the cutting forces were just in the form of values of the cutting forces. These cutting forces were directly imported into the excel spreadsheet. These values were in the form of data files and there is a special feature in the excel spreadsheet that allows the user to convert data files into Excel spreadsheets. The data that will be obtained from the CNC machine software will be in the form of thousands of numbers. This data needed to be organized so that mathematical models could be derived.

3.6 Statistical Techniques Using Microsoft Excel

There was a large amount of data collected in the form of Surface Texture parameters and also cutting forces by directly reading it from the CNC machine. This data was stored as data files and was imported into the Microsoft Excel Software for its analysis. The cutting was done in three directions, the X, XY, and the Y. For each of the axis the data was sorted in the ascending order of the speed, feed and the depth of cut. The average, maximum, and the minimum of each of the parameters of the Surface Texture and the Cutting Forces were found out by using the inbuilt Statistical Formulae. For eg. the maximum of a particular range was found by the formula = max (range) , Similarly the minimum = min (range), and for the average = average (range). For the ease of use of Multiple Regression Analysis Technique the ln values for each of the Operating parameters, Surface Texture Parameters and the Cutting forces were found using ln (number). Their log std. deviations was also calculated to see how much do they deviate from the average value. These calculations were done for both the Surface Texture Parameters and Cutting Forces. The Signal to noise ratios were also found out using the appropriate formula from the formulae mentioned earlier. A list of the formulae that could be used from Microsoft Excel are shown in table 3.1.

3.7 Mathematical Models

After all the data was collected and now organized there were 36 values for each operating parameter for cutting in each of the directions X, XY, and Y. This data was now to be converted into a Mathematical model giving relationship between the Surface Texture and the Operating parameters of speed, feed and depth of cut and also between the cutting force and the operating parameter of speed, feed and depth of cut. The Multiple Linear Regression Software written in QBASIC was used for this purpose. Then relationship was also established between the Surface Texture parameter and the Cutting Force and a more advanced software called the Table Curve Software was used for the same.

3.8 Multiple Linear Regression Analysis Technique

The Multi-Linear Regression analysis was selected as it was the most adequate statistical technique. This statistical technique was used to establish the relationship between

1) Surface Texture (Rku, Ra, Rq, Rp, Rt) and Milling Operating

Parameters (Spindle speed, feed rate, depth of cut).

2) Cutting Forces (Fmax, Favg) and Milling Operating Parameter (Spindle speed, feed rate, depth of cut).

An explanation as to why the above model was used is as follows.

In any statistical model there are dependent variables and independent variables. In the Surface Texture model, the Rku value for e.g. is the dependent variable and the operating parameters of speed, feed and depth of cut are the independent variables. In the Cutting Force model, the Fmax value for e.g. is the dependent variable and the operating parameters of speed, feed and depth of cut are the independent variables.

The relationship between the dependent and the independent variables can be mathematically represented as follows:

$$Y_i = X_0 * X_1^{n1} * X_2^{n2} * X_3^{n3}$$

This non-linear relationship can then be written linearly as :

$$\ln (Y_i) = \ln (X_0) + n1 * \ln (X_1) + n2 * \ln (X_2) + n3 * \ln (X_3)$$

Using the Multiple Regression technique it becomes possible to determine the values of X_0, n1, n2, and n3. This is the statistical technique that is used to determine the equation of the line or the curve which minimizes the deviations between the observed data and the regression equation values. Since, there is more than one independent variable the Multiple Regression technique has been applied.

3.9 Analysis of Variances

After using the Multiple Regression Technique the models were established and the ANOVA i.e. Analysis of Variance has been performed to determine the adequacy of the models. The correlation coefficient and the F value are the main output of the ANOVA. The Correlation Coefficient is a measure of how well a specific regression equation explains the observed variation. Hence, Higher the R value better is the regression model. the F test is used to examine the adequacy of the model. The F value is the ratio of the regression sum of squares and the sum of squares error. Residual analysis is necessary to draw a conclusion about the regression model. Since all the above measures are based on the assumption of normality, the residual analysis is the tool to confirm this assumption. In this Research Standardized Residuals were calculated, the assumption of normality thus being confirmed. Thus using the above guidelines the model was developed and the relationships were established. It was now required to further establish a relationship between the Surface Texture and the Cutting Forces.

3.10 Curve Fitting Techniques

The table Curve software has been developed by Jandel Scientific. This software is ideally used when one has to determine the relation between two parameters, in which one is the dependent variable and the other is the independent variable. In the Research work this software has been used to develop relationship between the Surface Texture parameters and the Cutting Force parameters for cutting in the 3 directions of X, XY and Y. This software has a File Menu which allows us to import data from Excel and Lotus spreadsheets. The data can be imported directly, it can be imported after digital filtration or it can also be imported from a Clipboard which has been previously saved. Next it has the Edit Menu. This software has an Ascii Editor and also a table editor in which we can directly type in the numbers to obtain the relations. This software has a Table and the Calculate Menu which calculates the integral, differential, Bessels function and various other desired mathematical and algebraic calculations. Next it has a Process menu in which the selected data gets processed and the software comes up with a graph listing the equations and the graph that was desired, it has a variety of options for the type of fit desired.

For this purpose the Table Curve Software was utilized. In this research work the software imports the data from the clipboard of a spread sheet, reads it, analyzes the same and comes up with a graph for Best Fit and also gives the Best Fit Equation. It calculates the Correlation Coefficient and thus we can determine the adequacy of the model. This software has a limitation that it can take just two variables and establish the relation between the two of them. This is the reason why this software was not used for determining the relation between the Surface Texture, Cutting Forces and the milling Operating Parameters. To use the table curve software the entire data was put on the spread sheet, then the table curve software was made to import the Surface Texture and the Cutting Force values, one at a time and the graphs and the relations were established for each of the 36 values in each of the three directions for cutting (X, XY andY)

The data so transformed into mathematical models has to be analyzed and thereby conclusions can be made. With the help of the empirical relations obtained from these various softwares it would be possible to predict the nature of the cutting force and the value of the Surface Texture parameters before the cutting process would actually take place.

Table 3.1 List of formulae from Microsoft Excel

Statistical Functions

AVEDEV	Returns the average of the absolute deviations of data points from their mean
AVERAGE	Returns the average of its arguments
BETADIST	Returns the cumulative beta probability density function
BETAINV	Returns the inverse of the cumulative beta probability density function
BINOMDIST	Returns the individual term binomial distribution probability
CHIDIST	Returns the one-tailed probability of the chi-squared distribution
CHIINV	Returns the inverse of the one-tailed probability of the chi-squared distribution
CHITEST	Returns the test for independence
CONFIDENCE	Returns the confidence interval for a population mean
CORREL	Returns the correlation coefficient between two data sets
COUNT	Counts how many numbers are in the list of arguments
COUNTA	Counts how many values are in the list of arguments
COVAR	Returns covariance, the average of the products of paired deviations
CRITBINOM	Returns the smallest value for which the cumulative binomial distribution is less than or equal to a criterion value
DEVSQ	Returns the sum of squares of deviations
EXPONDIST	Returns the exponential distribution
FDIST	Returns the F probability distribution
FINV	Returns the inverse of the F probability distribution
FISHER	Returns the Fisher transformation
FISHERINV	Returns the inverse of the Fisher transformation
FORECAST	Returns a value along a linear trend
FREQUENCY	Returns a frequency distribution as a vertical array
FTEST	Returns the result of an F-test
GAMMADIST	Returns the gamma distribution
GAMMAINV	Returns the inverse of the gamma cumulative distribution
GAMMALN	Returns the natural logarithm of the gamma function, $\Gamma(x)$
GEOMEAN	Returns the geometric mean
GROWTH	Returns values along an exponential trend
HARMEAN	Returns the harmonic mean
HYPGEOMDIST	Returns the hypergeometric distribution
INTERCEPT	Returns the intercept of the linear regression line
KURT	Returns the kurtosis of a data set
LARGE	Returns the k-th largest value in a data set
LINEST	Returns the parameters of a linear trend
LOGEST	Returns the parameters of an exponential trend
LOGINV	Returns the inverse of the lognormal distribution
LOGNORMDIST	Returns the cumulative lognormal distribution
MAX	Returns the maximum value in a list of arguments
MEDIAN	Returns the median of the given numbers
MIN	Returns the minimum value in a list of arguments
MODE	Returns the most common value in a data set
NEGBINOMDIST	Returns the negative binomial distribution

Table 3.1
(Continued)

NORMDIST	Returns the normal cumulative distribution
NORMINV	Returns the inverse of the normal cumulative distribution
NORMSDIST	Returns the standard normal cumulative distribution
NORMSINV	Returns the inverse of the standard normal cumulative distribution
PEARSON	Returns the Pearson product moment correlation coefficient
PERCENTILE	Returns the k-th percentile of values in a range
PERCENTRANK	Returns the percentage rank of a value in a data set
PERMUT	Returns the number of permutations for a given number of objects
POISSON	Returns the Poisson distribution
PROB	Returns the probability that values in a range are between two limits
QUARTILE	Returns the quartile of a data set
RANK	Returns the rank of a number in a list of numbers
RSQ	Returns the square of the Pearson product moment correlatin coefficient
SKEW	Returns the skewness of a distribution
SLOPE	Returns the slope of the linear regression line
SMALL	Returns the k-th smallest value in a data set
STANDARDIZE	Returns a normalized value
STDEV	Estimates standard deviation based on a sample
STDEVP	Calculates standard deviation based on the entire population
STEYX	Returns the standard error of the predicted y-value for each x in the regression
TDIST	Returns the Student's t-distribution
TINV	Returns the inverse of the Student's t-distribution
TREND	Returns values along a linear trend
TRIMMEAN	Returns the mean of the interior of a data set
TTEST	Returns the probability associated with a Student's t-Test
VAR	Estimates variance based on a sample
VARP	Calculates variance based on the entire population
WEIBULL	Returns the Weibull distribution
ZTEST	Returns the two-tailed P-value of a z-test

CHAPTER 4

CASE STUDY AND RESULTS

4.1 Method of Experiment, Set Up and Procedure

The workpiece (3 in x 3 in) is placed on the load cell and it is fixed with the aid of a vice.

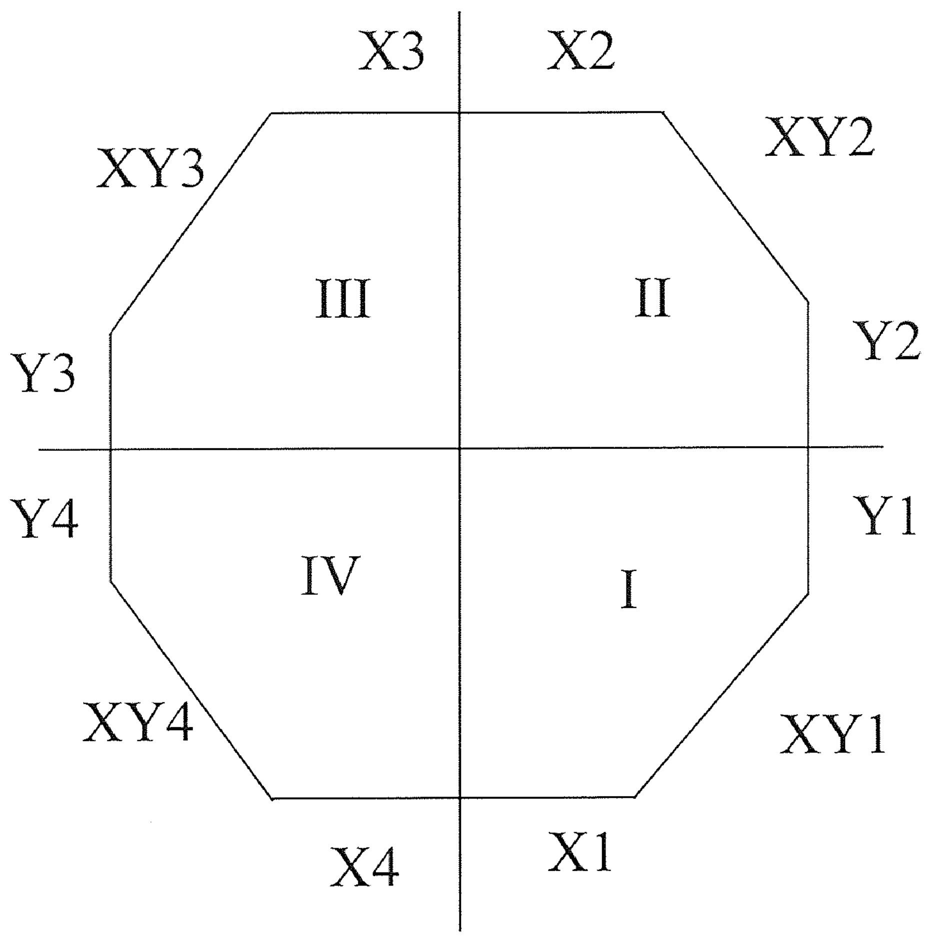


Fig 4.1 Workpiece and the feed rates in the order as the component was cut

The above figure represents the workpiece used in the experiments on the milling machine. The workpiece was made from the material Al 6060. The cutter that was used for the milling operation was made out of high speed steel. The workpiece was cut in the order as represented by the number in the figure.

The data acquisition board is kept ready and all the necessary information is entered to the UEI-Win 30. After that the amplifier is set up after a warm up of 1 hr. The CNC milling machine and the NC part program are kept ready. The data acquisition program is then actuated and the process is performed. If there is no overload signal the data is saved. The surface finish of the workpiece is measured by the Surtronic 3 + and the collected data is transferred to the Surface Finish software.

The cutting force varies due to the stochastic nature of the process at each moment of time and thereby it leads to the variation in the surface roughness every time. Thus the cutting forces were also to be recorded at the same time. In this research, a transducer was used for converting the vibrations of the cutting force to analog signals. The transducer measured each separate component of the force at the same time. A Kistler 9067 force transducer was used to measure the three orthogonal components of the cutting forces in arbitrary directions. The workpiece was an eight sided polygon that was connected with 4 screws to the fixture and after every 4 experiments the workpiece was changed to another one. The transducer was calibrated with the fixture as a perload.

The Fadal CNC machine was used to perform the milling process. The Fadal CNC machine is a 5 axis milling machine. It moves on the X,Y, and Z axis and rotates to both directions of rotations. The high speed processor increases the machine capability to use faster feedrates. These higher feedrates may be attained without emptying the machine buffer. There are also additional G and M code capabilities. The macro capabilities provides a programmer with full mathematical calculations within a program.

Four 1/2 in. size flute side mills were used to perform the cutting operation. All the cutters were constructed from a high speed steel matr. (HSS). First, the roughing operation was performed and then the finishing operation was performed and the data was collected. For these experiments the workpiece was made from the AL 6060. Each experiment consisted of three different paths as follows X direction, XY direction and the Y direction under the same conditions.

4.2 Design of Experiments

In this research the factorial design of 2^3 was adopted and the selected experimental points created the vertices of the cube. Based on the capacity of the milling machine used three levels (lower, central, and upper) were selected for each cutting condition. The table below shows the combination of the different parameters involved in the machining of the component.

Table 4.1 Operating Parameters and levels of cutting

SPEED	FEED	DEPTH OF CUT
1500 RPM	0.001 in/min	0.001 in
3000 RPM	0.005 in/min	0.02 in
4500 RPM	0.01 in/min	0.05 in
	0.02 in/min	

The above table shows the different operating parameters involved in the machining operation and the different levels of cutting. After the machining was carried out the data was collected and transferred to excel spreadsheet.

4.3 Total Time for 4 Experiments

There was a total of 4 experiments performed per combination of the operating parameters. These 4 experiments represent the cutting if the workpiece was divided into 4 quadrants. The milling process of each of the workpiece took as follows :

When the spindle speed = 1500 RPM, total time = 304.2 secs.

When the spindle speed = 3000 RPM, total time = 153.6 secs.

When the spindle speed = 4500 RPM, total time = 76.8 secs.

When the spindle speed was increased the milling process was shorter. The total sampling rate that was collected is as follows :

For a total time of 307.2 secs. the signals per channel were 1024. For a total time of 153.6 secs. the signals per channel were 512 and when the total time was 76.8 secs. the signals per channel were 256.

There were 4 experiments performed on each workpiece. The workpiece was divided into 4 quadrants and each feedrate was used in each quadrant and the readings were recorded from the software. The Surface Quality results and the Cutting force results were all recorded from the software. Initially this data was in the form of .dat file from the software. It was imported into the Excel

Spreadsheet so that there could be ease of calculation. For this conversion a special feature in excel was used that allows us to convert each .dat file into a .xls format. Once the .xls format was obtained all the calculations could be performed like a normal excel spreadsheet. Given below are the results from the excel spreadsheet for the Surface Quality and Cutting Forces. The formulae that were described in the previous chapter were utilized to obtain the Signal to noise ratio for all the parameters.

4.4 Data Organization

The data that was obtained from the CNC machine software was in the form of thousands of numbers. This data needed to be organized so that mathematical models could be derived. The Surface texture data was first imported in the Excel Spreadsheet. It is to be noted that there were 3 spindle speeds, 4 feed rates and 3 depths of cut. Thus if we have a single value for a single combination for cutting in each direction we should end with 3 x 4 x 3 = 36 values for cutting in each direction. Thus each of the surface texture parameter was averaged or maximized or minimized to obtain the 36 values for cutting in each direction. Rku, Ra and Rq values were averaged as the average value would give optimum results. The Rp and Rt values which are the peak values were minimized because of the fact that minimum the distance between peaks the better it is. These values were calculated using the Excel spreadsheet. The cutting force data was split into the Fmax value and the Favg. value to obtain optimum results.

For this purpose also Excel spread sheet was used. Before performing these functions the data files had to be converted from the .dat format to the .xls format and this feature was available through a software in Excel.

Taguchi's method was used to calculate the S/N Ratios. The following formulae are available and they were used according to the conditions.

a. When nominal is the best

$(S/N) = 20 * \log (Y/S)$

where Y is the average of a number of readings = S

b. When small is the best (min function)

$(S/N) = -10 * \log (1/n (\Sigma Y^2))$

where Y is the reading and n is the number of readings.

c. When big is the best (max. function)

$(S/N) = -10 * \log (1/n (\Sigma 1/Y^2))$

where Y is the reading and n is the total number of readings.

Thus using the above formulae the Signal to noise ratios were calculated using either min. the better or max. the better.

Similar results were also obtained for the cutting forces. In this case there were only two parameters

Fmax - The maximum cutting force.

Favg - The average cutting force.

The standard deviations and the signal to noise ratios were calculated for the Fmax. in a similar manner as for the Surface texture Results. The cutting was carried out in three directions X, XY and the Y Directions. Therefore, a set of readings was obtained for each of the three directions.

There were thousands of numbers involved and to develop a mathematical model it was necessary that the data be organized so that sense could be made out of it after feeding it to the various softwares. Since there are three spindle speeds, four feed rates and three depths of cut 3 x 4 x 3 = 36 values of each operating parameter was obtained for cutting in each of the X, XY and the Y direction. The entire data which was consolidated and organized is shown in the tables 4.2, 4.3, 4.4, 4.5, 4.6, and 4.7. Tables 4.2, 4.3 and 4.4 show the surface quality parameter values of Rku, Ra, Rq, Rp and Rt, their ln values, the standard deviations and the signal to noise ratios for cutting in each of the three directions X, XY and Y respectively. The tables 4.5, 4.6 and 4.7 show the maximum cutting force and the average cutting force, their ln values, standard deviations and the signal to noise ratios for cutting in all the three directions X, XY and Y respectively.

The tables were created by using excel functions. On the Microsoft Excel screen there are lots of icons. There is an icon for " Function Wizard " which comes up with the numerous statistical formulae that can be used for mathematical and algebraic calculations. Not all of these functions were utilized during the course of the data organization.

Table 4.2 Cutting in X Direction

speed	ln speed	feed	ln feed	depth	ln depth	Rku(avg)	Ln Rku	std k	logstd k	S/N Rku	Avg Ra	ln Ra	std Ra	logstd Ra	S/N Ra
1500	7.31322	0.001	-6.90776	0.001	-6.90776	2.966667	1.087439	0.057735	-1.23856	-9.44647	16.73333	2.817403	2.274496	0.356885	-24.5248
1500	7.31322	0.001	-6.90776	0.02	-3.91202	3.8	1.335001	0.754983	-0.12206	-11.7085	24.96667	3.217542	7.409678	0.869799	-28.195
1500	7.31322	0.001	-6.90776	0.05	-2.99573	3.466667	1.243194	0.64291	-0.19185	-10.8967	22.83333	3.128221	3.629509	0.559848	-27.2439
1500	7.31322	0.005	-5.29832	0.001	-6.90776	5.666667	1.734601	3.894012	0.590397	-16.7299	21.73333	3.078847	14.23388	1.153323	-27.8348
1500	7.31322	0.005	-5.29832	0.02	-3.91202	5.7	1.740466	2.946184	0.46926	-15.8293	14.93333	2.703596	3.098925	0.491211	-23.6061
1500	7.31322	0.005	-5.29832	0.05	-2.99573	3.266667	1.18377	0.5	-0.30103	-11.1815	16.03333	2.77467	0.907377	-0.04221	-24.1097
1500	7.31322	0.01	-4.60517	0.001	-6.90776	3.266667	1.18377	0.288675	-0.53959	-10.3046	23.53333	3.158418	2.37557	0.375768	-27.4631
1500	7.31322	0.01	-4.60517	0.02	-3.91202	2.966667	1.087439	0.305505	-0.51498	-9.47597	27.63333	3.319023	6.404165	0.806463	-28.9815
1500	7.31322	0.01	-4.60517	0.05	-2.99573	2.7	0.993252	0.264575	-0.57745	-8.65499	32.26667	3.474035	3.385754	0.529655	-30.2068
1500	7.31322	0.02	-3.91202	0.001	-6.90776	3.233333	1.173514	1.877054	0.273477	-11.0732	37.73333	3.630544	5.508478	0.741032	-31.5058
1500	7.31322	0.02	-3.91202	0.02	-3.91202	2.166667	0.77319	0.305505	-0.51498	-6.77303	44.7	3.799974	5.910161	0.771599	-33.0565
1500	7.31322	0.02	-3.91202	0.05	-2.99573	2.1	0.741937	0.43589	-0.36062	-6.56737	44.1	3.78646	7.108446	0.851775	-32.9634
3000	8.006368	0.001	-6.90776	0.001	-6.90776	4.033333	1.394593	0.378594	-0.42183	-12.1387	17.36667	2.854553	3.338163	0.523508	-24.9
3000	8.006368	0.001	-6.90776	0.02	-3.91202	4.933333	1.596015	1.674316	0.223837	-14.1841	16.83333	2.823361	3.092464	0.490305	-24.62
3000	8.006368	0.001	-6.90776	0.05	-2.99573	4.833333	1.575536	1.877054	0.273477	-14.101	17.8	2.879198	9.42974	0.9745	-25.7533
3000	8.006368	0.005	-5.29832	0.001	-6.90776	3.133333	1.142097	0.503322	-0.29815	-9.99421	12.3	2.509599	1.216553	0.085131	-21.8263
3000	8.006368	0.005	-5.29832	0.02	-3.91202	3.3	1.193922	0.608276	-0.2159	-10.4676	10.83333	2.382628	1.350309	0.130433	-20.74
3000	8.006368	0.005	-5.29832	0.05	-2.99573	3.533333	1.262242	1.078579	0.032852	-11.2254	9.4	2.24071	1.3	0.113943	-19.5176
3000	8.006368	0.01	-4.60517	0.001	-6.90776	3.666667	1.299283	0.85049	-0.07033	-11.4385	15.83333	2.762117	3.855299	0.586058	-24.1598
3000	8.006368	0.01	-4.60517	0.02	-3.91202	4.766667	1.561647	1.795364	0.254153	-13.9568	13.5	2.60269	1.410674	0.149427	-22.6382
3000	8.006368	0.01	-4.60517	0.05	-2.99573	5.566667	1.716796	0.208167	-0.68159	-14.916	20.4	3.015535	2.821347	0.450457	-26.2476
3000	8.006368	0.02	-3.91202	0.001	-6.90776	2.166667	0.77319	0.152753	-0.81601	-6.73021	36.03333	3.584444	4.206344	0.623905	-31.1734
3000	8.006368	0.02	-3.91202	0.02	-3.91202	2.033333	0.709676	0.351188	-0.45446	-6.24969	55.3	4.012773	3.740321	0.572909	-34.8677
3000	8.006368	0.02	-3.91202	0.05	-2.99573	2.8	1.029619	1.053565	0.022661	-9.33487	33.3	3.505557	5.940539	0.773826	-30.5401
4500	8.411833	0.001	-6.90776	0.001	-6.90776	3.4	1.223775	0.5	-0.30103	-10.6917	15.7	2.753661	3.109662	0.492713	-24.0301
4500	8.411833	0.001	-6.90776	0.02	-3.91202	7.933333	2.071073	5.006329	0.699519	-19.0117	19.33333	2.961831	14.73001	1.168203	-27.1469
4500	8.411833	0.001	-6.90776	0.05	-2.99573	3.633333	1.290151	0.873689	-0.05864	-11.3704	13.66667	2.61496	3.354599	0.525641	-22.8843
4500	8.411833	0.005	-5.29832	0.001	-6.90776	3.2	1.163151	0.458258	-0.33889	-10.162	15.53333	2.742988	1.258306	0.099786	-23.8443
4500	8.411833	0.005	-5.29832	0.02	-3.91202	4.1	1.410987	0.818535	-0.08696	-12.3696	13.13333	2.575154	1.93477	0.286629	-22.4299
4500	8.411833	0.005	-5.29832	0.05	-2.99573	3.5	1.252763	0.1	-1	-10.8837	12.16667	2.4987	2.050203	0.311797	-21.7849
4500	8.411833	0.01	-4.60517	0.001	-6.90776	4.5	1.504077	3.119295	0.494056	-14.2711	21.16667	3.052428	4.350096	0.638499	-26.6336
4500	8.411833	0.01	-4.60517	0.02	-3.91202	4	1.386294	1.734935	0.239283	-12.5543	24.83333	3.212187	6.092892	0.784823	-28.0716
4500	8.411833	0.01	-4.60517	0.05	-2.99573	3.933333	1.369487	1.882374	0.274706	-12.5123	17.96667	2.888518	0.70946	-0.14907	-25.0939
4500	8.411833	0.02	-3.91202	0.001	-6.90776	2.733333	1.005522	0.057735	-1.23856	-8.73514	29.43333	3.382128	1.955335	0.291221	-29.3895
4500	8.411833	0.02	-3.91202	0.02	-3.91202	4.8	1.568616	3.477068	0.541213	-14.9276	45.4	3.815512	18.21977	1.260543	-33.584
4500	8.411833	0.02	-3.91202	0.05	-2.99573	2.033333	0.709676	0.152753	-0.81601	-6.18048	54.76667	4.003082	2.050203	0.311797	-34.7744

Avg Rq	ln Rq	Std Rq	logstd Rq	S/N Rq	Avg Rp	ln Rp	Std Rp	logstd Rp	S/N Rp	Avg Rt	ln Rt	Std Rt	logstd Rt	S/N Rt
20.86667	3.038153	2.750152	0.439357	-26.4391	65.66667	4.184591	8.621678	0.935592	-36.3965	118	4.770685	18.35756	1.263815	-41.5072
32.63333	3.485334	10.73421	1.03077	-30.5757	101.3333	4.618415	45.54485	1.658439	-40.6638	194	5.267858	56.02678	1.748396	-45.991
28.83333	3.361532	3.917057	0.59296	-29.251	88	4.477337	13	1.113943	-38.9524	174.3333	5.160969	20.84067	1.318912	-44.8688
30.26667	3.410047	22.45135	1.351243	-30.9764	135.3333	4.907741	142.4792	2.153752	-45.0309	216.3333	5.37682	183.3939	2.263385	-48.4025
21	3.044522	6.656576	0.823251	-26.726	75.33333	4.321923	47.07795	1.672818	-38.5447	140.6667	4.946393	64.04165	1.806463	-43.5259
20.5	3.020425	1.4	0.146128	-26.2486	63	4.143135	5.567764	0.745681	-36.0094	129	4.859812	20.80865	1.318244	-42.2865
29.53333	3.38552	2.542309	0.405228	-29.4277	92.33333	4.525405	9.291573	0.968089	-39.3364	163	5.09375	6.557439	0.816734	-44.2484
34.46667	3.539993	7.600877	0.880864	-30.8866	89.66667	4.496099	14.57166	1.163509	-39.1284	180.6667	5.196654	27.46513	1.438782	-45.204
39.7	3.681351	10.95628	1.039663	-32.009	101.6667	4.621699	18.00926	1.255496	-40.2335	197.6667	5.286582	23.35237	1.368331	-45.9589
45.7	3.822098	9.26013	0.966617	-33.3156	171.3333	5.143611	108.8592	2.036865	-45.7119	253.3333	5.534706	130.6688	2.116172	-48.783
51.83333	3.948033	6.115826	0.786455	-34.3323	128.3333	4.854631	12.50333	1.097026	-42.1942	214.3333	5.367532	19.75686	1.295718	-46.6463
51	3.931826	7.218726	0.858461	-34.209	122	4.804021	9.192388	0.963428	-41.7356	216.6667	5.37836	16.77299	1.224611	-46.7332
22.36667	3.107572	3.865661	0.587224	-27.0777	87.66667	4.473542	31.39002	1.496792	-39.2129	153.6667	5.034786	32.39341	1.510457	-43.8584
23.16667	3.142714	5.493026	0.739812	-27.4571	87.66667	4.473542	29.36551	1.467838	-39.17	162.3333	5.089652	54.19717	1.733977	-44.5194
25.03333	3.220208	13.37174	1.126188	-28.7266	88.66667	4.484884	47.35328	1.67535	-39.7112	161.6667	5.085537	87.75154	1.943255	-44.9512
15.4	2.734368	1.509967	0.178967	-23.7782	49.33333	3.8986	8.621678	0.935592	-33.9504	90	4.49981	9.165151	0.96214	-39.1148
13.7	2.617396	1.868154	0.271413	-22.7879	42.66667	3.753418	14.57166	1.163509	-32.927	82.33333	4.410776	18.87679	1.275928	-38.4611
11.83333	2.47092	2.013289	0.303906	-21.5452	38	3.637586	11.35782	1.055295	-31.8469	72	4.276666	21.16601	1.325639	-37.3899
19.73333	2.982309	4.878866	0.688319	-26.0775	81	4.394449	37.51	1.574147	-38.75	125	4.828314	40.73082	1.609923	-42.2352
17.36667	2.854553	1.450287	0.161454	-24.8145	59.33333	4.083171	4.041452	0.606537	-35.4794	112	4.718499	4.358899	0.639377	-40.9887
28.76667	3.359217	3.098925	0.491211	-29.2113	111.6667	4.715518	24.02776	1.380713	-41.0905	188.6667	5.239982	16.16581	1.208597	-45.5351
42.1	3.740048	4.728636	0.674736	-32.522	113.3333	4.730333	9.291573	0.968089	-41.1066	191.6667	5.255758	9.291573	0.968089	-45.6577
63.8	4.155753	3.732292	0.571976	-36.1063	136.3333	4.915103	15.30795	1.184917	-42.7284	262.6667	5.570886	12.01388	1.079683	-48.3942
40.36667	3.698004	9.176237	0.962665	-32.2676	104.6667	4.650781	49.69239	1.69629	-41.0042	189	5.241747	63.37981	1.801951	-45.8432
20.1	3.00072	4.784349	0.679823	-26.2249	65	4.174387	21	1.322219	-36.5504	121.3333	4.798542	40.50103	1.607466	-41.9908
30.63333	3.422089	26.73955	1.427154	-31.5078	153	5.030438	172.5022	2.236795	-46.3596	234.3333	5.456745	206.7519	2.315449	-49.2122
18.03333	2.892222	4.891148	0.689411	-25.3295	59.33333	4.083171	20.42874	1.310242	-35.7963	115.6667	4.750712	42.35957	1.626952	-41.6361
19.93333	2.992393	2.023199	0.306039	-26.0213	57	4.043051	8.660254	0.937531	-35.1838	110.6667	4.706523	15.94783	1.202702	-40.9401
17.46667	2.860294	3.098925	0.491211	-24.9344	66	4.189655	20.22375	1.305862	-36.6546	118.6667	4.776318	25.57994	1.4079	-41.6191
15.5	2.74084	2.685144	0.428968	-23.8927	48	3.871201	10.81665	1.034093	-33.7694	96.33333	4.567814	15.885	1.200987	-39.7536
28.33333	3.344039	8.991848	0.953849	-29.3282	116	4.75359	81.6272	1.911835	-42.528	175	5.164786	99.71459	1.998759	-45.7117
33.13333	3.50054	10.30356	1.012987	-30.6766	118.6667	4.776318	67.89207	1.831819	-42.3438	191	5.252273	87	1.939519	-46.1833
22.53333	3.114996	0.057735	-1.23856	-27.0565	67.33333	4.209655	4.932883	0.693101	-36.5801	133	4.890349	19.69772	1.294416	-42.5401
35.86667	3.579808	2.514624	0.400473	-31.108	112	4.718499	3.605551	0.556972	-40.9874	181	5.198497	11.53256	1.061926	-45.1653
62.16667	4.129819	35.16566	1.546119	-36.7109	242	5.488938	261.4211	2.417341	-50.1755	367.6667	5.907177	302.4968	2.480721	-52.9266
63.26667	4.147359	2.672702	0.42695	-36.0287	122.3333	4.80675	12.34234	1.091397	-41.7803	266.6667	5.585999	17.24336	1.236622	-48.5315

Table 4.3 Cutting in XY Direction

speed	ln speed	feed	ln feed	depth	ln depth	Rku	ln Rku	std Rku	logstd Rku	S/N Rku	Ra	ln Ra	std Ra	logstd Ra	S/N Ra
1500	7.31322	0.001	-6.90776	0.001	-6.90776	2.7	0.993252	0.3	-0.52288	-8.66287	14.7	2.687847	3.551056	0.550358	-23.5121
1500	7.31322	0.001	-6.90776	0.02	-3.91202	5.8	1.757858	2.685144	0.428968	-15.8486	29.5	3.38439	21.31267	1.328638	-30.6932
1500	7.31322	0.001	-6.90776	0.05	-2.99573	3	1.098612	0.1	-1	-9.54564	17.9	2.884801	2.605763	0.415935	-25.118
1500	7.31322	0.005	-5.29832	0.001	-6.90776	5.266667	1.661398	3.614323	0.558027	-15.6166	23.8	3.169686	4.06325	0.608874	-27.6151
1500	7.31322	0.005	-5.29832	0.02	-3.91202	3.033333	1.109662	0.416333	-0.38056	-9.69261	20.8	3.034953	5.367495	0.729772	-26.5499
1500	7.31322	0.005	-5.29832	0.05	-2.99573	5.1	1.629241	3.740321	0.572909	-15.4823	25.8	3.250374	2.364318	0.373706	-28.2566
1500	7.31322	0.01	-4.60517	0.001	-6.90776	5.9	1.774952	3.551056	0.550358	-16.3565	28.53333	3.351073	19.18576	1.282979	-30.2512
1500	7.31322	0.01	-4.60517	0.02	-3.91202	5.233333	1.655048	2.700617	0.431463	-15.0853	23.4	3.152736	2.651415	0.423478	-27.4213
1500	7.31322	0.01	-4.60517	0.05	-2.99573	3.566667	1.271631	1.069268	0.029086	-11.298	22.8	3.126761	7.107742	0.851732	-27.4313
1500	7.31322	0.02	-3.91202	0.001	-6.90776	2.433333	0.889262	0.305505	-0.51498	-7.76943	30.26667	3.410047	0.85049	-0.07033	-29.6216
1500	7.31322	0.02	-3.91202	0.02	-3.91202	2.766667	1.017643	0.907377	-0.04221	-9.1399	39.03333	3.664416	11.3059	1.053305	-32.0651
1500	7.31322	0.02	-3.91202	0.05	-2.99573	3.433333	1.233532	0.665833	-0.17663	-10.8219	36.46667	3.596399	1.36504	0.135145	-31.242
3000	8.006368	0.001	-6.90776	0.001	-6.90776	4.066667	1.402824	2.193931	0.341223	-12.9549	20.6	3.025291	10.64378	1.027096	-26.9887
3000	8.006368	0.001	-6.90776	0.02	-3.91202	3.933333	1.369487	1.069268	0.029086	-12.1041	15.13333	2.7169	0.152753	-0.81601	-23.599
3000	8.006368	0.001	-6.90776	0.05	-2.99573	3.533333	1.262242	0.321455	-0.49288	-10.9876	7.866667	2.062634	0.950438	-0.02208	-17.9579
3000	8.006368	0.005	-5.29832	0.001	-6.90776	6.066667	1.802809	4.712041	0.673209	-17.1271	21.63333	3.074235	7.550717	0.877988	-27.0416
3000	8.006368	0.005	-5.29832	0.02	-3.91202	6.066667	1.802809	4.101626	0.612956	-16.8142	15.86667	2.76422	4.808673	0.682025	-24.2678
3000	8.006368	0.005	-5.29832	0.05	-2.99573	3.8	1.335001	1.571623	0.196348	-12.0647	11.2	2.415914	0.6245	-0.20447	-20.9934
3000	8.006368	0.01	-4.60517	0.001	-6.90776	2.933333	1.076139	0.351188	-0.45446	-9.38853	16.03333	2.77467	1.628906	0.211896	-24.1303
3000	8.006368	0.01	-4.60517	0.02	-3.91202	3.466667	1.243194	0.723418	-0.14061	-10.9225	18.03333	2.892222	1.962991	0.292918	-25.1557
3000	8.006368	0.01	-4.60517	0.05	-2.99573	3.966667	1.377926	2.193931	0.341223	-12.7746	15.23333	2.723486	1.686219	0.226914	-23.6912
3000	8.006368	0.02	-3.91202	0.001	-6.90776	2.133333	0.757686	0.152753	-0.81601	-6.59599	32.56667	3.483289	2.386071	0.377683	-30.271
3000	8.006368	0.02	-3.91202	0.02	-3.91202	1.8	0.587787	0.1	-1	-5.11438	63.26667	4.147359	5.658033	0.752665	-36.0466
3000	8.006368	0.02	-3.91202	0.05	-2.99573	1.933333	0.659246	0.404145	-0.39346	-5.85085	40.73333	3.707047	6.013596	0.779134	-32.2816
4500	8.411833	0.001	-6.90776	0.001	-6.90776	3.133333	1.142097	0.208167	-0.68159	-9.93289	14.16667	2.650892	0.763763	-0.11704	-23.0338
4500	8.411833	0.001	-6.90776	0.02	-3.91202	5.833333	1.763589	3.013857	0.479123	-16.0296	12.96667	2.562382	2.993883	0.476235	-22.4082
4500	8.411833	0.001	-6.90776	0.05	-2.99573	5.933333	1.780586	4.128357	0.615777	-16.6808	14.63333	2.683302	5.390114	0.731598	-23.6829
4500	8.411833	0.005	-5.29832	0.001	-6.90776	3.8	1.335001	1.014889	0.006419	-11.7974	16.46667	2.801338	2.003331	0.301753	-24.3748
4500	8.411833	0.005	-5.29832	0.02	-3.91202	3.866667	1.352393	0.776745	-0.10972	-11.862	19.06667	2.947942	2.746513	0.438782	-25.6652
4500	8.411833	0.005	-5.29832	0.05	-2.99573	2.733333	1.005522	0.251661	-0.59918	-8.75833	17.3	2.850707	1.53948	0.187374	-24.7838
4500	8.411833	0.01	-4.60517	0.001	-6.90776	2.933333	1.076139	0.251661	-0.59918	-9.36849	18.5	2.917771	2.051828	0.312141	-25.3789
4500	8.411833	0.01	-4.60517	0.02	-3.91202	2.933333	1.076139	0.152753	-0.81601	-9.35507	23.96667	3.176664	5.749203	0.759608	-27.7556
4500	8.411833	0.01	-4.60517	0.05	-2.99573	2.8	1.029619	0.4	-0.39794	-9.00185	21.36667	3.061832	2.569695	0.409882	-26.6364
4500	8.411833	0.02	-3.91202	0.001	-6.90776	2.6	0.955511	0.173205	-0.76144	-8.3123	30.26667	3.410047	1.101514	0.04199	-29.6231
4500	8.411833	0.02	-3.91202	0.02	-3.91202	3.866667	1.352393	2.494661	0.397012	-12.8103	39.23333	3.669527	9.948534	0.997759	-32.0554
4500	8.411833	0.02	-3.91202	0.05	-2.99573	1.866667	0.624154	0.11547	-0.93753	-5.4324	53.83333	3.985893	5.787343	0.762479	-34.6544

Rq	ln Rq	std Rq	logstd Rq	S/N Rq	Rp	ln Rp	std Rp	logstd Rp	S/N Rp	Rt	ln Rt	std Rt	logstd Rt	S/N Rt
18.06667	2.894069	4.135618	0.61654	-22.8998	52	3.951244	12.12436	1.083659	-34.4747	93	4.532599	19	1.278754	-39.4889
41.96667	3.736876	33.38298	1.523525	-33.6521	184	5.214936	178.404	2.251405	-47.4095	270.6667	5.600888	196.6223	2.293633	-49.9578
22.53333	3.114996	3.239341	0.510457	-24.9558	65.33333	4.179502	15.14376	1.180234	-36.4555	126	4.836282	17.4356	1.241437	-42.0625
33.16667	3.501545	10.37368	1.015933	-29.5836	134	4.89784	97.8928	1.990751	-43.864	250	5.521461	171.7091	2.234793	-49.1464
26.16667	3.264486	6.85298	0.835879	-25.5047	75.66667	4.326338	35.10461	1.545364	-38.1604	144.3333	4.972125	47.07795	1.672818	-43.4849
35.46667	3.568593	8.451233	0.92692	-29.8415	135.6667	4.910201	97.04295	1.986964	-43.9241	259	5.556828	164.3198	2.21569	-49.2984
40.6	3.703768	30.51278	1.484482	-25.5495	196.6667	5.28151	200.8291	2.302827	-48.1668	307.6667	5.729017	259.7197	2.414505	-51.4497
31.76667	3.458418	6.724086	0.827633	-28.8565	103	4.634729	69.63476	1.842826	-41.4119	187	5.231109	59.57348	1.775053	-45.7212
30.63333	3.422089	12.3553	1.091853	-25.6604	76	4.330733	30.34798	1.48213	-38.055	180.3333	5.194807	88.93443	1.94907	-45.7741
36.03333	3.584444	1.750238	0.243097	-29.5822	110	4.70048	6.557439	0.816734	-40.8381	177.6667	5.179909	15.37314	1.186762	-45.0137
46.63333	3.842316	11.82765	1.072899	-30.7508	119.6667	4.78471	35.07611	1.545011	-41.8014	217.6667	5.382965	28.0238	1.447527	-46.8036
46.1	3.830813	0.9	-0.04576	-31.5979	145	4.976734	6.082763	0.784101	-43.2325	256.6667	5.547778	21.96209	1.341674	-48.2085
28.63333	3.354572	17.97674	1.254711	-29.4579	117	4.762174	116.3959	2.065938	-43.5643	187	5.231109	150.5722	2.177745	-46.997
20.1	3.00072	1.058301	0.024609	-24.4808	65	4.174387	8	0.90309	-36.3019	134	4.89784	26.22975	1.418794	-42.6516
10.03333	2.305913	1.305118	0.11565	-18.3969	32	3.465736	7.937254	0.89967	-30.2776	64	4.158883	10.81665	1.034093	-36.2055
31.93333	3.46365	17.32234	1.238606	-30.0707	160.3333	5.077255	165.4882	2.218767	-46.431	236	5.463832	198.0227	2.296715	-49.1296
24.56667	3.201391	12.64608	1.101956	-27.4286	128	4.85203	128.0195	2.107276	-44.3632	211	5.351858	181.4277	2.258704	-48.2259
14.5	2.674149	0.264575	-0.57745	-21.4072	41	3.713572	4.582576	0.66111	-32.2917	86.66667	4.462069	11.01514	1.04199	-38.8036
19.86667	2.989043	2.307235	0.363092	-24.5912	63.33333	4.148412	10.21437	1.009212	-36.1073	114.6667	4.742029	24.66441	1.392071	-41.3207
21.8	3.08191	4.613025	0.663986	-24.041	78.66667	4.36522	27.30079	1.436175	-38.2512	133	4.890349	29.46184	1.46926	-42.6168
19.83333	2.987364	3.601851	0.556526	-24.9616	67	4.204693	34.87119	1.542467	-37.2425	105.6667	4.660289	51.00327	1.707598	-41.1058
38.06667	3.639339	2.706166	0.432354	-29.4982	99.33333	4.598481	5.686241	0.754825	-39.9514	172	5.147494	8.888194	0.948814	-44.7183
71.96667	4.276203	5.918051	0.772179	-35.6037	140.6667	4.946393	3.21455	0.50712	-42.9653	283.3333	5.646624	10.69268	1.029086	-49.0501
46.33333	3.835862	6.921223	0.840183	-31.0395	71	4.26268	11.26943	1.051902	-37.0975	170.6667	5.139712	28.29016	1.451635	-44.7218
17.93333	2.886661	1.137248	0.055855	-23.0013	54.33333	3.995138	3.785939	0.578174	-34.7154	101	4.615121	5.291503	0.723579	-40.0944
18.5	2.917771	6.579514	0.818194	-21.6369	76.33333	4.33511	55.41059	1.743593	-38.9618	129	4.859812	58.27521	1.765484	-42.7658
22.3	3.104587	12.85146	1.108952	-27.4322	118.3333	4.773506	110.97	2.045205	-43.4659	193	5.26269	171.403	2.234019	-47.5462
21.1	3.049273	2.986637	0.475182	-24.3167	81	4.394449	29.71532	1.47298	-38.5429	132.3333	4.885324	37.42103	1.573116	-42.6589
24.86667	3.213528	4.195633	0.622797	-25.6674	76	4.330733	15.71623	1.196348	-37.7384	142.6667	4.960511	22.18859	1.34613	-43.1559
21.36667	3.061832	1.70098	0.230699	-25.1733	59	4.077537	1	0	-35.4179	115.6667	4.750712	9.609024	0.982679	-41.2841
22.93333	3.132591	2.254625	0.353074	-25.4587	73	4.290459	2	0.30103	-37.2686	121.6667	4.801285	4.932883	0.693101	-41.7082
29.63333	3.3889	6.815668	0.833508	-26.6289	87.66667	4.473542	13.05118	1.11565	-38.9204	153.3333	5.032614	30.56687	1.485251	-43.8263
26.1	3.261935	3.1241	0.494725	-27.1514	80.33333	4.386185	11.06044	1.043772	-38.1525	133	4.890349	18.52026	1.267647	-42.5328
37.03333	3.611818	1.41892	0.151958	-29.5859	110.6667	4.706523	5.686241	0.754825	-40.888	192.6667	5.260962	15.885	1.200987	-45.7158
47.63333	3.863533	9.407621	0.97348	-32.2973	136.3333	4.915103	47.42714	1.676027	-43.029	250.6667	5.524124	51.3939	1.710912	-48.102
61.76667	4.123364	6.354001	0.803047	-34.3282	119.3333	4.781921	12.89703	1.11049	-41.5689	255.3333	5.54257	22.54625	1.353074	-48.1647

Table 4.4 Cutting in Y Direction

speed	ln speed	feed	ln feed	depth	ln depth	Rku	ln Rku	std k	log std k	S/N RKu	Ra	ln Ra	std Ra	log std Ra	S/N Ra
1500	7.31322	0.001	-6.90776	0.001	-6.90776	3.666667	1.299283	0.832666	-0.07953	-11.4322	15.5	2.74084	3.214032	0.50705	-23.9294
1500	7.31322	0.001	-6.90776	0.02	-3.91202	7.066667	1.955389	6.439203	0.808832	-18.8975	17.03333	2.835172	11.92323	1.076394	-25.8536
1500	7.31322	0.001	-6.90776	0.05	-2.99573	4	1.386294	1.479865	0.170222	-12.4204	15.46667	2.738687	3.056687	0.485251	-23.8996
1500	7.31322	0.005	-5.29832	0.001	-6.90776	3.433333	1.233532	1.101514	0.04199	-11.0026	21.46667	3.066501	1.861003	0.269747	-26.657
1500	7.31322	0.005	-5.29832	0.02	-3.91202	2.9	1.064711	0.1	-1	-9.2514	21.23333	3.055572	2.203028	0.34302	-26.5714
1500	7.31322	0.005	-5.29832	0.05	-2.99573	2.966667	1.087439	0.11547	-0.93753	-9.44976	23.4	3.152736	0.173205	-0.76144	-27.3845
1500	7.31322	0.01	-4.60517	0.001	-6.90776	3.466667	1.243194	0.665833	-0.17663	-10.9038	17.83333	2.881069	5.085601	0.706342	-25.2539
1500	7.31322	0.01	-4.60517	0.02	-3.91202	3	1.098612	0.34641	-0.46041	-9.58086	14.06667	2.643808	2.809508	0.44863	-23.0778
1500	7.31322	0.01	-4.60517	0.05	-2.99573	7.266667	1.983298	5.493026	0.739812	-18.6285	20.23333	3.007331	4.259499	0.629359	-26.2478
1500	7.31322	0.02	-3.91202	0.001	-6.90776	2.666667	0.980829	0.404145	-0.39346	-8.58537	32.4	3.478158	2.95973	0.471252	-30.235
1500	7.31322	0.02	-3.91202	0.02	-3.91202	2.6	0.955511	0.87178	-0.05959	-8.61335	39.7	3.681351	13.81774	1.140437	-32.3131
1500	7.31322	0.02	-3.91202	0.05	-2.99573	2.366667	0.861482	0.450925	-0.3459	-7.5866	45.2	3.811097	5.6	0.748188	-33.147
3000	8.006368	0.001	-6.90776	0.001	-6.90776	3.033333	1.109662	0.321455	-0.49288	-9.6708	16.23333	2.787067	5.331354	0.726838	-24.5097
3000	8.006368	0.001	-6.90776	0.02	-3.91202	8.233333	2.108191	7.43931	0.871533	-20.1988	12.96667	2.562382	6.703979	0.826333	-22.9688
3000	8.006368	0.001	-6.90776	0.05	-2.99573	3.733333	1.317301	0.907377	-0.04221	-11.6097	5.933333	1.780586	0.757188	-0.1208	-15.5129
3000	8.006368	0.005	-5.29832	0.001	-6.90776	3.4	1.223775	0.556776	-0.25432	-10.7065	12.8	2.549445	1.74356	0.241437	-22.1976
3000	8.006368	0.005	-5.29832	0.02	-3.91202	5.266667	1.661398	1.858315	0.269119	-14.777	18.33333	2.908721	12.30623	1.090125	-26.4055
3000	8.006368	0.005	-5.29832	0.05	-2.99573	3.9	1.360977	1.646208	0.216485	-12.3087	12.9	2.557227	3.9128	0.592488	-22.4703
3000	8.006368	0.01	-4.60517	0.001	-6.90776	2.633333	0.96825	0.208167	-0.68159	-8.42817	18.36667	2.910537	2.354428	0.371885	-25.3279
3000	8.006368	0.01	-4.60517	0.02	-3.91202	8.566667	2.147879	3.592121	0.555351	-19.1376	20.6	3.025291	2.330236	0.3674	-26.3142
3000	8.006368	0.01	-4.60517	0.05	-2.99573	3.1	1.131402	1.228821	0.089488	-10.2599	17.03333	2.835172	7.557998	0.878407	-25.1616
3000	8.006368	0.02	-3.91202	0.001	-6.90776	2.533333	0.929536	0.404145	-0.39346	-8.14691	27.56667	3.316607	3.073001	0.487563	-28.8435
3000	8.006368	0.02	-3.91202	0.02	-3.91202	2.8	1.029619	1.905256	0.279953	-10.1115	62.93333	4.142076	3.06159	0.485947	-35.9845
3000	8.006368	0.02	-3.91202	0.05	-2.99573	1.833333	0.606136	0.251661	-0.59918	-5.31904	38.43333	3.648925	4.966219	0.696026	-31.7422
4500	8.411833	0.001	-6.90776	0.001	-6.90776	5.1	1.629241	3.204684	0.505785	-15.1662	16.13333	2.780888	3.797806	0.579533	-24.312
4500	8.411833	0.001	-6.90776	0.02	-3.91202	5.633333	1.728701	1.527525	0.183988	-15.2231	11.33333	2.427748	1.800926	0.255496	-21.1597
4500	8.411833	0.001	-6.90776	0.05	-2.99573	3.133333	1.142097	0.251661	-0.59918	-9.93877	12.03333	2.487681	3.711244	0.56952	-21.8747
4500	8.411833	0.005	-5.29832	0.001	-6.90776	2.933333	1.076139	0.152753	-0.81601	-9.35507	16.86667	2.825339	3.415162	0.533411	-24.6577
4500	8.411833	0.005	-5.29832	0.02	-3.91202	8.4	2.128232	6.726812	0.827809	-20.0314	20.96667	3.042934	7.276217	0.861906	-26.766
4500	8.411833	0.005	-5.29832	0.05	-2.99573	3.333333	1.203973	0.750555	-0.12462	-10.6019	19.13333	2.951432	6.992377	0.844625	-26.0062
4500	8.411833	0.01	-4.60517	0.001	-6.90776	2.7	0.993252	0.1	-1	-8.63125	23.63333	3.162658	4.366158	0.640099	-27.5682
4500	8.411833	0.01	-4.60517	0.02	-3.91202	3.666667	1.299283	2.367136	0.374223	-12.3502	20.1	3.00072	2.424871	0.384689	-26.1059
4500	8.411833	0.01	-4.60517	0.05	-2.99573	3.7	1.308333	1.389244	0.142779	-11.7542	23.7	3.165475	11.63228	1.065665	-28.1418
4500	8.411833	0.02	-3.91202	0.001	-6.90776	2.6	0.955511	0.34641	-0.46041	-8.35056	36.76667	3.604592	10.88363	1.036774	-31.5557
4500	8.411833	0.02	-3.91202	0.02	-3.91202	2.233333	0.803495	0.450925	-0.3459	-7.09553	49.06667	3.89318	9.188217	0.963231	-33.9161
4500	8.411833	0.02	-3.91202	0.05	-2.99573	2.666667	0.980829	1.501111	0.176413	-9.35171	56.96667	4.042466	9.000741	0.954278	-35.1841

Rq	ln Rq	std Rq	log std Rq	S/N Rq	Rp	ln Rp	std Rp	logstd	S/N Rp	Rt	ln Rt	std Rt	log std Rt	S/N Rt
19.26667	2.958376	3.527511	1.181844	-25.7921	52	3.951244	5	0.69897	-34.3468	105.6667	4.660289	17.50238	1.243097	-40.5575
27.46667	3.312973	25.06199	1.130334	-30.6935	144	4.969813	178.4461	2.251507	-46.2288	201.6667	5.306616	209.0223	2.320193	-48.4383
20.43333	3.017168	5.378042	1.416641	-26.4029	70	4.248495	35.36948	1.548629	-37.5846	128	4.85203	44.91102	1.652353	-42.4868
27.13333	3.300763	1.497776	1.426511	-28.6789	91.33333	4.514516	22.47962	1.351789	-39.3845	157.3333	5.058367	21.38535	1.330116	-43.9896
26.66667	3.283414	2.800595	1.469822	-28.5512	74.66667	4.313034	10.59874	1.025254	-37.5205	150	5.010635	16.46208	1.216485	-43.5566
29.46667	3.38326	0.650641	1.469822	-29.388	84.33333	4.434777	2.886751	0.460409	-38.5234	166.3333	5.113994	3.785939	0.578174	-44.4211
22.36667	3.107572	6.185736	1.184691	-27.208	78	4.356709	33.18132	1.520894	-38.3366	136.3333	4.915103	47.07795	1.672818	-43.0242
17.66667	2.87168	3.652853	1.330414	-25.0651	52	3.951244	7.81025	0.892665	-34.3849	101.6667	4.621699	17.89786	1.252801	-40.2324
27.63333	3.319023	6.860272	1.322219	-29.0035	104	4.644391	74.10128	1.869826	-41.6067	204	5.31812	82.63776	1.917179	-46.6435
39.03333	3.664416	3.435598	1.568202	-31.8511	112.3333	4.721471	11.67619	1.067301	-41.0413	204.6667	5.321383	34.07834	1.532476	-46.3005
47.16667	3.853687	14.37231	1.737193	-33.7335	116.3333	4.75646	37.58102	1.574969	-41.6062	212.6667	5.359726	40.45162	1.606936	-46.6575
53.96667	3.988367	4.921721	1.773055	-34.6665	142	4.955827	14.73092	1.16823	-43.0768	237.6667	5.470869	23.35237	1.368331	-47.5472
20.83333	3.036554	7.565932	1.113943	-26.7412	60.33333	4.099885	16.04161	1.205248	-35.8111	115	4.744932	33.71943	1.52788	-41.456
22.76667	3.125297	18.64868	1.082785	-28.7516	138.3333	4.929666	174.6492	2.242167	-45.9628	224	5.411646	251.2449	2.400097	-49.6501
7.6	2.028148	0.953939	0.875061	-17.6616	24	3.178054	7	0.845098	-27.8438	49.66667	3.905334	11.37248	1.055855	-34.0705
16.13333	2.780888	2.064784	1.167317	-24.2016	59	4.077537	20.07486	1.302653	-35.7399	96.33333	4.567814	27.22744	1.435007	-39.9009
29.33333	3.378725	25.41069	1.033424	-31.109	152	5.023881	170.3174	2.231259	-46.278	244.6667	5.499897	253.2594	2.403566	-50.1124
17.26667	2.848778	7.050059	1.130334	-25.2019	53.66667	3.982792	29.29733	1.466828	-35.3811	107	4.672829	58.07753	1.764008	-41.3665
22.2	3.100092	2.3	1.346353	-26.958	64	4.158883	3	0.477121	-36.13	114	4.736198	10	1	-41.1603
34.76667	3.548659	9.011844	1.40654	-31.0136	218.3333	5.386023	108.7949	2.036609	-47.4476	349.6667	5.85698	167.8164	2.224834	-51.4935
21.66667	3.075775	11.38083	1.537819	-27.4491	72	4.276666	53.11309	1.725202	-38.4909	123.6667	4.81759	84.08527	1.92472	-43.0118
32.9	3.493473	3.559494	1.465383	-30.3777	97.66667	4.58156	4.163332	0.619441	-39.8002	164	5.099866	7.81025	0.892665	-44.3034
72.46667	4.283127	6.197849	1.835056	-37.2239	189	5.241747	98.77247	1.994636	-46.2557	337.3333	5.821072	122.7694	2.08909	-50.9287
43.66667	3.776585	5.828665	1.633468	-32.8543	84	4.430817	31.19295	1.494056	-38.8675	174.3333	5.160969	41.25934	1.615522	-44.9866
22.03333	3.092556	7.957596	1.494155	-27.2237	88.33333	4.481118	63.79916	1.804815	-40.2186	155.3333	5.045573	98.89557	1.995177	-44.8641
16.5	2.80336	3.148015	1.113943	-24.4538	63.66667	4.153661	11.01514	1.04199	-36.1641	122.3333	4.80675	31.26233	1.495021	-41.936
15.23333	2.723486	4.65009	1.181844	-23.9176	47	3.850148	17	1.230449	-33.8051	91	4.51086	29.51271	1.470009	-39.4752
20.7	3.030134	4.160529	1.235528	-26.4348	65	4.174387	14.17745	1.151598	-36.3939	112	4.718499	22.11334	1.344654	-41.0958
32.8	3.490429	17.3208	1.283301	-31.058	179.3333	5.189246	130.1704	2.114512	-46.3806	264.3333	5.577211	165.0374	2.217582	-49.4463
25.3	3.230804	11.17721	1.283301	-28.5936	70	4.248495	23.89561	1.378318	-37.2269	149.6667	5.008411	75.79798	1.879658	-44.188
28.7	3.356897	4.915282	1.426511	-29.2417	90.66667	4.50719	26.2742	1.419529	-39.3855	149.6667	5.008411	35.01904	1.544304	-43.6582
26.7	3.284664	7.264296	1.332438	-28.7394	89.66667	4.496099	55.82413	1.746822	-40.0508	162.3333	5.089652	88.11545	1.945052	-44.967
32.7	3.487375	20.63104	1.752048	-31.3131	96.66667	4.571269	47.12041	1.673209	-40.3441	203	5.313206	154.1817	2.188033	-47.5631
44.96667	3.805921	13.19482	1.569374	-33.3002	130	4.867534	31.48015	1.498037	-42.4454	232	5.446737	57.68882	1.761092	-47.4852
57	4.043051	9.357884	1.825426	-35.1948	103	4.634729	11.13553	1.046711	-40.2905	236	5.463832	18.24829	1.261222	-47.4755
65.1	4.175925	9.488941	1.857935	-36.3327	119.6667	4.78471	11.01514	1.04199	-41.5839	251	5.525453	27.18455	1.434322	-48.0273

Table 4.5 Cutting in X Direction

speed	feed	depth	Fmax	ln speed	ln feed	ln depth	ln Fmax	ln Favg	stdev	logstdev	S/N Ratio	Favg
1500	0.001	0.001	64.11	7.31	-6.91	-6.91	4.16	2.93	8.933	0.950997	-26.355	18.78
3000	0.001	0.001	64.96	8.01	-6.91	-6.91	4.17	3.38	10.07	1.003029	-29.82	29.31
4500	0.001	0.001	80.22	8.41	-6.91	-6.91	4.38	3.55	14.06	1.147985	-31.44	34.65
1500	0.001	0.02	93.34	7.31	-6.91	-3.91	4.54	3.59	20.67	1.31534	-32.42	36.34
3000	0.001	0.02	177.01	8.01	-6.91	-3.91	5.18	4.10	26.41	1.421768	-36.36	60.34
4500	0.001	0.02	122.45	8.41	-6.91	-3.91	4.81	4.65	5.7	0.755875	-40.38	104.37
1500	0.001	0.05	71.6	7.31	-6.91	-3.00	4.27	3.36	8.15	0.911158	-29.49	28.71
3000	0.001	0.05	36.76	8.01	-6.91	-3.00	3.60	3.16	9.62	0.983175	-28.09	23.5
4500	0.001	0.05	23.36	8.41	-6.91	-3.00	3.15	2.69	2.13	0.32838	-23.46	14.75
1500	0.005	0.001	108.39	7.31	-5.30	-6.91	4.69	4.32	8.94	0.951338	-37.62	75.51
3000	0.005	0.001	138.46	8.01	-5.30	-6.91	4.93	4.33	16.6	1.220108	-37.84	76.22
4500	0.005	0.001	118.94	8.41	-5.30	-6.91	4.78	4.52	11.25	1.051153	-39.33	91.97
1500	0.005	0.02	84.46	7.31	-5.30	-3.91	4.44	3.67	16.81	1.225568	-32.6	39.31
3000	0.005	0.02	134.87	8.01	-5.30	-3.91	4.90	4.45	23.66	1.374015	-38.98	85.77
4500	0.005	0.02	149.6	8.41	-5.30	-3.91	5.01	4.71	8.82	0.945469	-40.96	111.5
1500	0.005	0.05	70.18	7.31	-5.30	-3.00	4.25	3.68	8.16	0.91169	-32.12	39.55
3000	0.005	0.05	68.57	8.01	-5.30	-3.00	4.23	3.31	13.89	1.142702	-29.76	27.49
4500	0.005	0.05	31.84	8.41	-5.30	-3.00	3.46	2.71	6.89	0.838219	-24.36	15.06
1500	0.01	0.001	110.92	7.31	-4.61	-6.91	4.71	4.34	8.61	0.935003	-37.71	76.38
3000	0.01	0.001	130.12	8.01	-4.61	-6.91	4.87	4.37	17.47	1.242293	-38.14	78.91
4500	0.01	0.001	109.57	8.41	-4.61	-6.91	4.70	4.55	9.88	0.994757	-39.6	95.01
1500	0.01	0.02	90.97	7.31	-4.61	-3.91	4.51	3.78	18.16	1.259116	-33.48	43.62
3000	0.01	0.02	129.25	8.01	-4.61	-3.91	4.86	4.46	24.07	1.381476	-39.08	86.77
4500	0.01	0.02	133.06	8.41	-4.61	-3.91	4.89	4.70	5.22	0.717671	-40.87	110.48
1500	0.01	0.05	71.45	7.31	-4.61	-3.00	4.27	3.71	8.67	0.938019	-32.45	41.04
3000	0.01	0.05	64.64	8.01	-4.61	-3.00	4.17	3.36	12.21	1.086716	-29.92	28.9
4500	0.01	0.05	43.47	8.41	-4.61	-3.00	3.77	2.63	7.95	0.900367	-24.04	13.85
1500	0.02	0.001	75.07	7.31	-3.91	-6.91	4.32	4.23	5.385	0.731186	-36.8	68.57
3000	0.02	0.001	95.45	8.01	-3.91	-6.91	4.56	4.33	16.09	1.206556	-37.8	75.98
4500	0.02	0.001	134.85	8.41	-3.91	-6.91	4.90	4.66	10.34	1.014521	-40.5	105.45
1500	0.02	0.02	61.22	7.31	-3.91	-3.91	4.11	3.74	22.06	1.343606	-33.55	42.23
3000	0.02	0.02	90.57	8.01	-3.91	-3.91	4.51	4.21	25.32	1.403464	-37.17	67.65
4500	0.02	0.02	129.39	8.41	-3.91	-3.91	4.86	4.57	8.2	0.913814	-39.7	96.33
1500	0.02	0.05	22.56	7.31	-3.91	-3.00	3.12	2.75	1.21	0.082785	-23.93	15.68
3000	0.02	0.05	22.81	8.01	-3.91	-3.00	3.13	2.72	4.04	0.606381	-24.1	15.2
4500	0.02	0.05	60.84	8.41	-3.91	-3.00	4.11	3.25	9.97	0.998695	-28.79	25.8

Table 4.6 Cutting in XY Direction

speed	feed	depth	Fmax	ln speed	ln feed	ln depth	ln Fmax	ln Favg	stdev	logstdev	S/N Ratio	Favg
1500	0.001	0.001	92.31	7.31	-6.91	-6.91	4.53	3.46	13.39	1.13	-30.78	31.92
1500	0.001	0.02	118.08	7.31	-6.91	-3.91	4.77	3.60	19.46	1.29	-32.30	36.57
1500	0.001	0.05	58.85	7.31	-6.91	-3.00	4.07	3.44	7.05	0.85	-30.10	31.21
1500	0.005	0.001	111.44	7.31	-5.30	-6.91	4.71	4.26	9.22	0.96	-37.08	70.93
1500	0.005	0.02	107.603	7.31	-5.30	-3.91	4.68	3.62	16.67	1.22	-32.21	37.25
1500	0.005	0.05	82.58	7.31	-5.30	-3.00	4.41	3.64	7.71	0.89	-31.79	38.09
1500	0.01	0.001	112.99	7.31	-4.61	-6.91	4.73	4.36	7.32	0.86	-37.93	78.46
1500	0.01	0.02	137.62	7.31	-4.61	-3.91	4.92	3.83	19.07	1.28	-33.95	46.07
1500	0.01	0.05	95.8	7.31	-4.61	-3.00	4.56	3.63	12.23	1.09	-31.95	37.63
1500	0.02	0.001	81.42	7.31	-3.91	-6.91	4.40	4.28	5.61	0.75	-37.19	72.14
1500	0.02	0.02	119.88	7.31	-3.91	-3.91	4.79	3.80	27.54	1.44	-34.41	44.77
1500	0.02	0.05	31.14	7.31	-3.91	-3.00	3.44	2.98	5.79	0.76	-26.26	19.74
3000	0.001	0.001	84.19	8.01	-6.91	-6.91	4.43	3.59	15.74	1.20	-31.00	36.38
3000	0.001	0.02	105.59	8.01	-6.91	-3.91	4.66	4.11	25.28	1.40	-36.42	61.25
3000	0.001	0.05	64.18	8.01	-6.91	-3.00	4.16	3.18	12.00	1.08	-28.61	24.16
3000	0.005	0.001	137.26	8.01	-5.30	-6.91	4.92	4.26	17.77	1.25	-31.98	70.85
3000	0.005	0.02	143.67	8.01	-5.30	-3.91	4.97	4.36	25.03	1.40	-38.28	78.22
3000	0.005	0.05	76.26	8.01	-5.30	-3.00	4.33	3.21	15.60	1.19	-29.31	24.75
3000	0.01	0.001	126.67	8.01	-4.61	-6.91	4.84	4.39	17.32	1.24	-38.32	80.59
3000	0.01	0.02	173.81	8.01	-4.61	-3.91	5.16	4.48	24.21	1.38	-39.20	87.97
3000	0.01	0.05	73.91	8.01	-4.61	-3.00	4.30	3.48	14.50	1.16	-30.98	32.33
3000	0.02	0.001	99.39	8.01	-3.91	-6.91	4.60	4.31	16.55	1.22	-37.68	74.76
3000	0.02	0.02	89.81	8.01	-3.91	-3.91	4.50	4.16	23.05	1.36	-36.66	64.07
3000	0.02	0.05	20.37	8.01	-3.91	-3.00	3.01	2.81	2.17	0.34	-24.52	16.69
4500	0.001	0.001	68.69	8.41	-6.91	-6.91	4.23	3.77	15.07	1.18	-33.22	43.28
4500	0.001	0.02	115.23	8.41	-6.91	-3.91	4.75	4.66	5.37	0.73	-40.46	105.39
4500	0.001	0.05	62.49	8.41	-6.91	-3.00	4.14	2.78	8.69	0.94	-25.26	16.176
4500	0.005	0.001	121.475	8.41	-5.30	-6.91	4.80	4.40	15.16	1.18	-38.37	81.55
4500	0.005	0.02	150.67	8.41	-5.30	-3.91	5.02	4.72	9.49	0.98	-40.98	111.68
4500	0.005	0.05	66.61	8.41	-5.30	-3.00	4.20	2.80	12.13	1.08	-26.21	16.52
4500	0.01	0.001	132.22	8.41	-4.61	-6.91	4.88	4.62	11.24	1.05	-40.16	101.33
4500	0.01	0.02	152.01	8.41	-4.61	-3.91	5.02	4.75	8.82	0.95	-41.28	115.69
4500	0.01	0.05	53.88	8.41	-4.61	-3.00	3.99	2.88	13.05	1.12	-26.87	17.81
4500	0.02	0.001	126.12	8.41	-3.91	-6.91	4.84	4.67	10.31	1.01	-40.59	106.55
4500	0.02	0.02	141.03	8.41	-3.91	-3.91	4.95	4.74	8.50	0.93	-41.22	114.88
4500	0.02	0.05	61.28	8.41	-3.91	-3.00	4.12	3.21	13.94	1.14	-28.91	24.76

Table 4.7 Cutting in Y Direction

speed	feed	depth	Fmax	ln speed	ln feed	ln depth	ln Fmax	ln Favg	stdev	logstdev	S/N Ratio	Favg
1500	0.001	0.001	111.37	7.31	-6.91	-6.91	4.71	4.01	13.76	1.138618	-35.12	55.38
3000	0.001	0.001	121.19	8.01	-6.91	-6.91	4.80	3.93	18.76	1.273233	-34.65	50.7
4500	0.001	0.001	77.83	8.41	-6.91	-6.91	4.35	4.00	14.12	1.149835	-35.01	54.54
1500	0.001	0.02	114.34	7.31	-6.91	-3.91	4.74	3.61	22.17	1.345766	-32.66	36.83
3000	0.001	0.02	138.34	8.01	-6.91	-3.91	4.93	4.30	27.66	1.441852	-37.9	73.61
4500	0.001	0.02	110.85	8.41	-6.91	-3.91	4.71	4.63	4.88	0.68842	-40.24	102.78
1500	0.001	0.05	75.14	7.31	-6.91	-3.00	4.32	3.60	8.33	0.920645	-31.51	36.74
3000	0.001	0.05	69.32	8.01	-6.91	-3.00	4.24	3.18	14.59	1.164055	-28.96	24.021
4500	0.001	0.05	60.27	8.41	-6.91	-3.00	4.10	2.77	7.58	0.879669	-24.91	15.93
1500	0.005	0.001	114.38	7.31	-5.30	-6.91	4.74	4.18	11.73	1.069298	-36.47	65.58
3000	0.005	0.001	121.8	8.01	-5.30	-6.91	4.80	4.13	17.99	1.255031	-36.18	61.95
4500	0.005	0.001	115.51	8.41	-5.30	-6.91	4.75	4.23	18.83	1.27485	-37.08	69
1500	0.005	0.02	109.26	7.31	-5.30	-3.91	4.69	3.72	25.54	1.407221	-33.71	41.24
3000	0.005	0.02	144.33	8.01	-5.30	-3.91	4.97	4.35	26.86	1.429106	-38.28	77.58
4500	0.005	0.02	141.9	8.41	-5.30	-3.91	4.96	4.68	9.01	0.954725	-40.68	107.83
1500	0.005	0.05	79.46	7.31	-5.30	-3.00	4.38	3.62	9.77	0.989895	-31.76	37.49
3000	0.005	0.05	80.31	8.01	-5.30	-3.00	4.39	3.25	17.4	1.240549	-29.82	25.68
4500	0.005	0.05	60.77	8.41	-5.30	-3.00	4.11	2.70	11.5	1.060698	-25.47	14.92
1500	0.01	0.001	106.35	7.31	-4.61	-6.91	4.67	4.38	6.936	0.841109	-38.05	79.6
3000	0.01	0.001	114.23	8.01	-4.61	-6.91	4.74	4.41	16.98	1.229938	-38.46	82.1
4500	0.01	0.001	126.05	8.41	-4.61	-6.91	4.84	4.64	10.73	1.0306	-40.36	103.715
1500	0.01	0.02	61.59	7.31	-4.61	-3.91	4.12	3.51	18.65	1.270679	-31.68	33.6
3000	0.01	0.02	160.15	8.01	-4.61	-3.91	5.08	4.21	27.99	1.447003	-37.22	67.12
4500	0.01	0.02	131.83	8.41	-4.61	-3.91	4.88	4.76	6.25	0.79588	-41.36	116.805
1500	0.01	0.05	123.13	7.31	-4.61	-3.00	4.81	2.99	13.68	1.136086	-27.67	19.97
3000	0.01	0.05	90.98	8.01	-4.61	-3.00	4.51	3.47	17.92	1.253338	-31.32	32.21
4500	0.01	0.05	55.34	8.41	-4.61	-3.00	4.01	3.09	13.8	1.139879	-28.23	21.89
1500	0.02	0.001	83.53	7.31	-3.91	-6.91	4.43	4.34	5.83	0.765669	-37.7	76.59
3000	0.02	0.001	116.68	8.01	-3.91	-6.91	4.76	4.37	18.95	1.277609	-38.23	79.43
4500	0.02	0.001	130.49	8.41	-3.91	-6.91	4.87	4.64	11.19	1.04883	-40.34	103.43
1500	0.02	0.02	119.94	7.31	-3.91	-3.91	4.79	3.61	19.58	1.291813	-32.42	36.95
3000	0.02	0.02	76.79	8.01	-3.91	-3.91	4.34	4.07	22.04	1.343212	-35.91	58.52
4500	0.02	0.02	142.28	8.41	-3.91	-3.91	4.96	4.77	7.04	0.847573	-41.47	118.28
1500	0.02	0.05	29.62	7.31	-3.91	-3.00	3.39	3.00	5.28	0.722634	-26.36	20.13
3000	0.02	0.05	24.08	8.01	-3.91	-3.00	3.18	2.91	3.7	0.568202	-25.47	18.4
4500	0.02	0.05	50.15	8.41	-3.91	-3.00	3.92	3.14	10.28	1.011993	-28.07	23.2

4.5 Multiple Linear Regression Analysis

After all the data was consolidated and organized there was one value for a particular combination for speed, feed and depth of cut as can be observed from the tables showing the data. Now, It was required to convert these values into models which would have equations giving us the empirical releion between the operating parameters. For this purpose the Linear regression Software was chosen. This software has been written in QBASIC. It can take any number of dependent and independent variables and then on running the program the output comes in the form of equation giving the relation between the dependent and the independent variable. It also performs the ANOVA test and gives the Correlation coefficient. These values for cutting in all three directions were fed to the Qbasic program and the program was run.

As an eg. consider the Rku value for cutting in the X direction. The program asks for the number of dependent and independent variables first. For all the calculations the number of dependent variables is 1 and the number of independent variables is 3. In this example the dependent variable is the Rku value. For ease of developing the model the Ln values for each of the parameters were calculated and then they were fed into the software. After the dependent variable it asks for the independent variable. The independent variables are the three operating parameters of speed, feed and depth of cut. then it asks for the number of experiments. In all the calculations the number of experiments are 36 as there are 36 values for cutting in each direction. Then the sofware one by one asks for each of these values for the dependent and independent variables and after inputting all these required values it comes out with the Regression equation and also performs all the ANOVA tests and correlation coefficients.

The final equations for cutting in all the three directions are shown below. Thus a model was developed for cutting in each of the three directions.

4.6 Results of the MultiLinear Regression Software Analysis Regression Equations for Cutting in X Direction

1) ln Rku = (0.136077) * ln speed + (-0.1330632) * ln feed + (1.213256E-02) * ln depth + (-0.4251051).

2) ln Ra = (-0.2062035) * ln speed + (0.2404485) * ln feed + (1.6167E-02) * ln depth + 6.016497

3) ln Rq = (-0.17784) * ln speed + (0.2054301) * ln feed + (1.873142E-02) * ln depth + 5.87079

4) ln Rp = (-4.876471E-02) * ln speed + (0.1021114) * ln feed + (-3.2936E-02) * ln depth + 5.527573

5) ln Rt = (-0.0680707) * ln speed + (8.135596E-02) * ln feed + (-1.5319E-03) * ln depth + (-0.4251051).

6) ln Fmax = (0.1186844) * ln speed + (7.133371E-03) * ln feed + (-0.1441128) * ln depth + 2.804687

7) ln Favg = (0.1781353) * ln speed + (-0.1317902) * ln feed + (-0.1881687) * ln depth + (-0.4251051).

4.7 Regression Equations for Cutting in XY Direction

1) $\ln Rku = (-0.1261514) * \ln speed + (-0.1423992) * \ln feed + (-5.987179E-04) * \ln depth + 1.514614$

2) $\ln Ra = (-0.1716371) * \ln speed + (0.2690618) * \ln feed + (2.824453E-03) * \ln depth + 5.851625$

3) $\ln Rq = (-0.2058754) * \ln speed + (0.2282762) * \ln feed + (1.639987E-02) * \ln depth + 6.220438$

4) $\ln Rp = (-0.3946911) * \ln speed + (3.852698E-02) * \ln feed + (-4.633745E-02) * \ln depth + 7.929195$

5) $\ln Rt = (-0.3712539) * \ln speed + (6.579253E-02) * \ln feed + (-1.701049E-02) * \ln depth + 8.563513$

6) $\ln Fmax = (5.9946E-02) * \ln speed + (6.914892E-04) * \ln feed + (-9.943058E-02) * \ln depth + 3.585588$

7) $\ln Favg = (0.2276881) * \ln speed + (0.1099545) * \ln feed + (-0.1939957) * \ln depth + (1.742931)$.

4.8 Regression Equations for Cutting in Y Direction

1) $\ln Rku = (1.138669E-02) * \ln speed + (-0.1745235) * \ln feed + (4.151705E-02) * \ln depth + 0.4749272$

2) $\ln Ra = (-5.948769E-03) * \ln speed + (0.3370222) * \ln feed + (8.871399E-03) * \ln depth + 4.873497$

3) $\ln Rq = (1.213428E-02) * \ln speed + (0.2893321) * \ln feed + (2.253844E-02) * \ln depth + 4.811023$

4) $\ln Rp = (6.484896E\text{-}02) * \ln speed + (0.1049619) * \ln feed + (0.0548048) * \ln depth + 5.093226$

5) $\ln Rt = (0.1523802) * \ln speed + (0.1158374) * \ln feed + (7.026348E\text{-}02) * \ln depth + 5.097253$

6) $\ln Fmax = (0.0577496) * \ln speed + (-5.724295E\text{-}02) * \ln feed + (-0.1086182) * \ln depth + 3.273687$

7) $\ln Favg = (0.2608871) * \ln speed + (3.964887E\text{-}02) * \ln feed + (-0.2237481) * \ln depth + 0.9777973$

The above equations give the relationship between the various Surface Quality parameters, Cutting Forces and the operating parameters of speed, feed and depth of cut. Thus, by plugging in numbers it is now possible to predict the Surface Quality and the Cutting force before the actual machining could be carried out. This gives the operator an idea as to what the Surface Finish could be after the machining would be done. Due to this, the operator could actually be able to select before hand the almost accurate speed, feed and depth of cut that he would need to obtain the desired surface finish. Thus, the Multiple Regression Analysis Software was used to develop these models.

4.9 Table Curve Software

The table Curve Software was used to develop the relation between the Surface Quality parameters and the Cutting force parameters. This software is much more sophisticated than the Multiple Linear Regression Software. This software has been developed by Jindel Scientific. The working of this software was described in bried in the earlier chapter. In this software there is a FILE Menu which enables us to import data from excel or Lotus spreadsheet into the software. The data that was consolidated was saved on excel spreadsheet and the columns which had this data were saved onto a clipboard. This clipboard was imported from the excel spreadsheet into the Jandel Scientific Table Curve Software. After the import was carried out, the processing of the data was done by selecting the process menu. the best fit curve was selected. This software gives the output of only 2 different parameters, one is the dependent and the other is the independent. The interest of the research was to develop a relation between the Surface Quality parameter and the Cutting force parameter. Here. the Surface texture parameter was highlighted as the X value and the cutting force as the Y. The equation was in the form of Y = constant x X, thus giving the relation between the Surface Quality parameter and the Cutting force parameter. In this research work there are 5 Surface Texture parameters, the maximum cutting force and the avg. cutting force. Hence, this software gave 10 graphs taking into consideration all the combinations. Since there are 3 directions of cutting , it gave these 10 graphs for each of the three directions, thus resulting into 30 graphs, which took care of all the combinations.

Plottings in figures 4.1, 4.2, 4.3, 4.4 are some of the core graphs which give the relationship between the cutting force and the surface quality parameters. The remaining graphs are attached in the appendix.

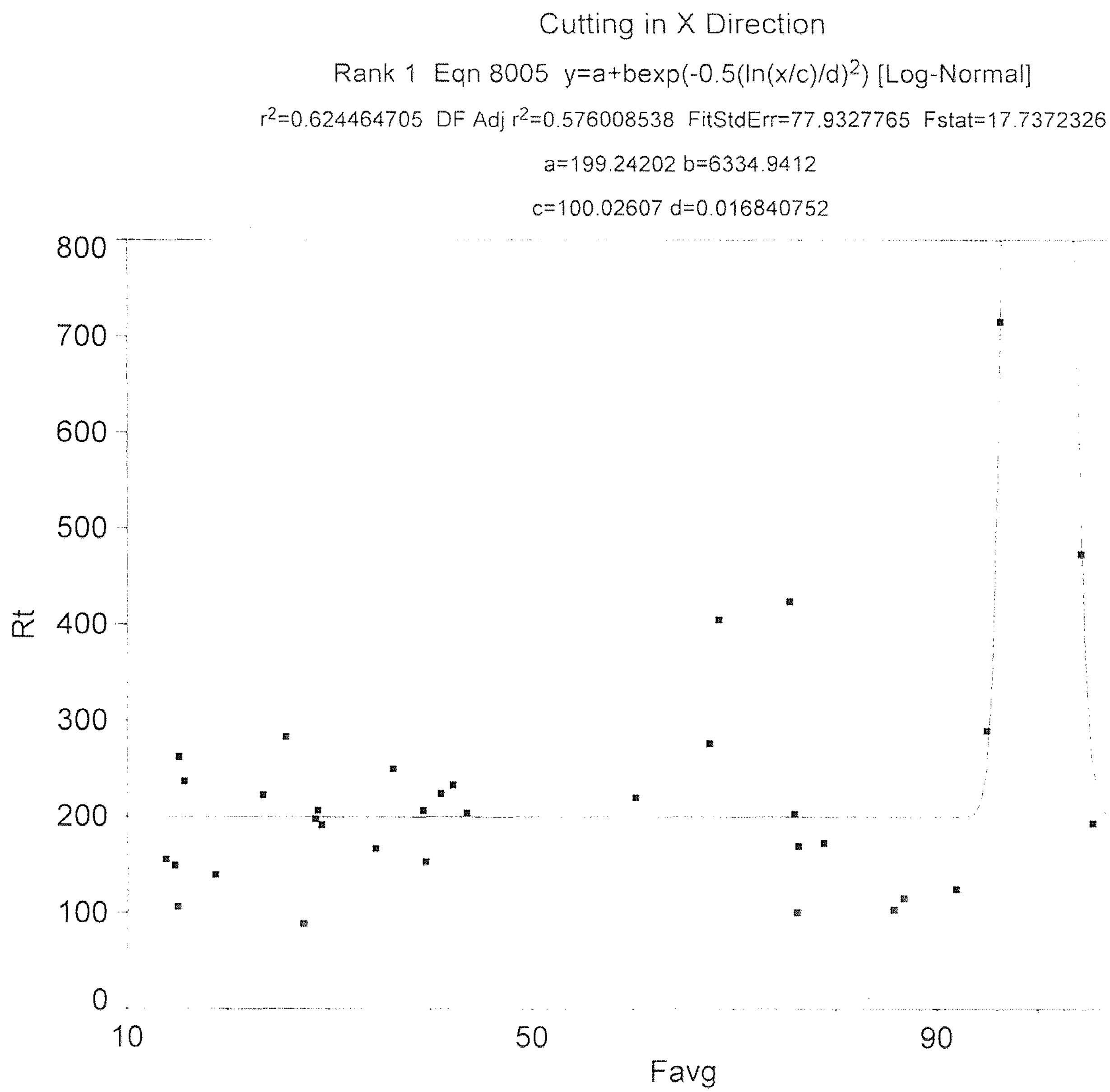


Fig 4.1 Curve Fit using Table Curve

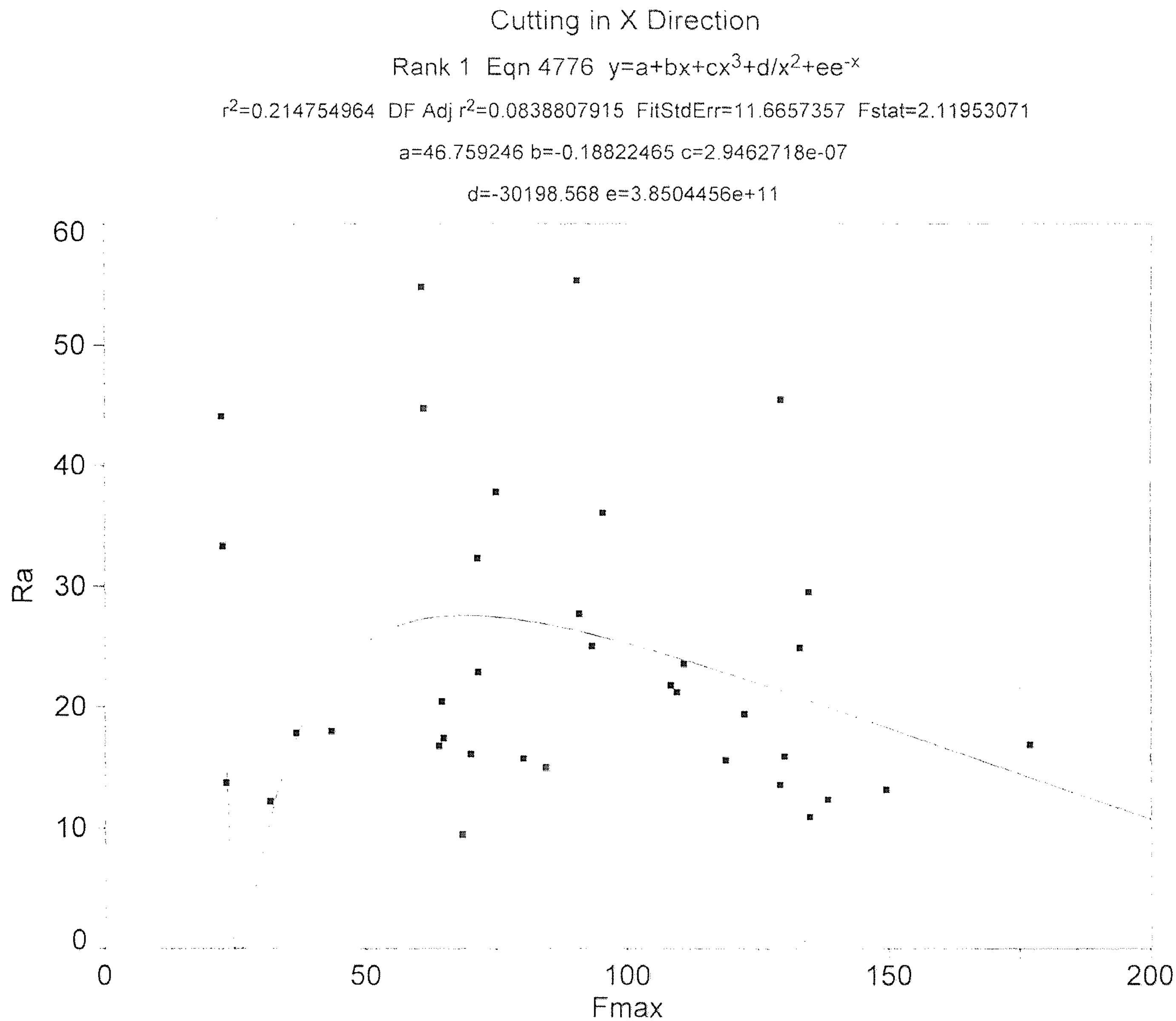


Fig 4.2 Curve Fit using Table Curve

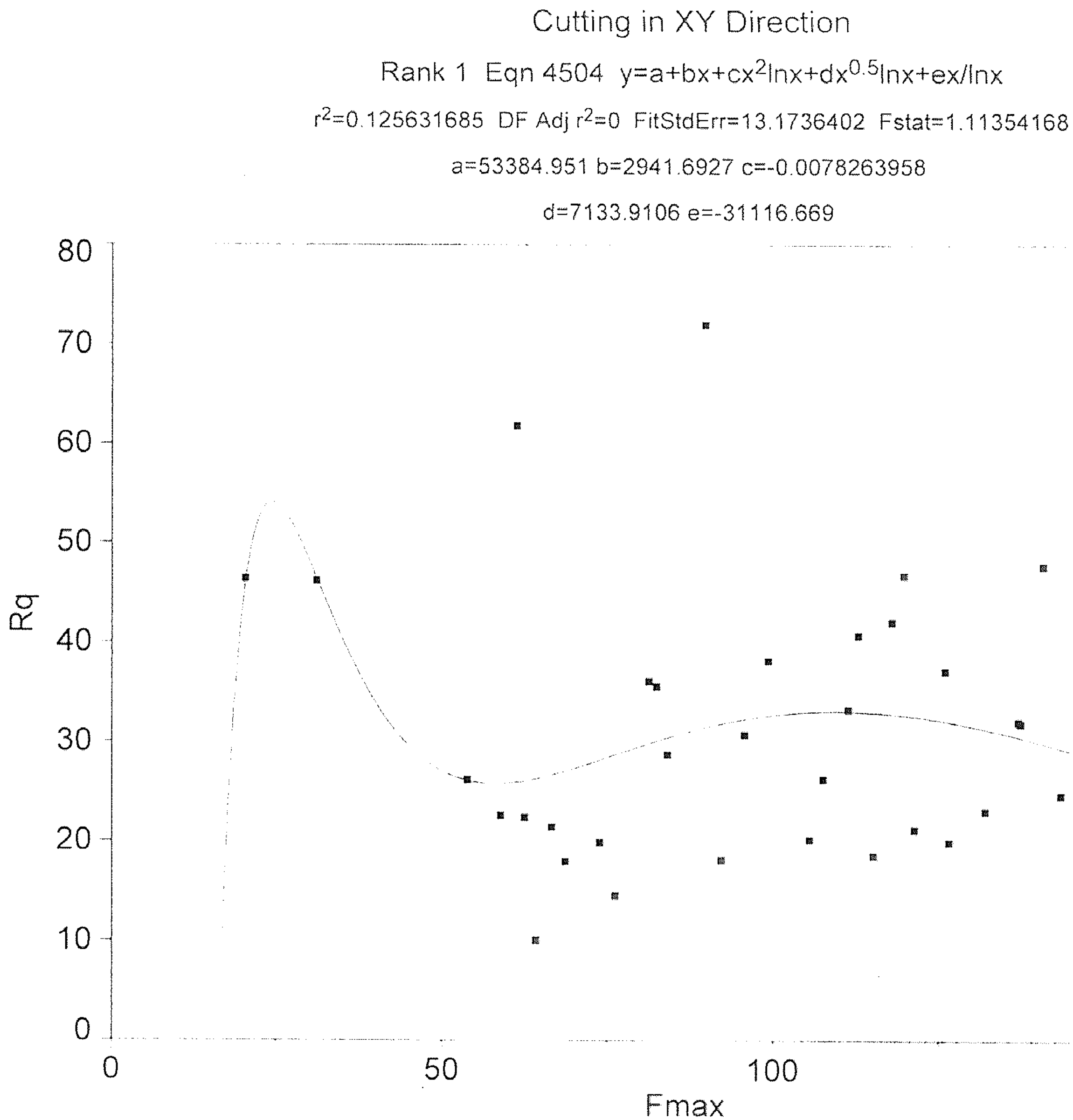


Fig 4.3 Curve Fit using Table Curve

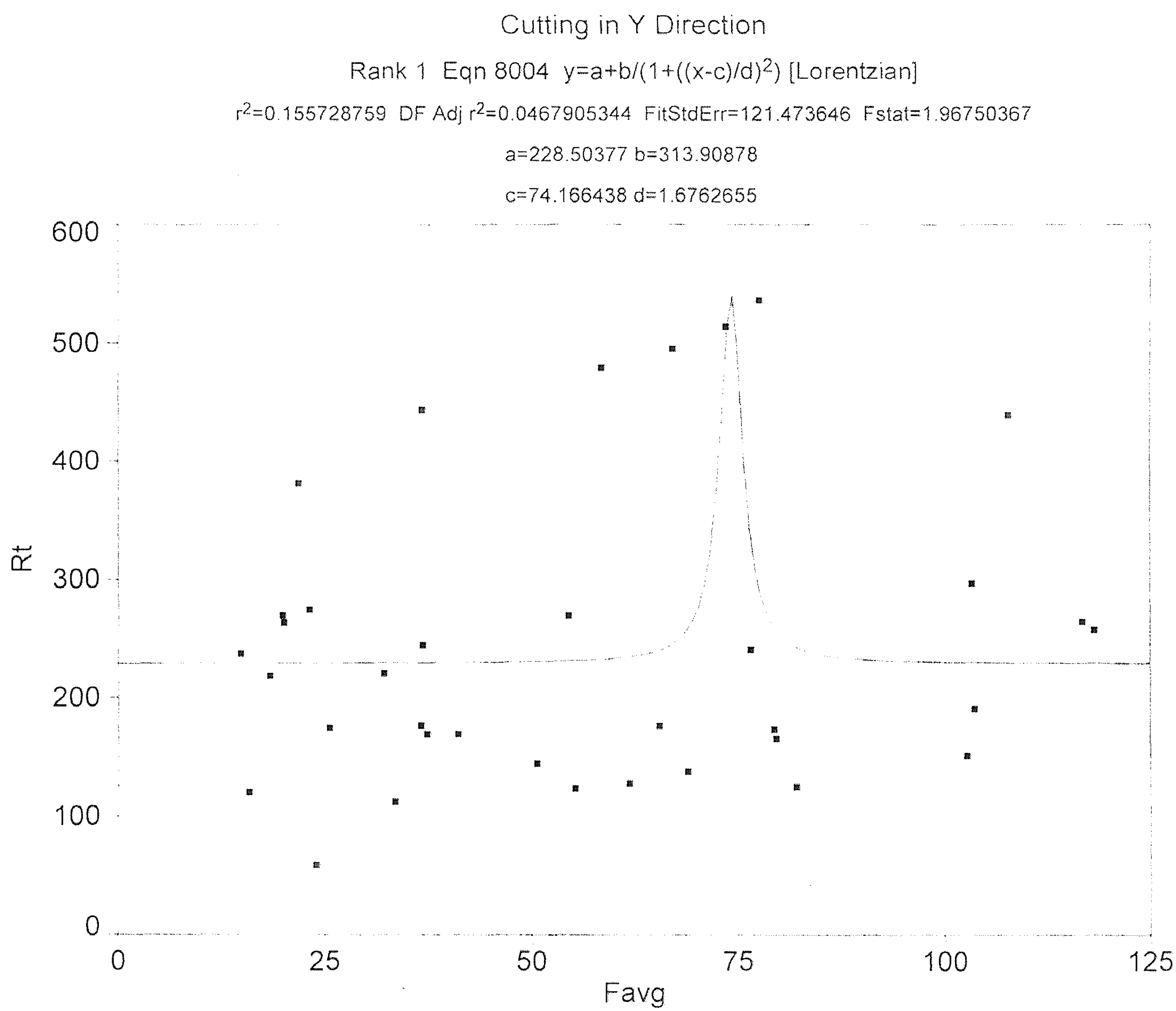


Fig 4.4 Curve Fit using Table Curve

4.10 Comparison of Different Operating Parameters at Different Levels of Cutting

Once these relations were established it was further of interest of the research work to compare the different operating parameters at different levels of cutting. The entire data was sorted in the ascending order of speed, feed and depth of cut and then graphs were plotted with the Surface Quality parameter on the Y axis and the feedrates on the X axis. Each graph would have 9 lines on it and this would help to compare visually between the different operating parameters at the different levels of cutting.

The graphs 4.5, 4.6, 4.7, 4.8, 4.9, 4.10, and 4.11 show the core comparisons for cutting in the three different directions. The remaining graphs are attached in the appendix.

For e.g. a graph with the Rku values on the Y axis and the feedrates on the X axis gives the comparison between the Rku values at different levels of cutting in the X direction. Similarly graphs were obtained for analysis for all other Surface Texture parameters and Cutting forces for cutting in the X, XY and Y direction.

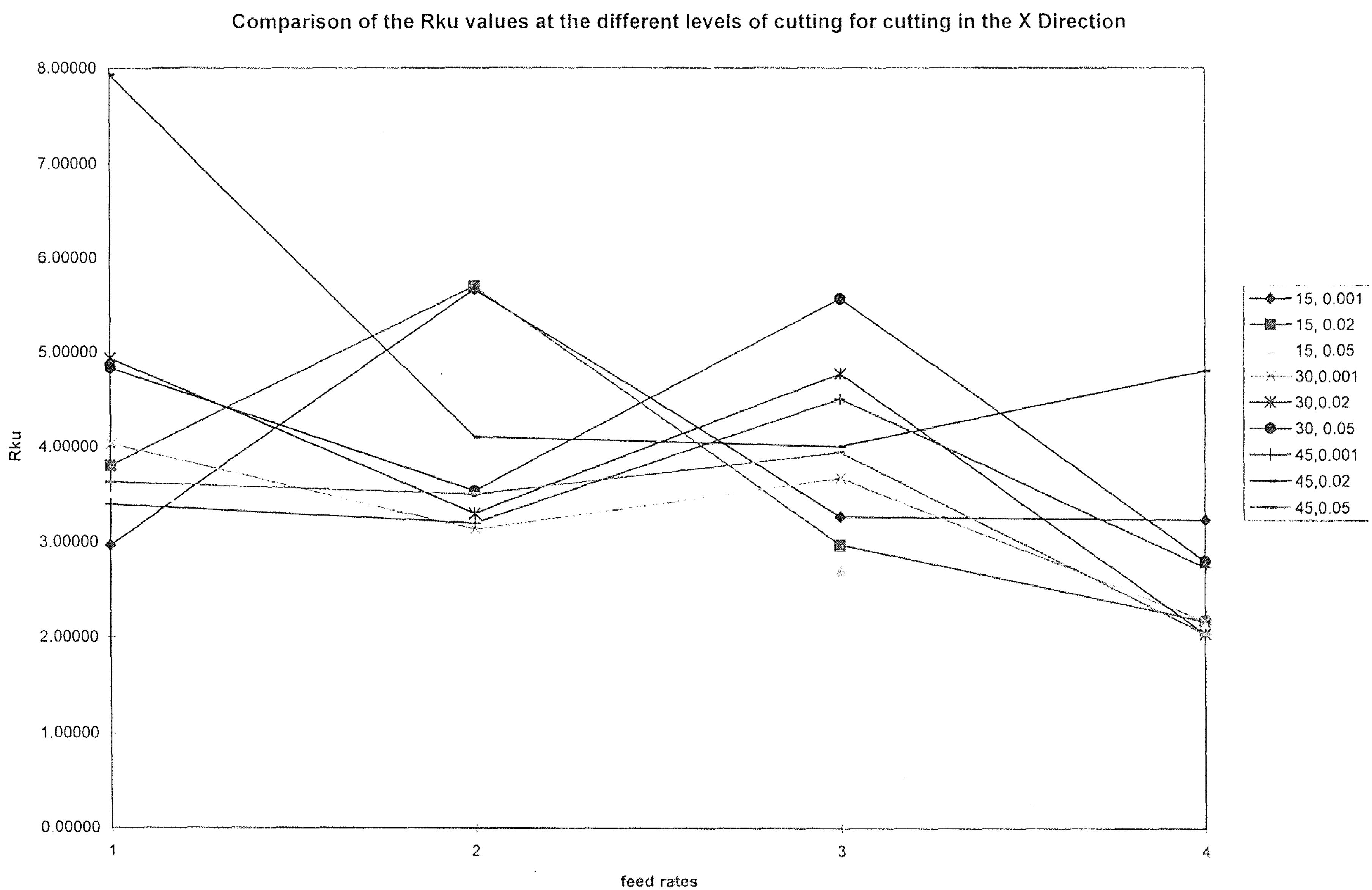


Fig 4.5 Comparison graph

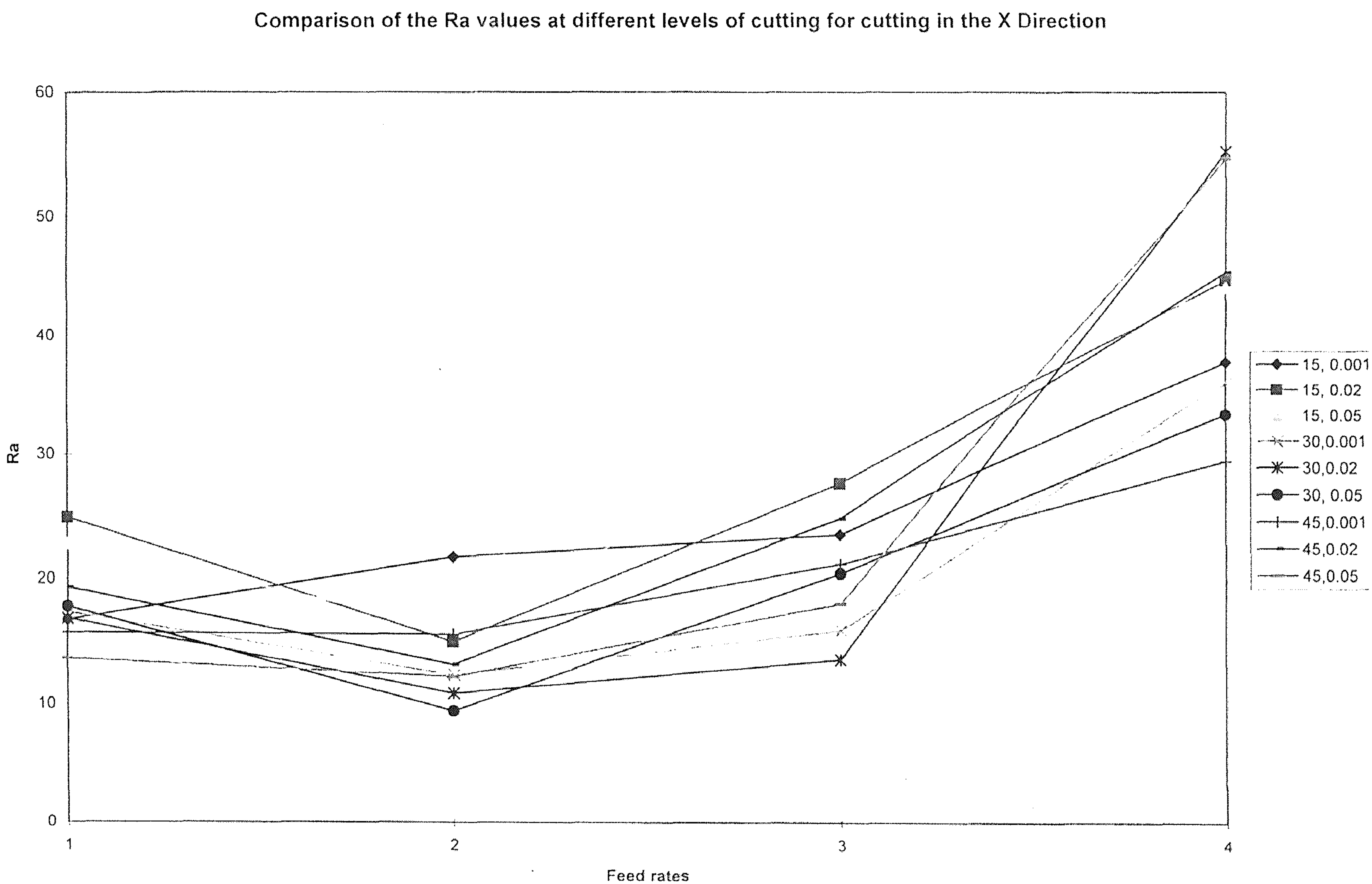


Fig 4.6 Comparison graph

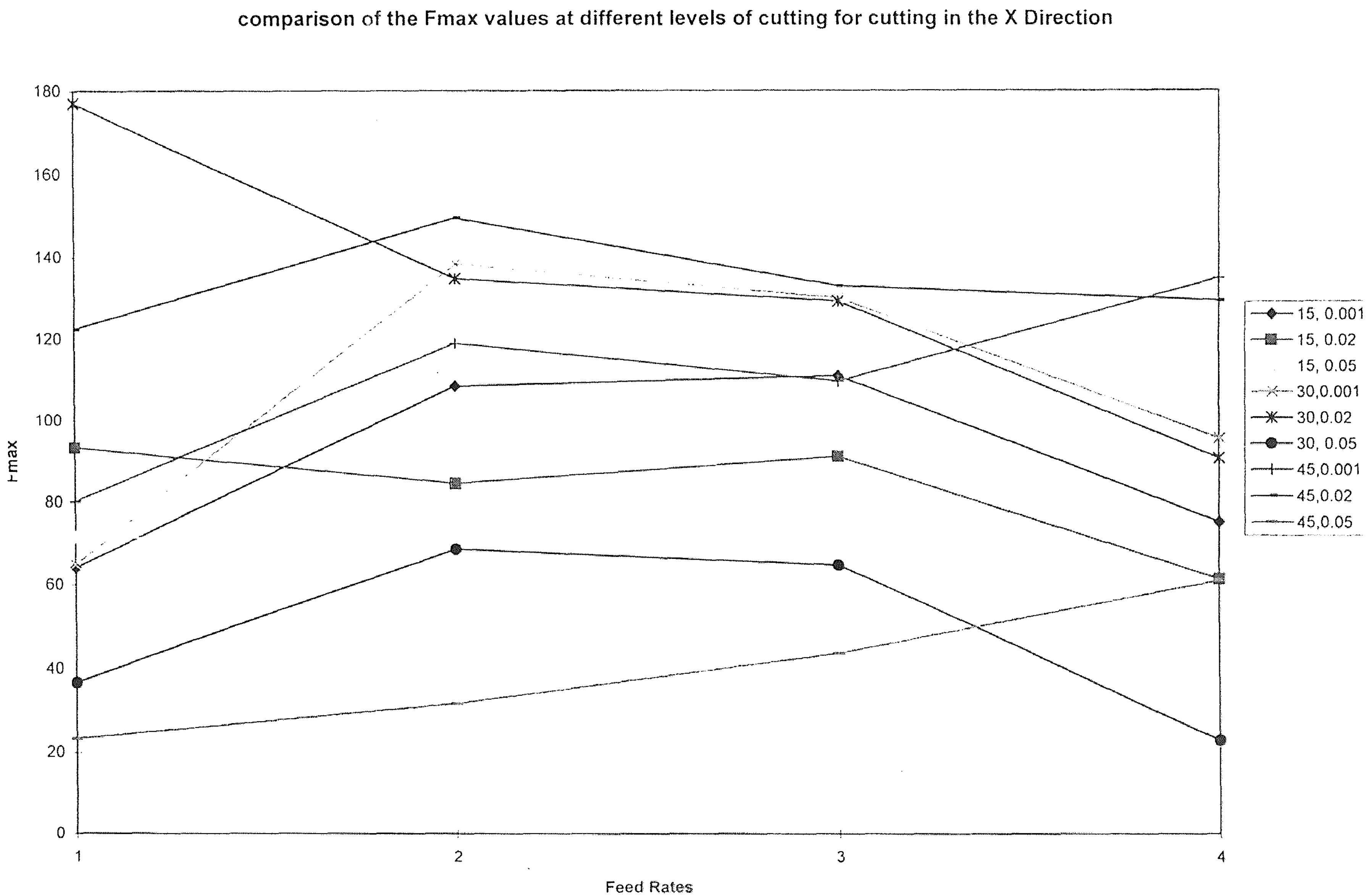


Fig 4.7 Comparison graph

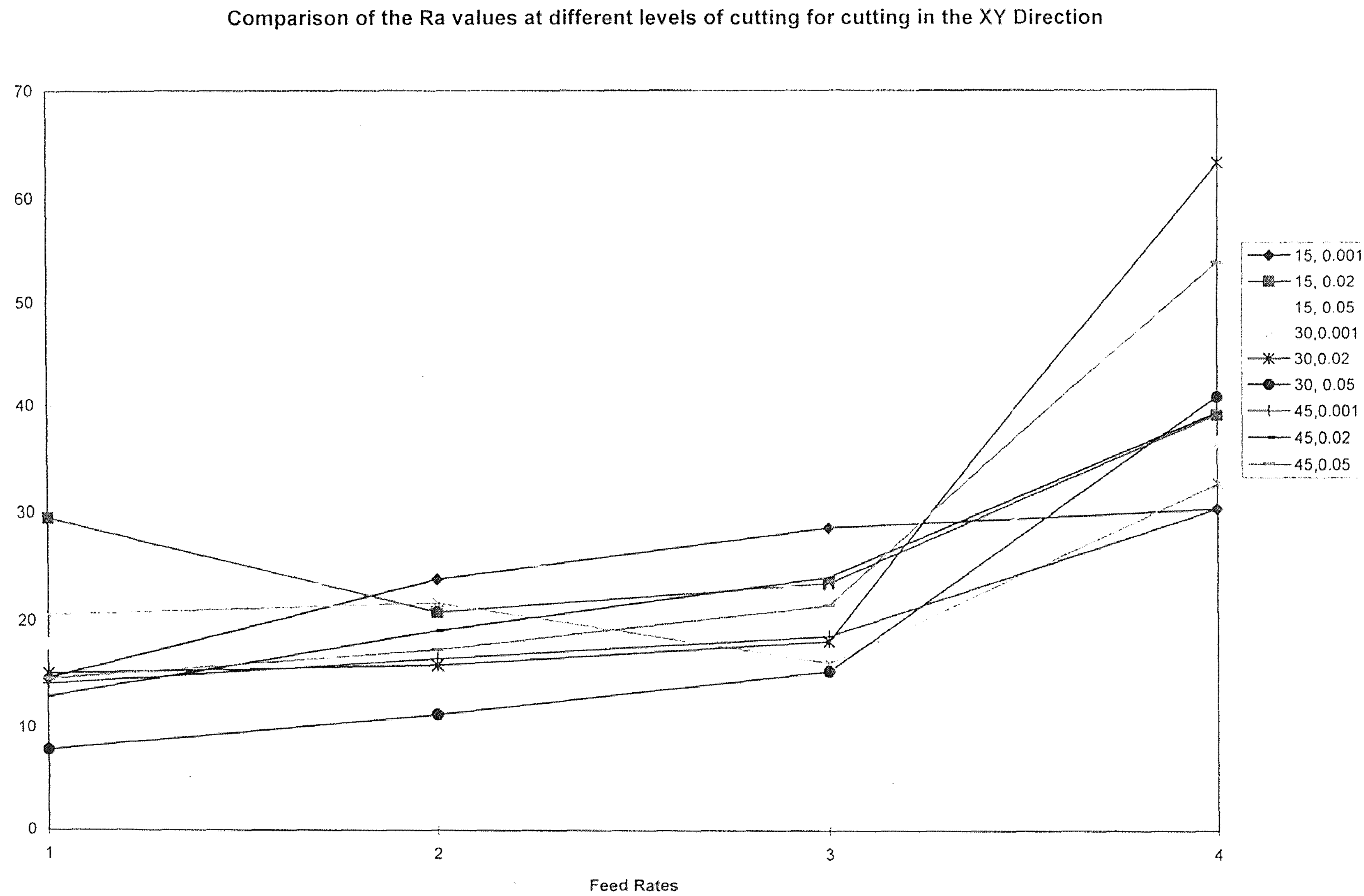


Fig 4.8 Comparison graph

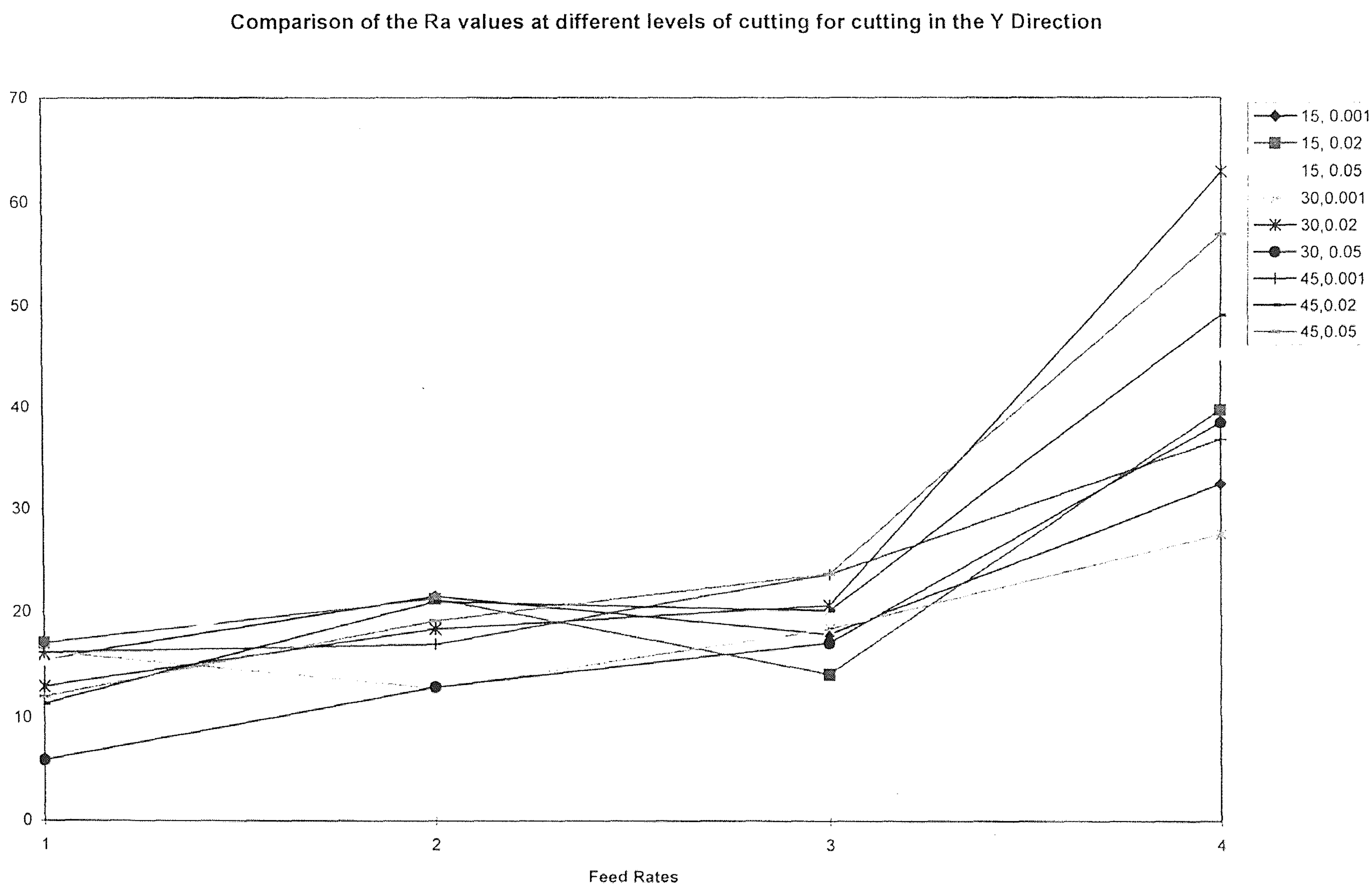


Fig 4.9 Comparison graph

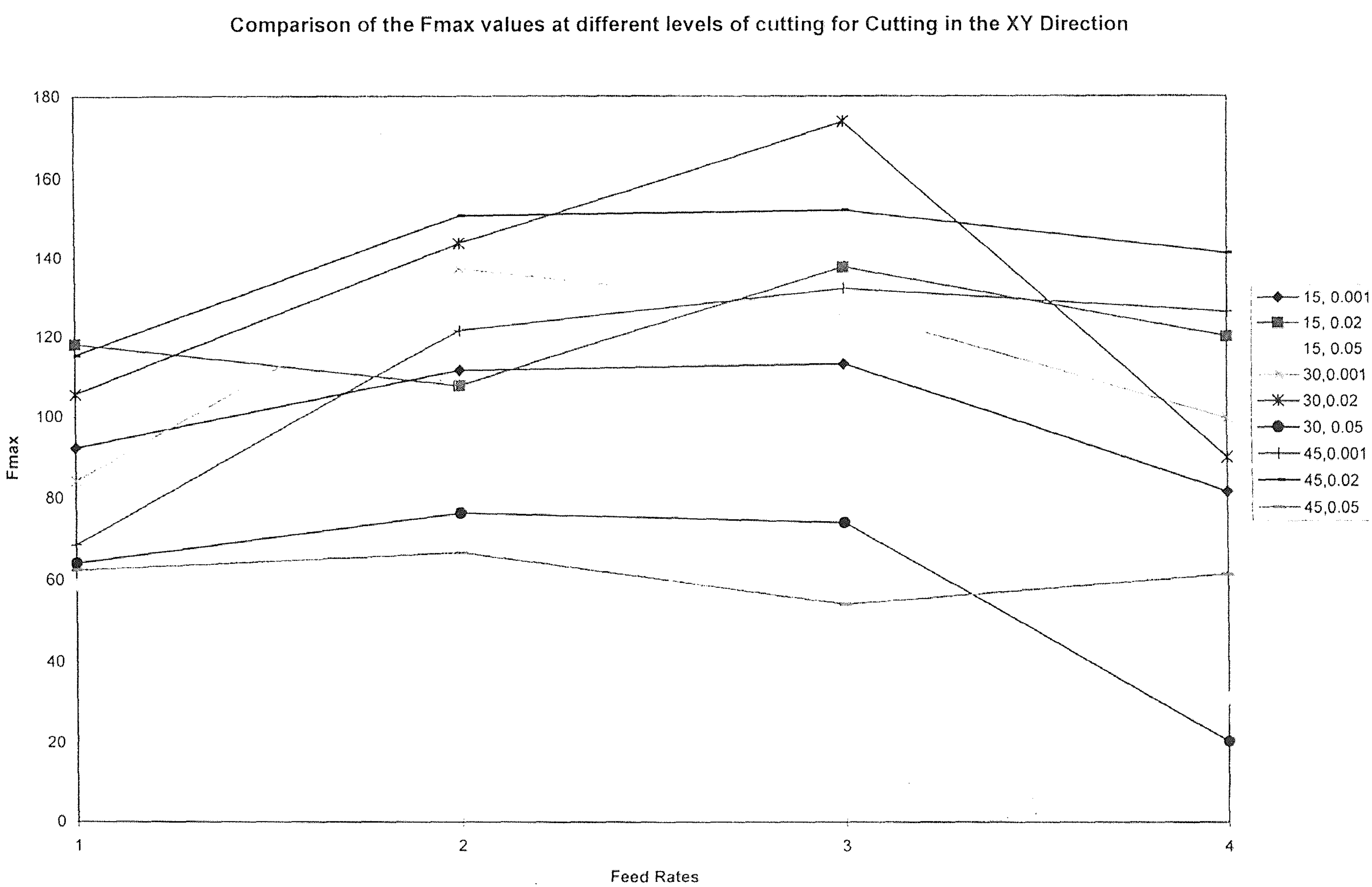


Fig 4.10 Comparison graph

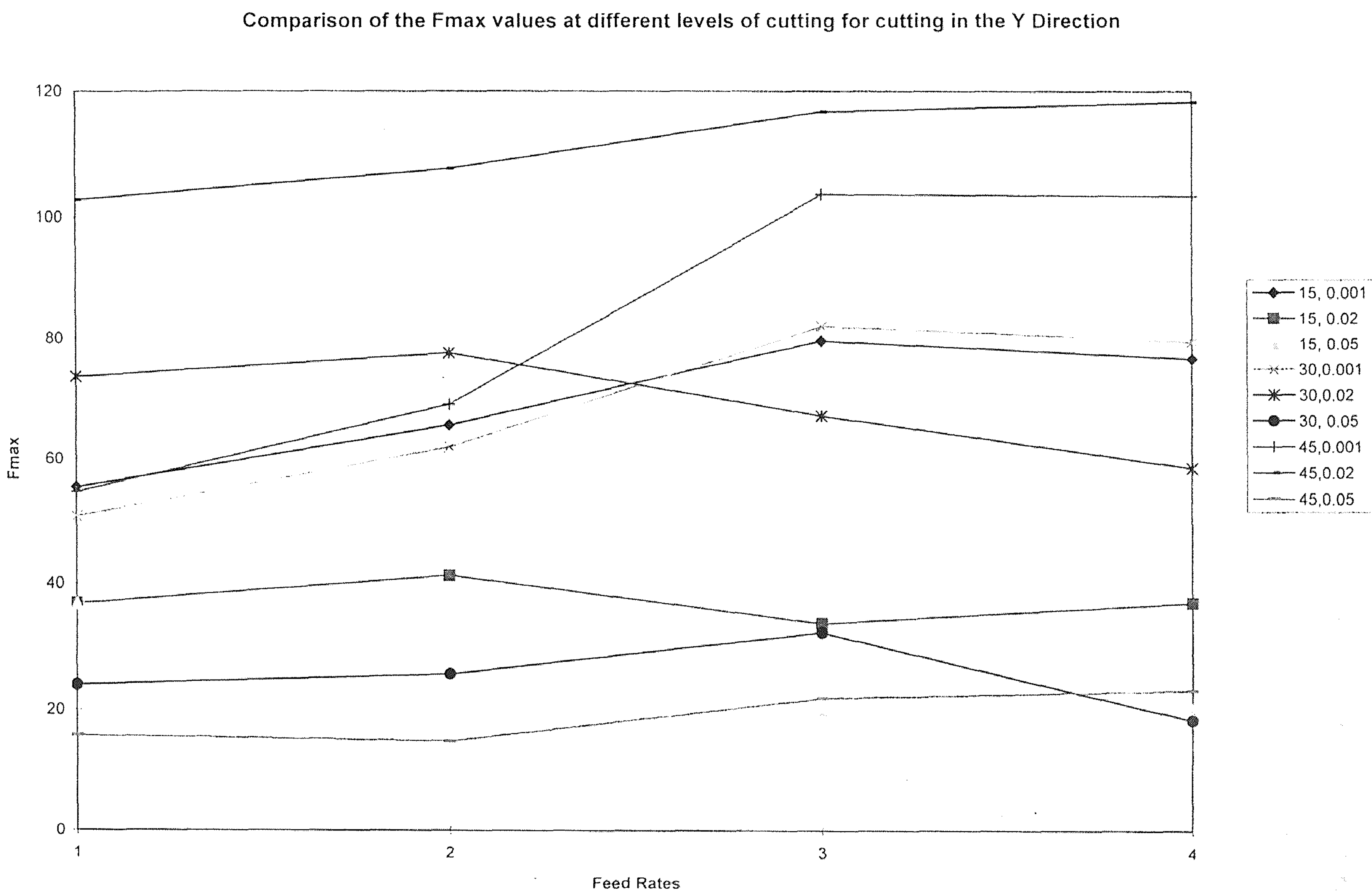


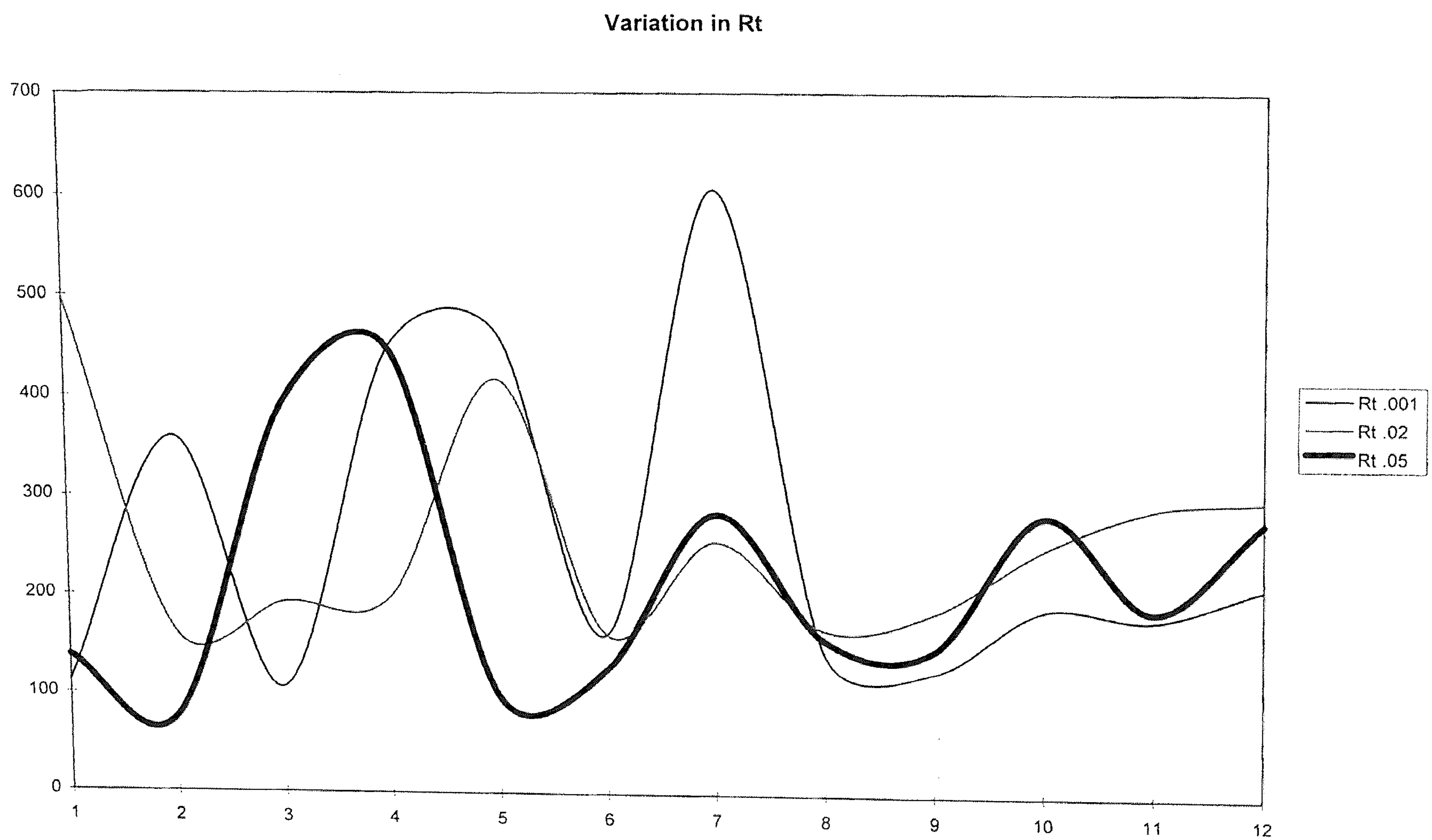
Fig 4.11 Comparison graph

4.11 Variation in the Surface Texture Parameters and the Cutting forces

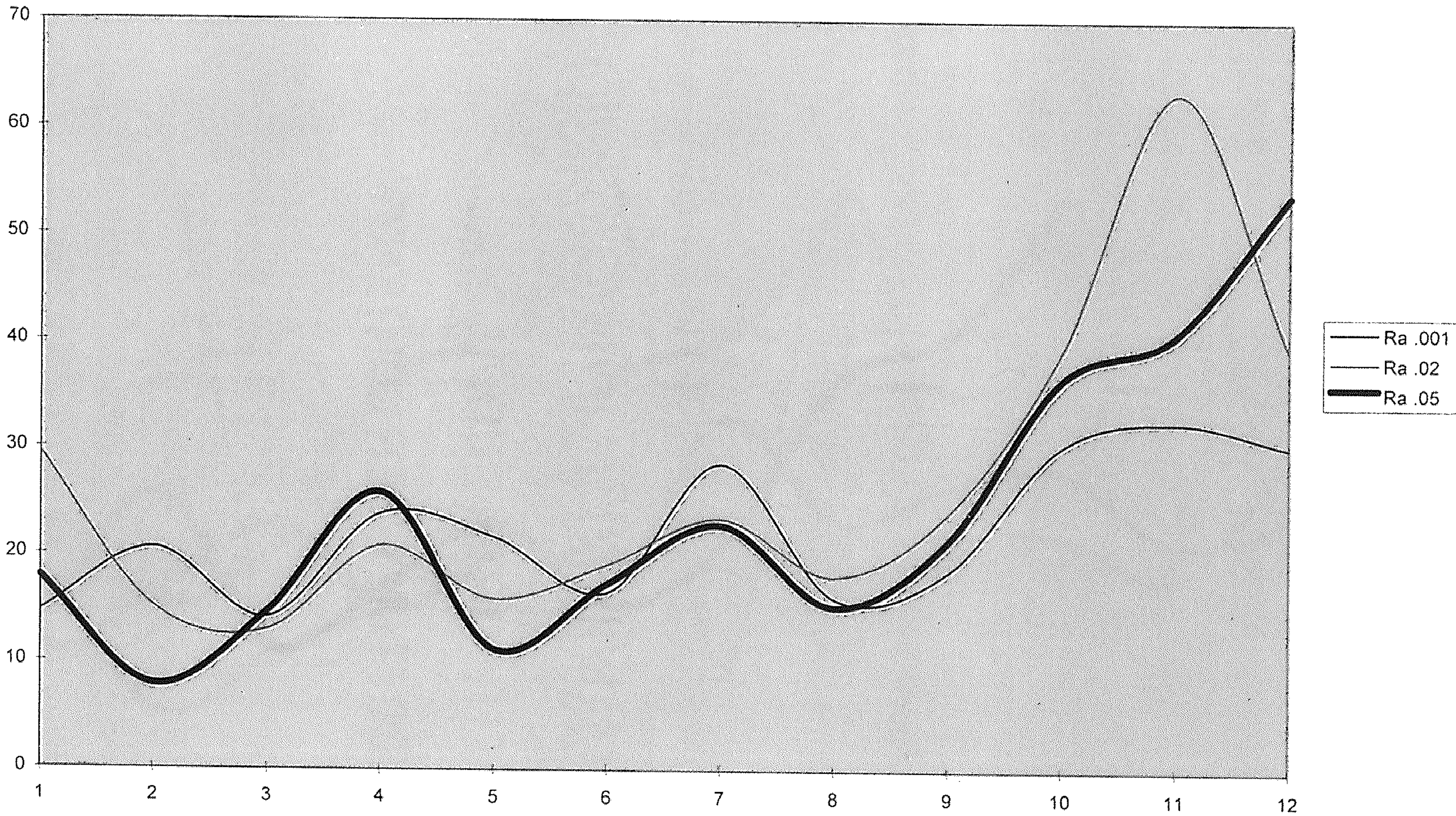
Proceeding towards the final stage of the case study, graphs were plotted which show the variation of the Surface Texture parameter / cutting force parameter at the different feedrates. In these graphs the Y axis is the Surface Texture / Cutting force parameter and the X axis is the number of points for the corresponding operating parameter under consideration.

There are 36 values for each of the cutting directions. There are 3 speeds 4 feeds and 3 depths of cuts. If the variation of Rku for eg. has to be studied with respect to the different spindle speeds then the Y axis will have all the Rku values and the X axis will have the 12 points for each spindle speed. The graph will show 3 curves, one for each spindle speed , thus making it very simple to visually analyze the variation of the parameter under consideration.

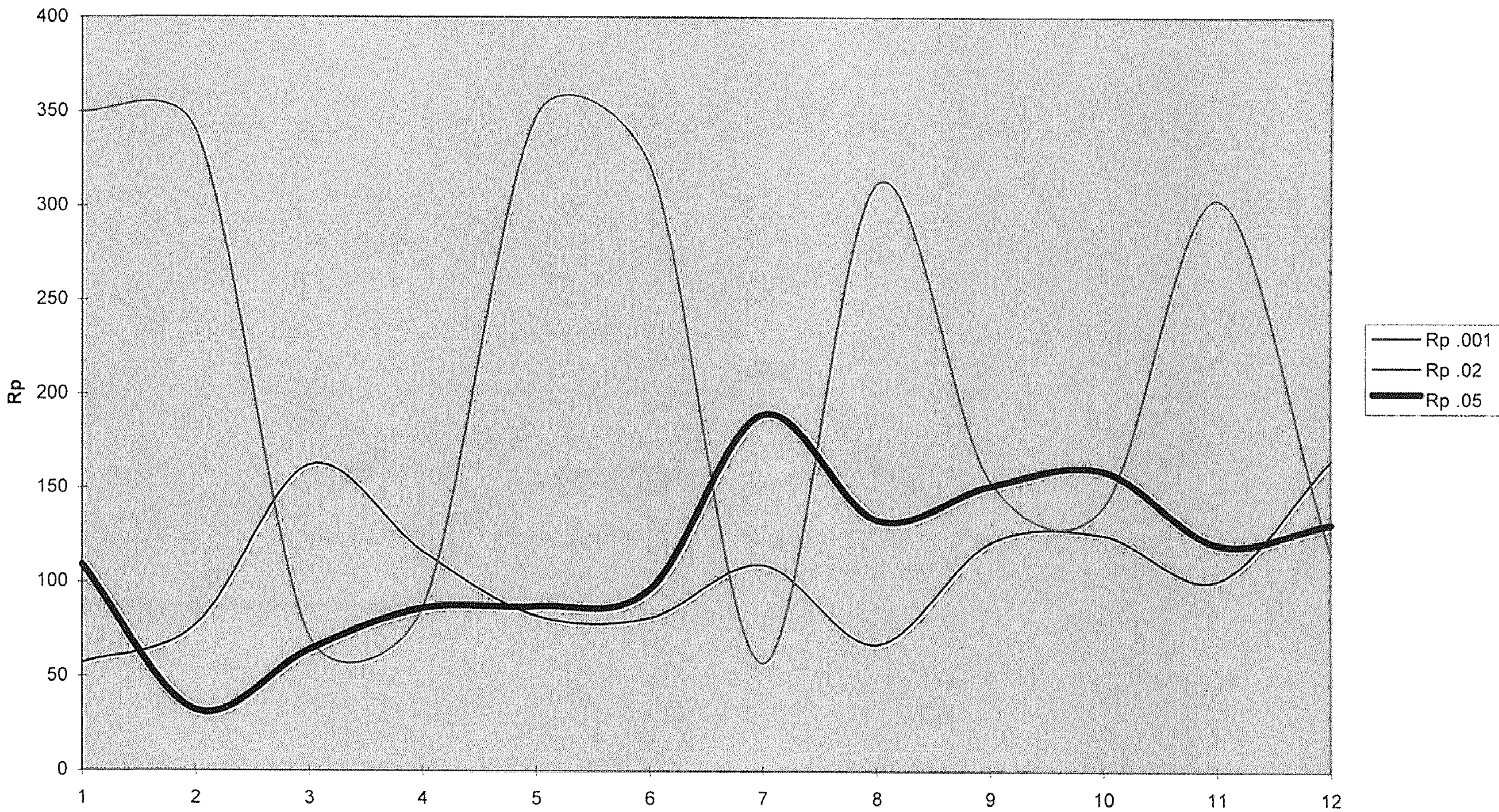
Similarly the variation graphs for other parameters and directions of cutting were plotted. It was observed that the Ra and Rq showed a similar variation pattern for cutting in all the three directions. Similarities were also observed between the Rp and the Rt values. That consistency supports the fact that Rp and Rt are the peak value measurements and that Rq is the RMS parameter for Ra. Some of the important graphs are shown below and the rest are attached in the appendix.

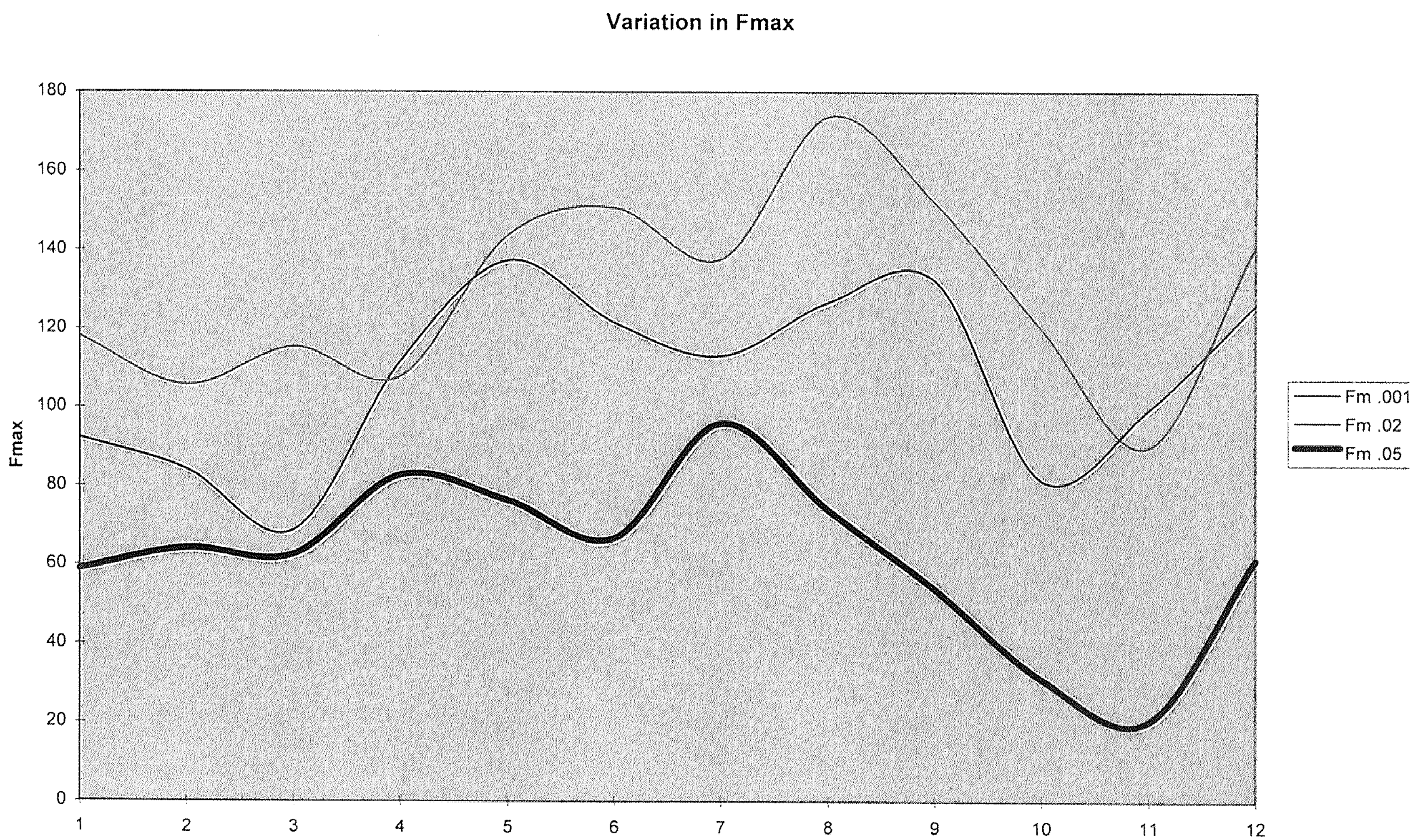

Variation in Rt
700
600
500
400
300
200
100
0
1
2
3
4
5
6
7
8
9
10
11
12
Rt .001
Rt .02
Rt .05

Variation in Ra

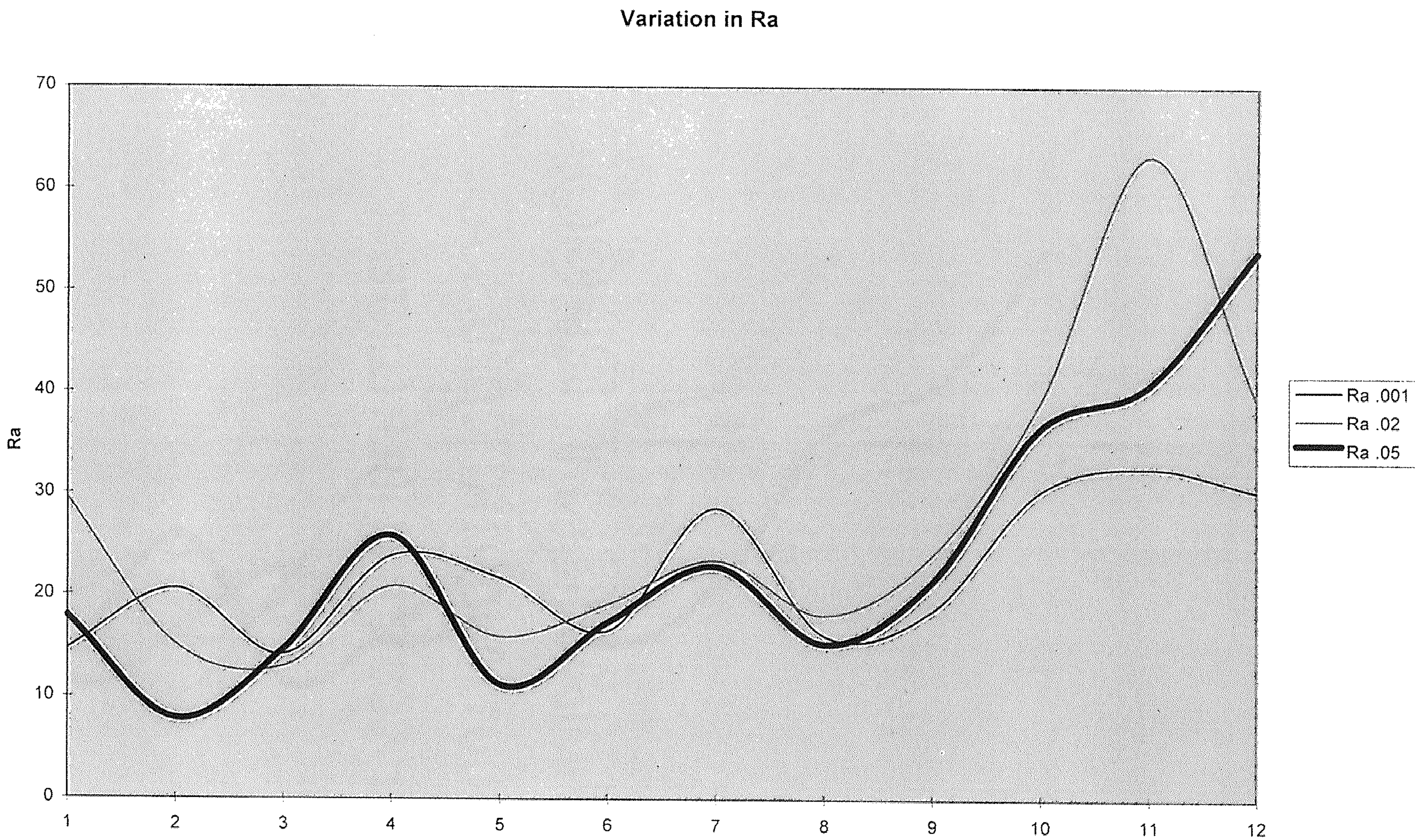


Variation in Rp

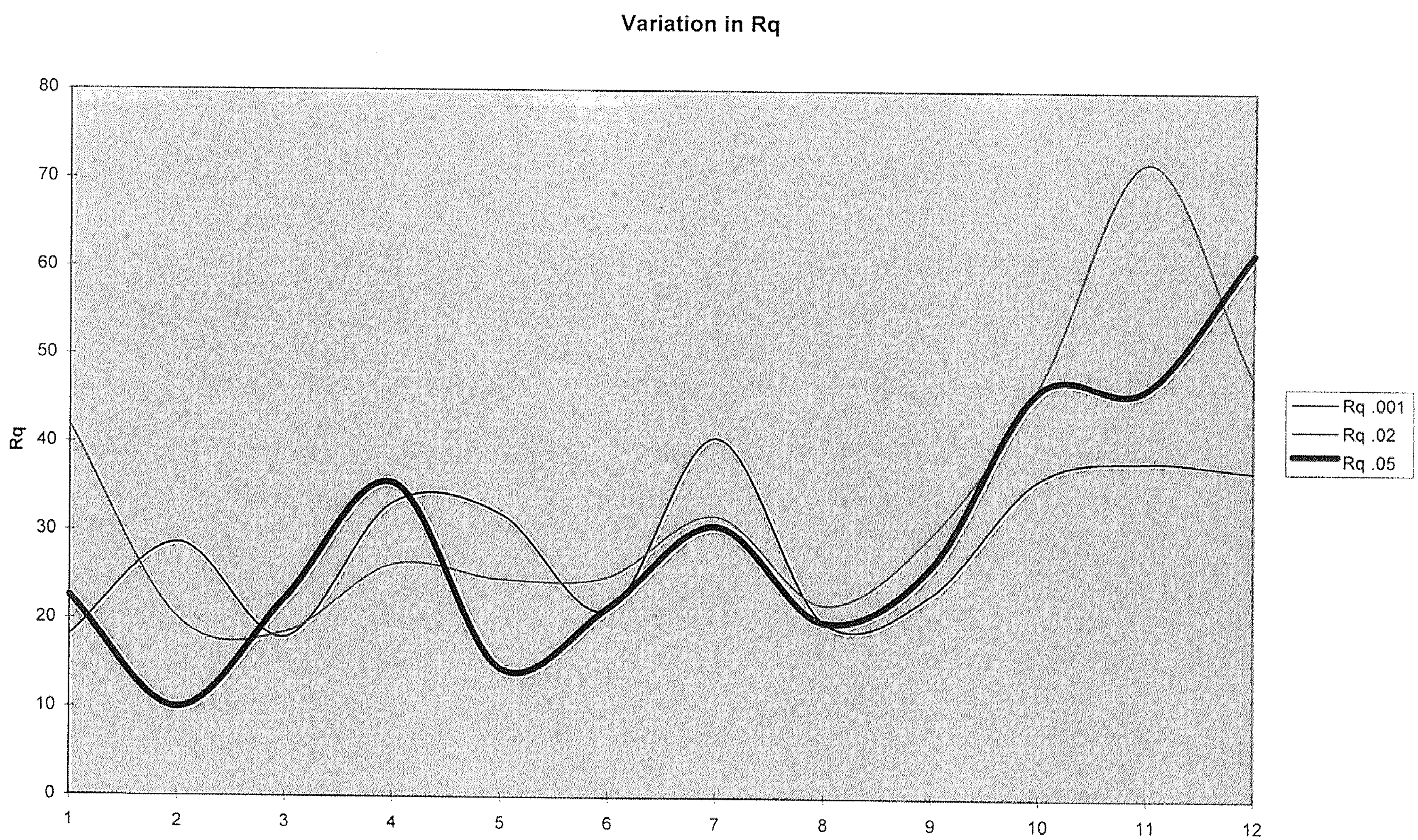


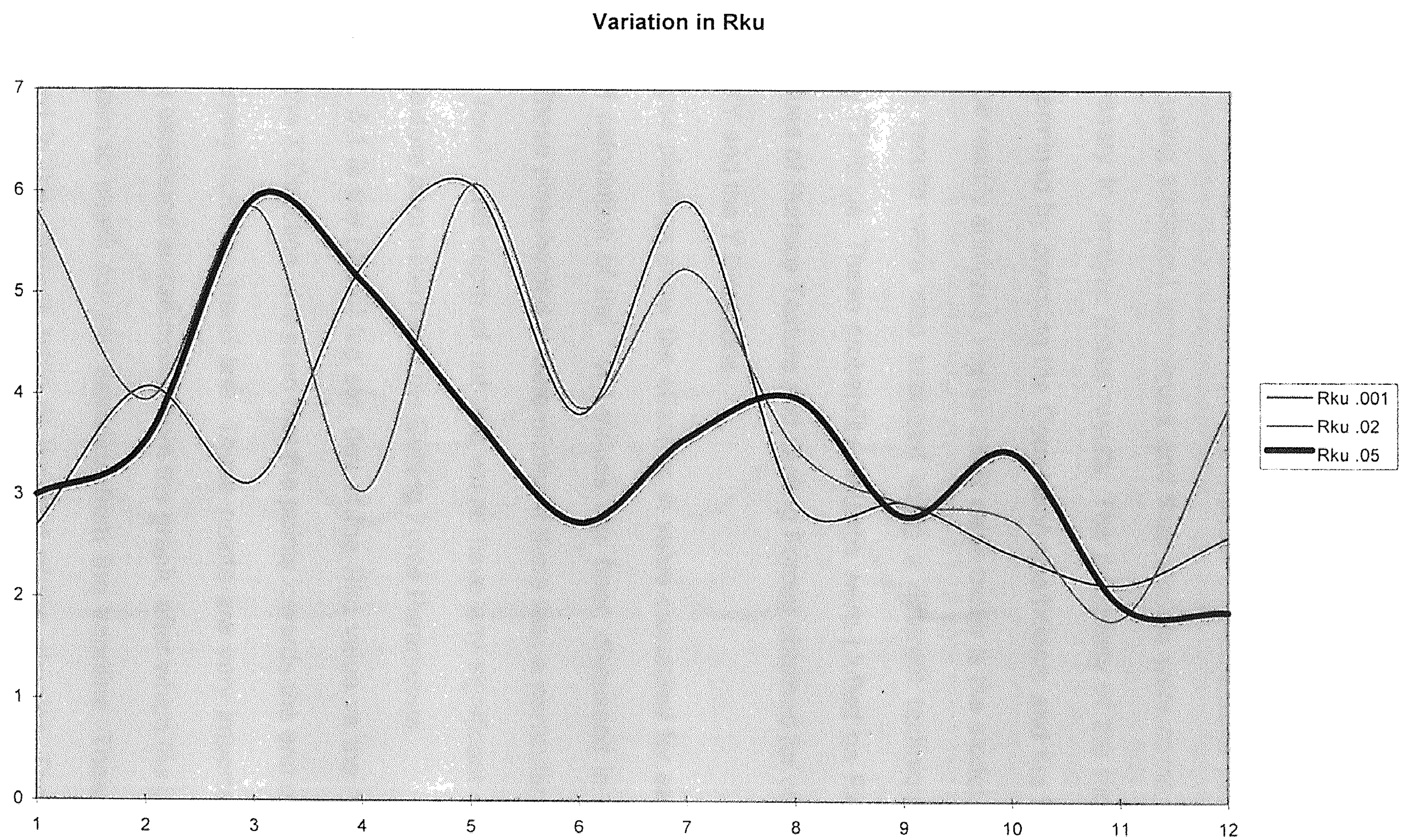


Variation in Fmax
Fmax
180
160
140
120
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
11
12
Fm .001
Fm .02
Fm .05



Variation in Ra
Ra
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
11
12
Ra .001
Ra .02
Ra .05


Variation in Rq
80
70
60
50
40
30
20
10
0
Rq
1
2
3
4
5
6
7
8
9
10
11
12
Rq .001
Rq .02
Rq .05



Variation in Rku
7
6
5
4
3
2
1
0
1
2
3
4
5
6
7
8
9
10
11
12
Rku .001
Rku .02
Rku .05

CHAPTER 5

5.1 ANALYSIS OF RESULTS

The results that were obtained from the number of experiments performed were analyzed using statistical techniques and thus models were come up with. It is now necessary to analyze these results. The adequacy of the models can be easily determined by checking the Correlation coefficients and the F values and they can be readily analyzed. Higher the R value better is the model.

The results were also analyzed using a different technique called the Probability Plottings. These probability plottings were plotted on Excel by using the 36 values of Surface Texture and Cutting Forces obtained for cutting in each of the X, XY and the Y Directions.

These plottings show the effect vs vi value calculated for each plot. The method of calculation of the " vi " values has been discussed in the previous chapter. These plots helped in determining if there was a particular combination of speed, feed , and depth of cut that would have any significant effect on the Surface Texture parameters and the Cutting Force Parameters.

Fig. 5.1 is the plot of log std. dev of the Rku value vs the "Vi" value for cutting in the X Direction. It is seen that the points towards the end of the plotting deviate largely from the trend line. These points are very important and they have to be separated and removed from the graph, after which the graph can be plotted again to check for any deviation from the trendline. These points are summarized in the analysis table at the end of the chapter. The figures 5.2

through 5.11 are the plottings for the effects of the different surface quality and cutting force parameters.

These are the possible combinations and any of the above combinations may have a significant effect on the Surface Texture parameter or/and the Cutting force parameter. Thus for a particular parameter, e.g. Rku, the effect was calculated for the Rku value for cutting in the X Direction. The effect is calculated as the difference between the maximum and the minimum of the Rku value for that particular combination. Similarly the effects were calculated for Ra, Rq, Rp, Rt, Fmax, their log standard deviations and the Signal to noise ratios. These effects were arranged in the ascending order and then vi was calculated.

$$vi = (n - 0.5)/n * 100$$

where n is the number of combinations into consideration for that particular probability plot.

Thus, the vi values and the effects are calculated and then the graph of effect versus the vi is plotted. After the graph is plotted a linear trendline is established to check whether all the points follow the trend or not. If any point does not seem to follow the trend it is separated and the graph is plot again. This procedure is carried out until a linear trend is observed. These probability plottings determine any significance of any particular operating parameter as main effect, or the two interaction effect or the triple interaction effect.

Some of the important probability plots are as shown below and the remaining are attached in the appendix. The analysis of these probability plottings for the Surface Texture parameters are shown in the excel spreadsheet which has been imported from Microsoft Excel after summarizing the entire data from the probability plottings.

It was observed after the analysis that the operating parameters of speed , feed and depth of cut by themselves had no significant effect on the various R values. Even the two interaction effect did not have any significant influence on the R values. But it was observed that the triple interaction effect of speed, feed and depth of cut did have a significant influence in some cases. They are mentioned below.

The analysis for X Axis

speed	feed	depth	Rku	logstd Rk	S/N Rku	Ra	log std Ra	S/N Ra	Rq	logstd Rq	S/N Rq	Rp	logstd Rp	S/N Rp	Rt	logstd Rt	S/N Rt
3000	0.02	0.05	2.033														
4500	0.02	0.05	2.033														
1500	0.001	0.001		-1.23													
4500	0.02	0.001		-1.23													
4500	0.02	0.05			-6.18												
4500	0.001	0.05					-0.14										
4500	0.01	0.05								-1.23							
3000	0.005	0.05										38					
4500	0.02	0.001											0.55				
3000	0.005	0.05												-31.84			
3000	0.005	0.05													72		
1500	0.01	0.001														0.817	
3000	0.005	0.05															-37.389

The Analysis for XY Axis

speed	feed	depth	Rku	logstd Rk	S/N Rku	Ra	log std Ra	S/N Ra	Rq	logstd Rq	S/N Rq	Rp	logstd Rp	S/N Rp	Rt	logstd Rt	S/N Rt
3000	0.001	0.05				7.866											
3000	0.001	0.02					-0.8161										
3000	0.001	0.05						-17.95									
3000	0.001	0.05							10.033								
3000	0.005	0.05								-0.577							
3000	0.001	0.05									-18.39						
3000	0.001	0.05										41					
4500	0.005	0.05											0				
3000	0.001	0.05												-30.27			
3000	0.001	0.05													88		
4500	0.01	0.001														0.6931	
3000	0.001	0.05															-36.2

The analysis for Y Axis

speed	feed	depth	Rku	logstd Rk	S/N Rku	Ra	log std Ra	S/N Ra	Rq	logstd Rq	S/N Rq	Rp *	logstd Rp	S/N Rp	Rt *	logstd Rt	S/N Rt
3000	0.02	0.02	1.833														
1500	0.005	0.02		-1													
4500	0.01	0.001		-1													
1500	0.005	0.05					-0.7614										
3000	0.001	0.05									-17.66						
3000	0.001	0.05										32					
1500	0.005	0.05											0.46				
3000	0.001	0.05												-27.84			
3000	0.001	0.05													59		
1500	0.005	0.05														0.57	
3000	0.001	0.05															-34.07

it was seen that for Rp and Rt even the 2 factor interaction of sd has a significant effect .

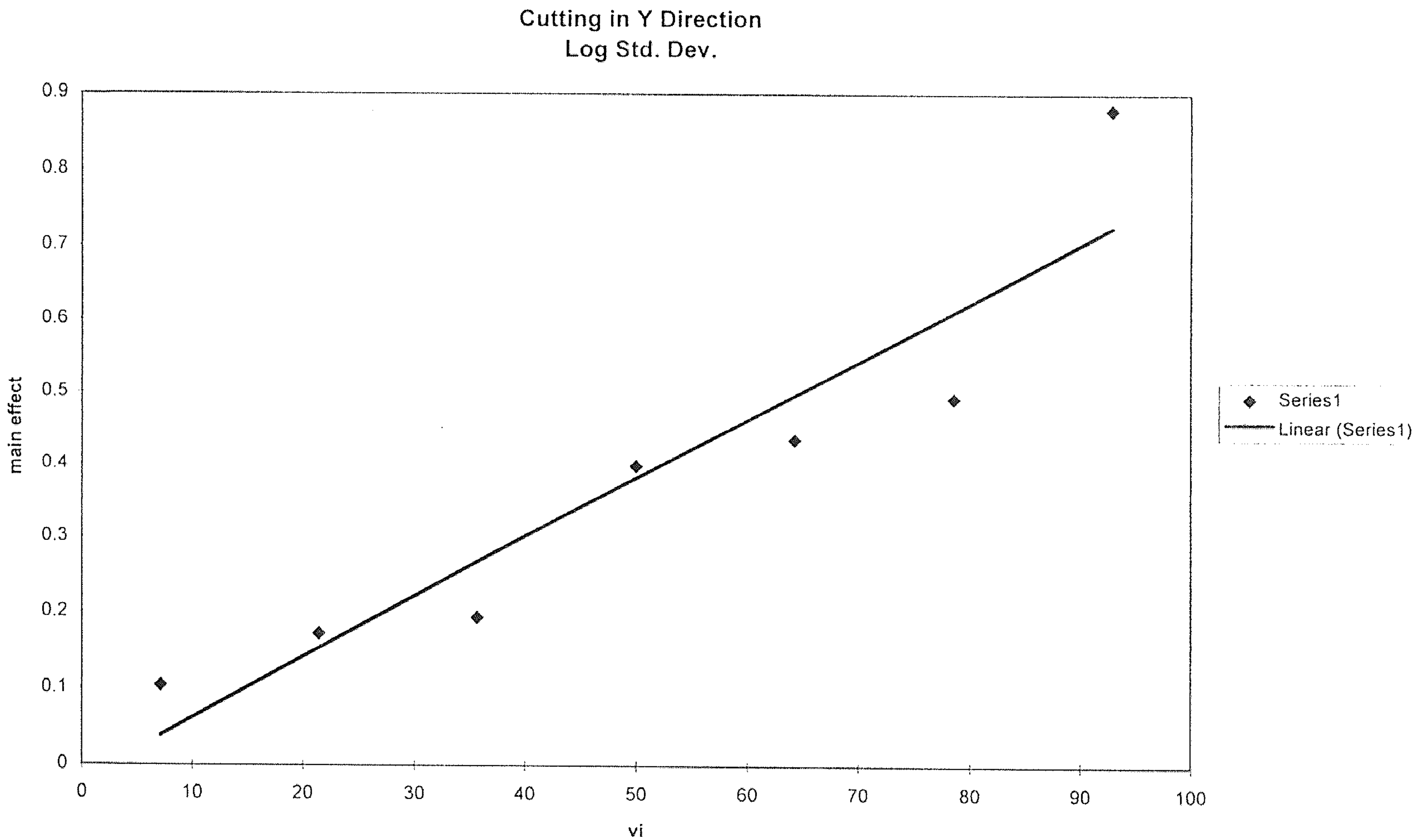


Fig 5.1 Probability Plotting

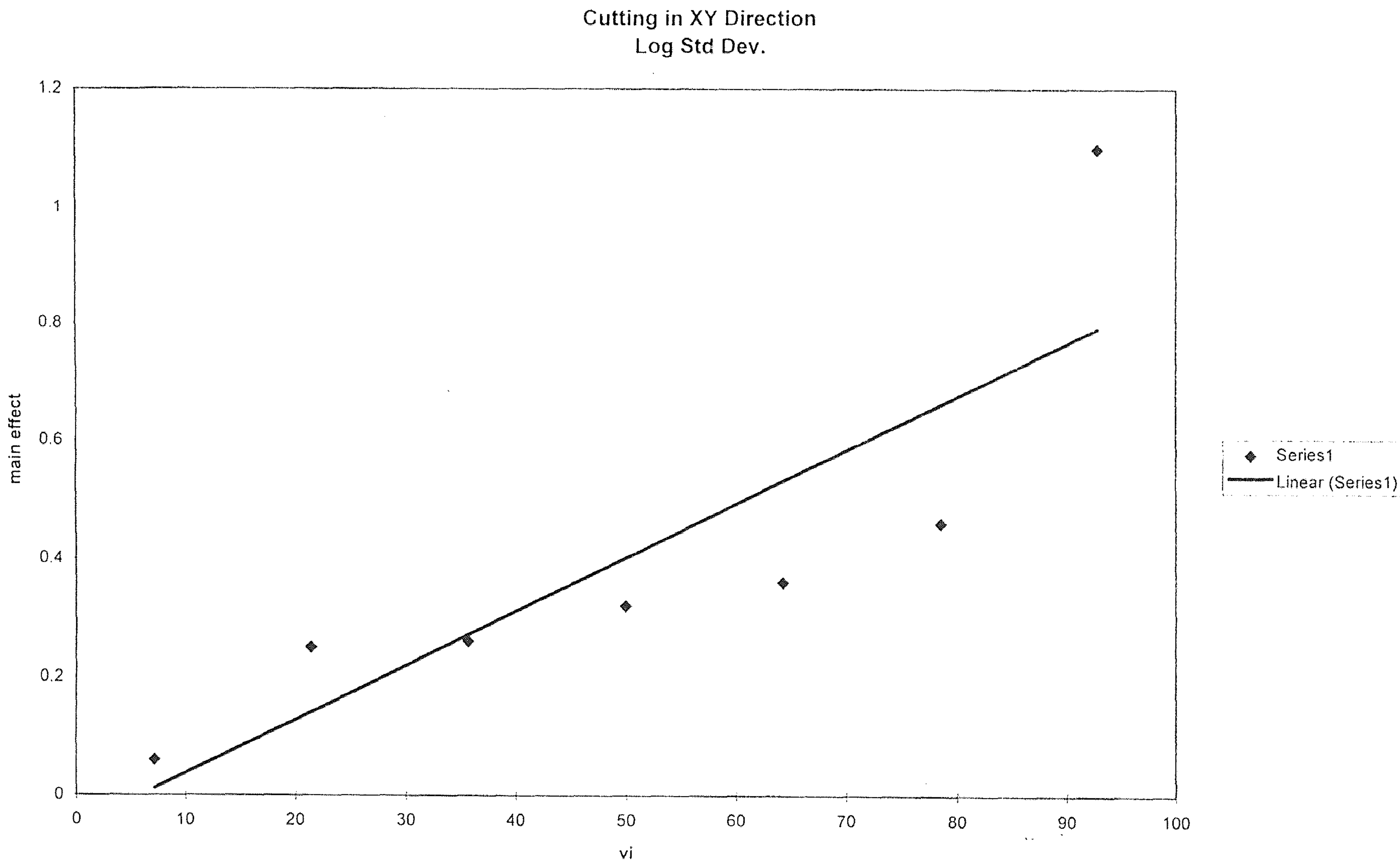


Fig 5.2 Probability Plotting

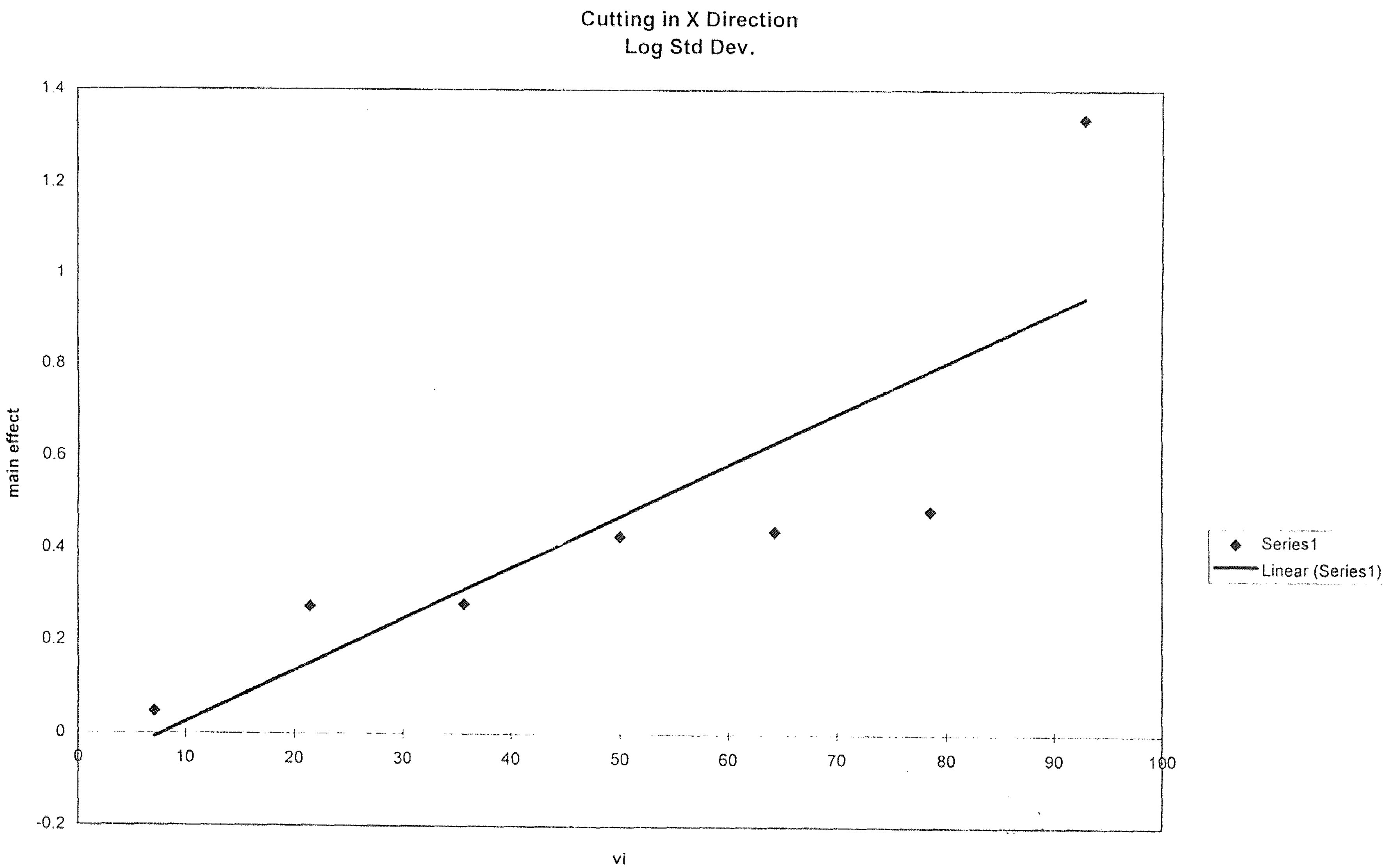


Fig 5.3 Probability Plotting

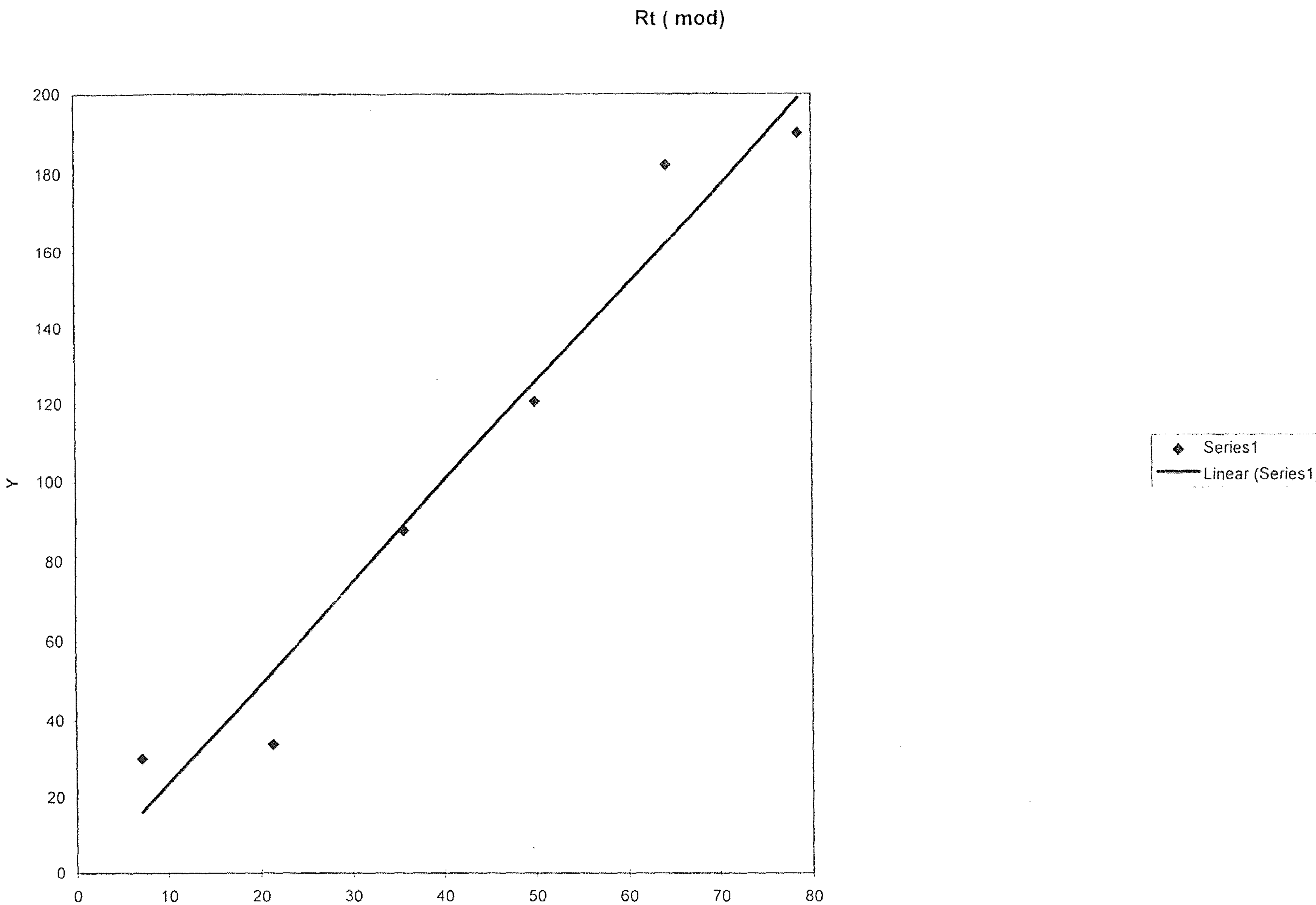


Fig 5.4 Probability Plotting

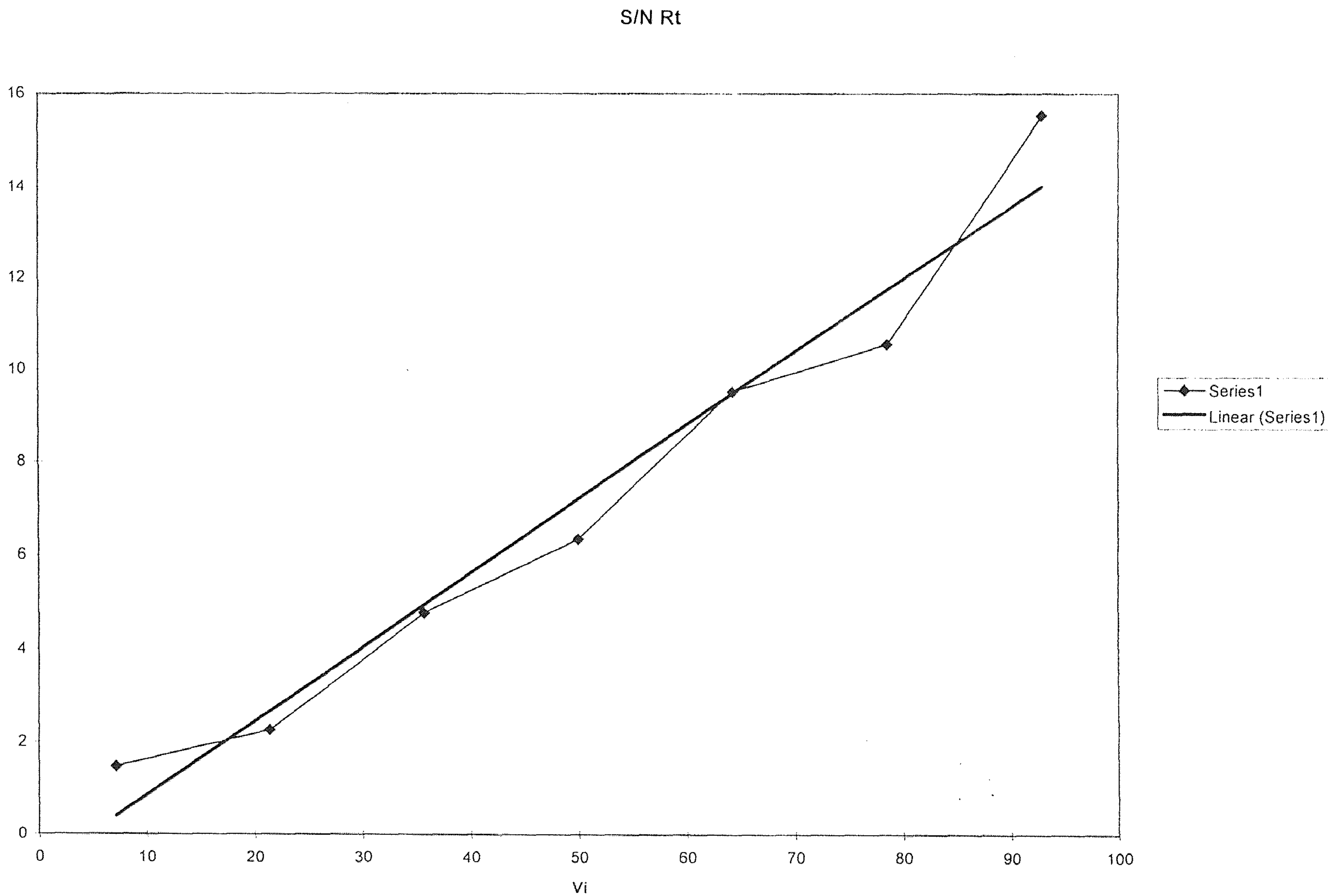


Fig 5.5 Probability Plotting

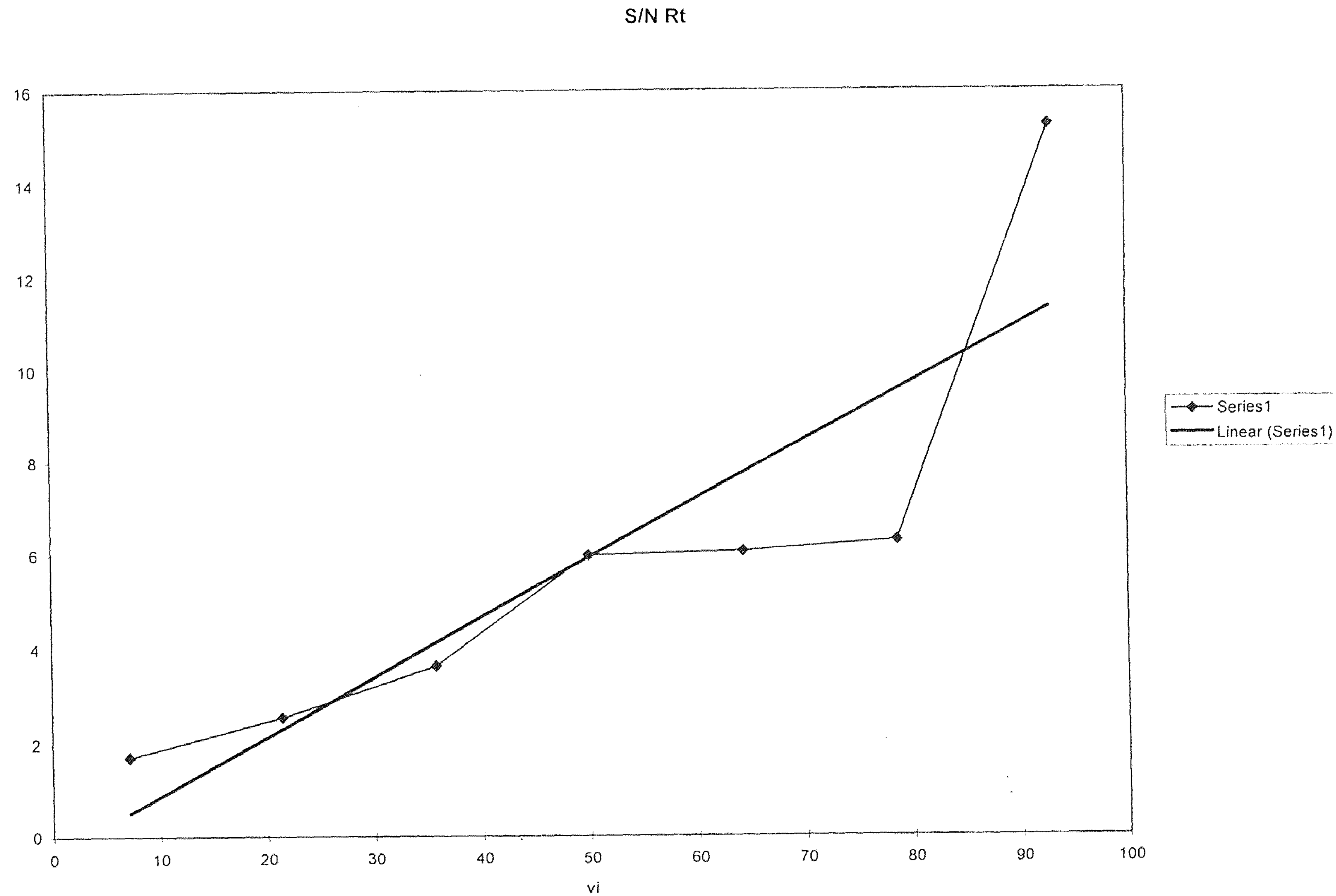


Fig 5.6 Probability Plotting

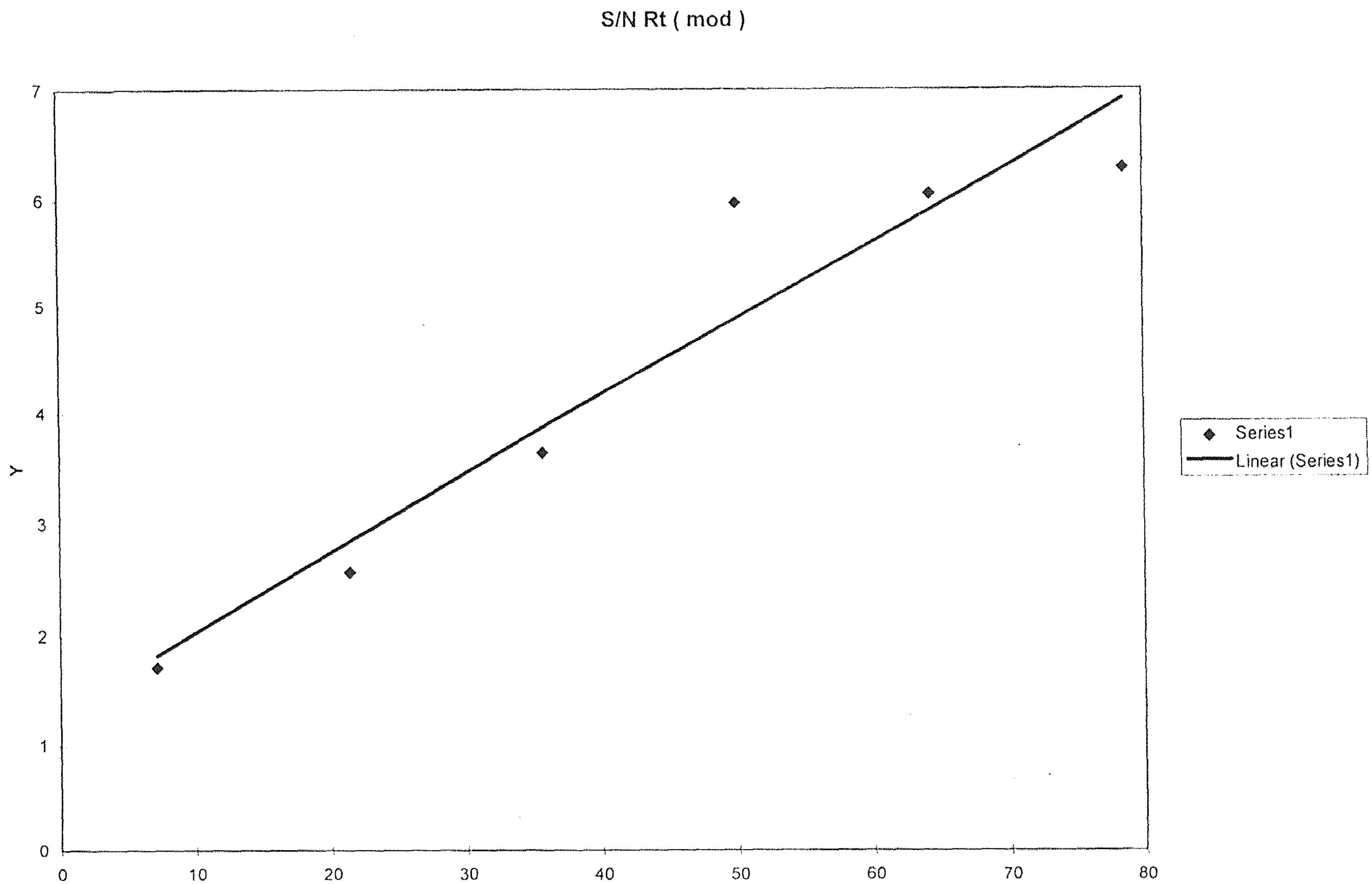


Fig 5.7 Probability Plotting

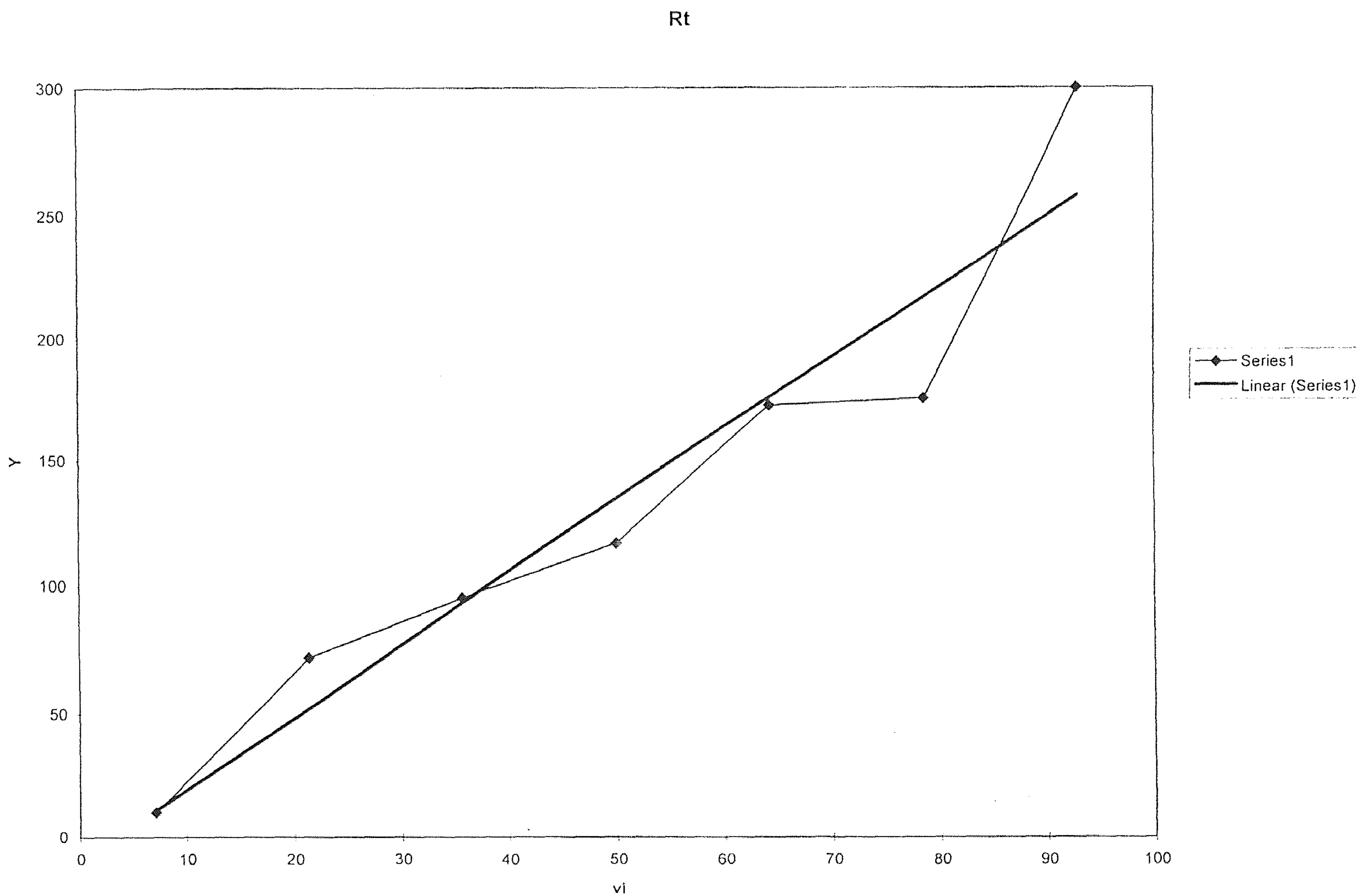


Fig 5.8 Probability Plotting

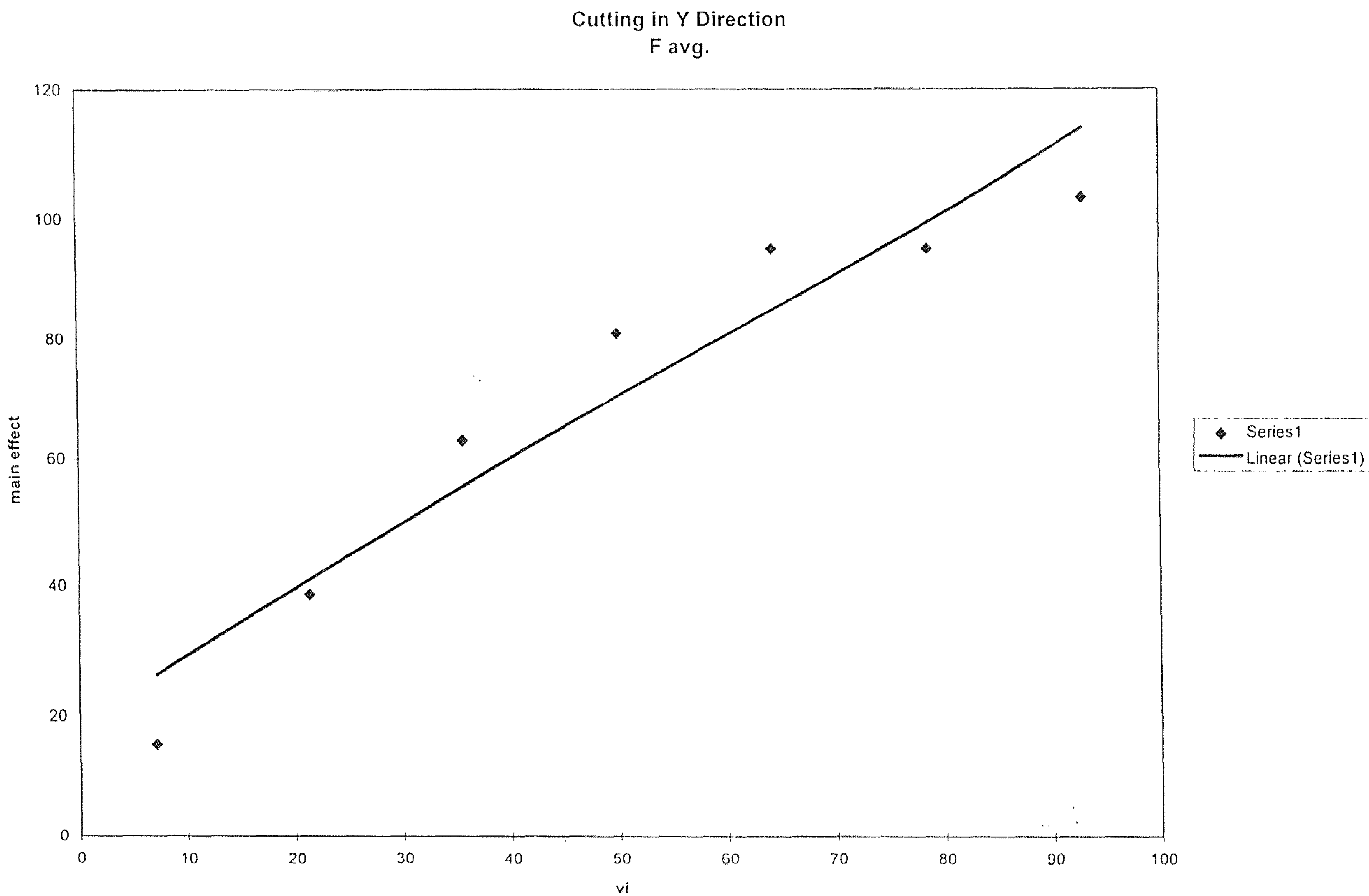


Fig 5.9 Probability Plotting

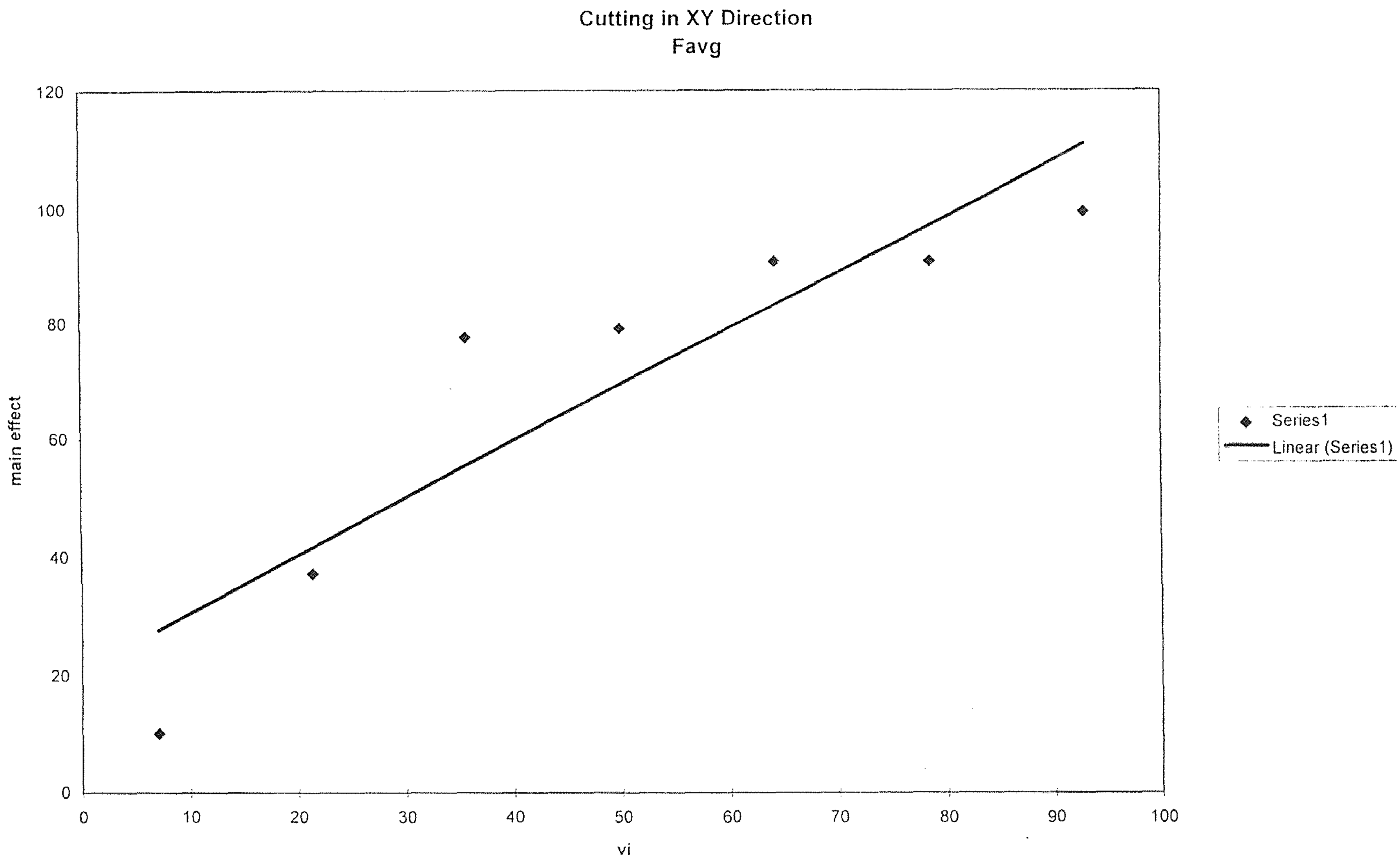


Fig 5.10 Probability Plotting

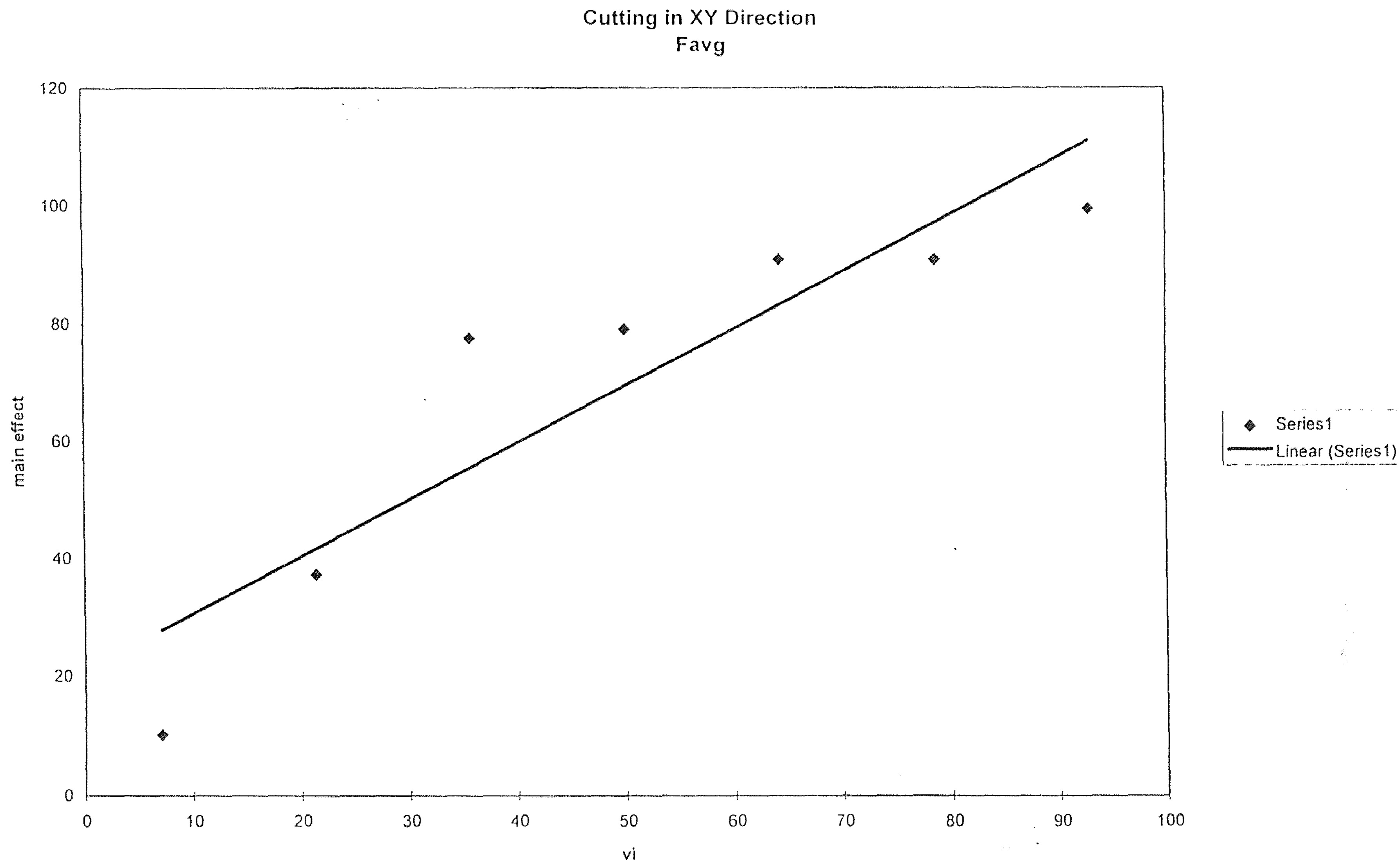


Fig 5.11 Probability Plotting

5.2 Cutting in X Direction

For cutting in the X Direction it was observed that the two interaction effect of speed-feed, feed-depth of cut, speed-depth of cut had a significant effect on the maximum cutting force. The two interaction effect of speed-feed and the single effect of depth of cut had a significant effect on the average value of the cutting forces. The triple interaction effect of speed-feed-depth of cut had a significant effect on the log stdev of the Fmax values.

5.3 Cutting in XY Direction

For cutting in the XY Direction it was observed that the single effect of depth of cut had a significant effect on the average value of the cutting forces. There was no significant effect of any particular operating parameter seen on the maximum value of the cutting forces. The triple interaction effect of speed-feed-depth of cut had a significant effect on the log stdev of the Fmax values.

5.4 Cutting in Y Direction

For cutting in the Y Direction it was seen that the two interaction effect of speed-feed and the single effect of depth of cut had a significant effect on the maximum value of the cutting forces. The triple interaction effect of speed-feed-depth of cut had a significant effect on the log stdev of the Fmax values. There was no significant effect of any particular operating parameter seen on the average value of the cutting forces.

It was observed that for cutting in any of the three directions, the S/N Ratio of the Fmax values did not show any significance at any level of cutting.

The following table summarizes the above results, showing the factor, level of cutting, main effect for cutting in the three directions.

Table 5.1 Analysis of Results of Probability Plottings

Analysis for X Axis

speed	feed	depth	Fmax(Effect)	Favg(effect)	log Fmax(effect)	stdev
3000	**0.001**	0.02	116.17			
3000	**0.001**	**0.02**	101.94			
4500	0.02	**0.001**		85.7		
4500	**0.005**	0.02		75.16		
4500	0.005	**0.02**		70.46		
1500	**0.02**	**0.05**			1.338	

Analysis for XY Axis

speed	feed	depth	Fmax(Effect)	Favg(effect)	log Fmax(effect)	stdev
4500	0.02	**0.001**		77.6		
3000	**0.02**	**0.05**			1.1	

Table 5.1 (Continued)

Analysis for Y Axis						
speed	feed	depth	Fmax(effect)	Favg(effect)	log Fmax(effect)	stdev
3000	**0.01**	0.02	49.3			
3000	0.01	**0.02**	37.02			
3000	**0.02**	**0.05**			0.86	

After the analysis of the results, It was observed that the level of speed to obtain the maximum cutting force is 3000 RPM.

The feed at which the maximum cutting force can be obtained is 0.001 in the X Direction and 0.01 in the Y Direction. If these are the feed rates in the X and Y Directions then theoretically, according to the geometry of the workpiece the feed in the XY direction should be a little over 0.01 inches/min. However practically it would not be possible to achieve that feed rate and we could go to a feed rate of 0.02.

The depth of cut at which the maximum cutting force can be obtained is 0.02 in. in the X and the Y Direction, for maximum cutting force in the XY direction the depth of cut could be reduced to 0.001.

From these above observations and results it can be concluded that the optimum level of cutting to obtain the maximum cutting forces would be

speed = 3000 RPM

feedrate = 0.001 (X Direction), 0.02 (XY Direction), 0.01 (Y Direction) in/min.

5.5 Analysis of the Comparisons of Different Surface Texture Parameters and Cutting Forces versus the 4 Different Feedrates at a Particular Spindle Speed and Depth of cut.

From the graphs in Chapter 5 it is very evident that the surface texture parameters display similar characteristics for cutting in the three directions. The Ra and Rq values for cutting in each direction show a similar trend and it is right as Rq is the RMS value of the Ra, thus proving that the results obtained and analysis carried out is quite accurate.

Rp, Rt and Fmax also have similarities in the trend for cutting in the three directions. These graphs give support to the probability plottings and after the analysis of these graphs it can be stated that the cutting conditions for optimum results would be

speed = 3000 RPM

feed rate = 0.005 in/min

depth of cut = 0.05 in.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The research work that has been done gives the empirical relationship between the different Surface Texture Parameters and the Milling Operation parameters. It gives the empirical relatioship between the maximum and the average cutting forces and the Milling operating parameters. It also gives us the empirical relationship between the Surface Texture parameters and the Cutting Forces.

Hence, It is now possible to have an estimate of the output of the Cutting Force or the Surface Texture result by the empirical relatinships. The equations that have been derived can be used to estimate the expected Surface Texture result and the expected Cutting force if a particular combination of spindle speed, feed rate and depth of cut be used.

Those equations having a higher value of the Correlation Coefficient should give better and more accurate predictions of the results. These equations shall be a great help when actual milling operation is being carried out. One can have an idea before hand as to what kind of Surface Texture should he expect and also what would the cutting forces be.

In an unattended machining environment it would be possible to predict the results before the actual machining and then set the operating parameters of speed, feed and depth of cut according to the results that are desired.

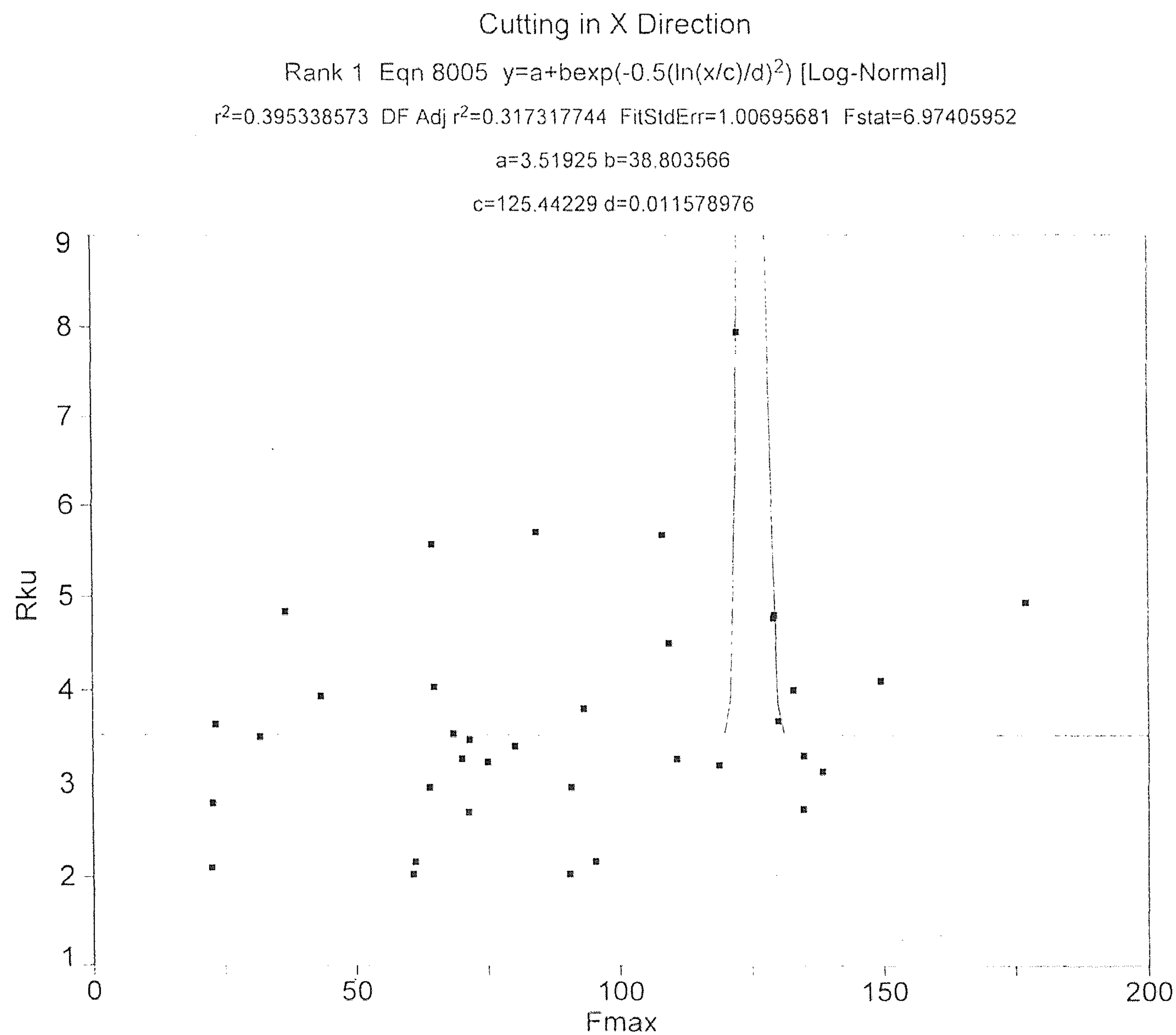
The probability plottings give us the significant factors and their effects in obtaining a particular Surface Texture result or a particular Cutting Force. These plottings have given an optimum level of cutting. When cutting would be done at that level one should get the most optimum results for Surface Texture and Cutting forces. This would greatly enhance the productivity and also improve the quality of the machined component.

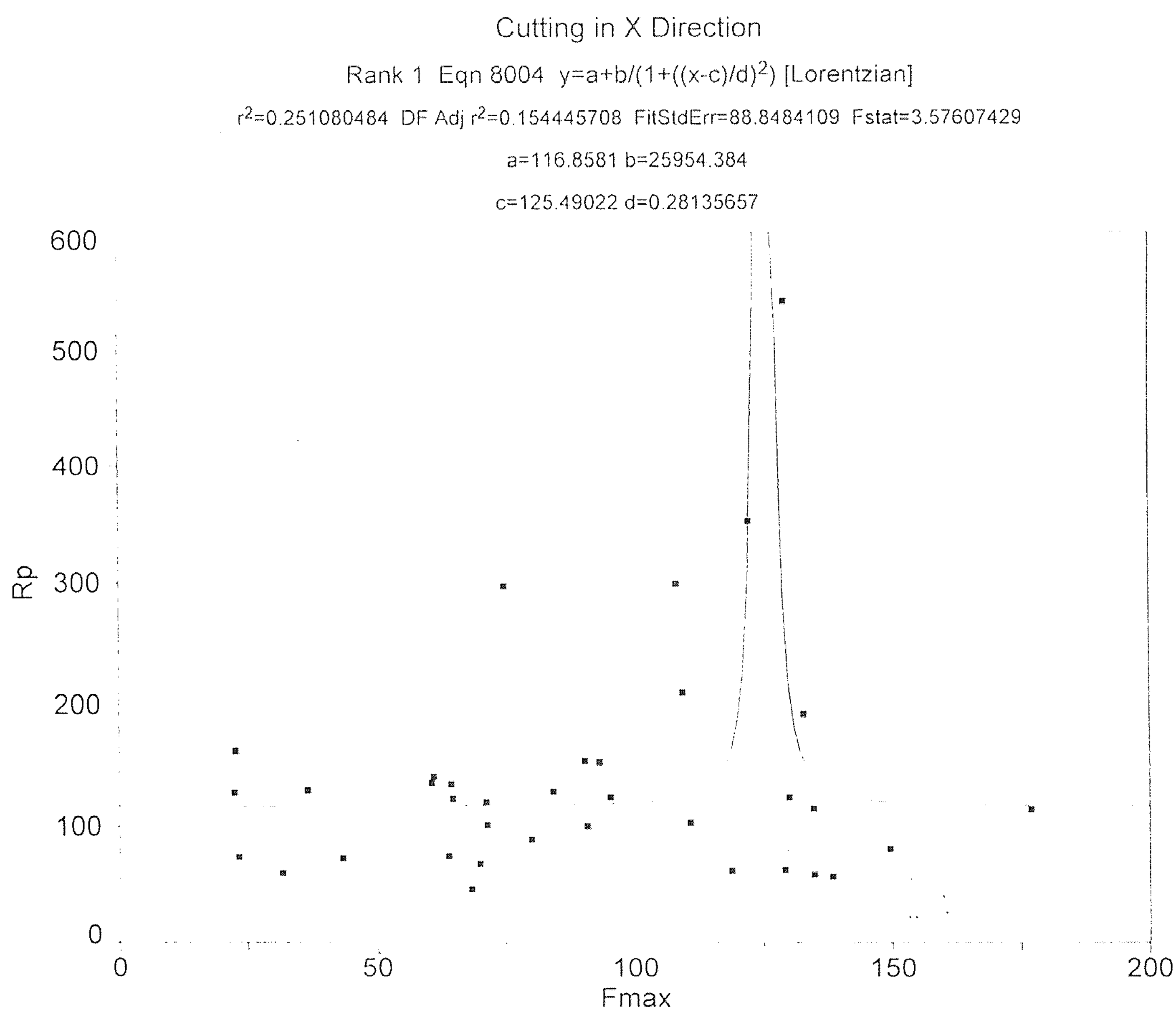
6.2 Recommendations

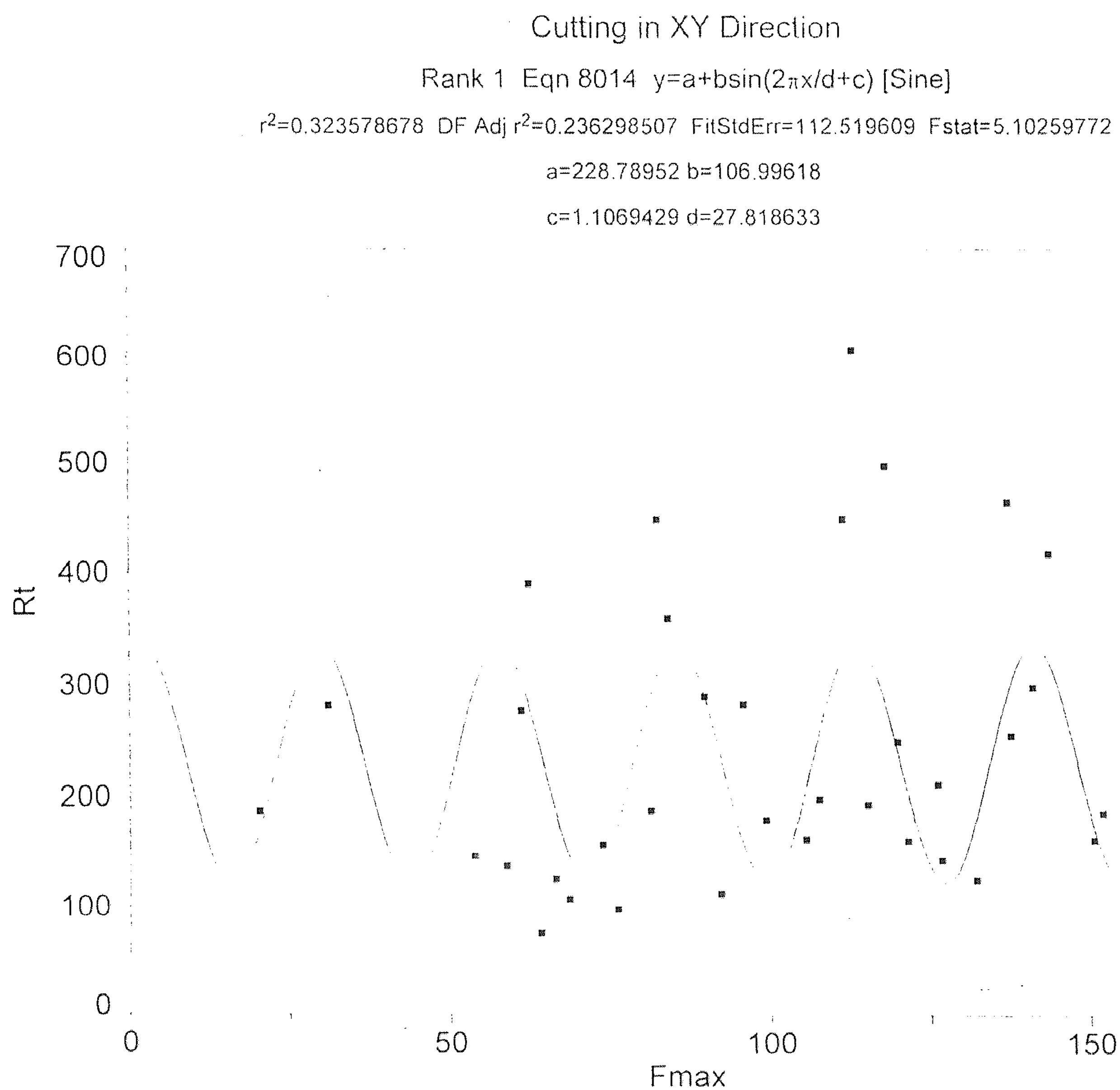
The research work that has been done helps greatly in determining the optimum conditions of cutting in a milling operation. In unattended machining environment, there should be an adaptive control system, which would give a constant feedback of the Surface Texture being obtained and the Cutting Forces being developed. This adaptive control system should be capable of comparing the actual obtained values of the forces and the texture to those that are desired. The desired values are calculated by the equations already derived. The adaptive control sytem would compare the desired and the actual value and then take corrective actions by either changing the speed or feed or the depth of cut or any combination of the three milling operating parameters. It can also be in the form of a G and M code where it would immediately halt the machining operation if the actual measured results deviate largely from the desired results.

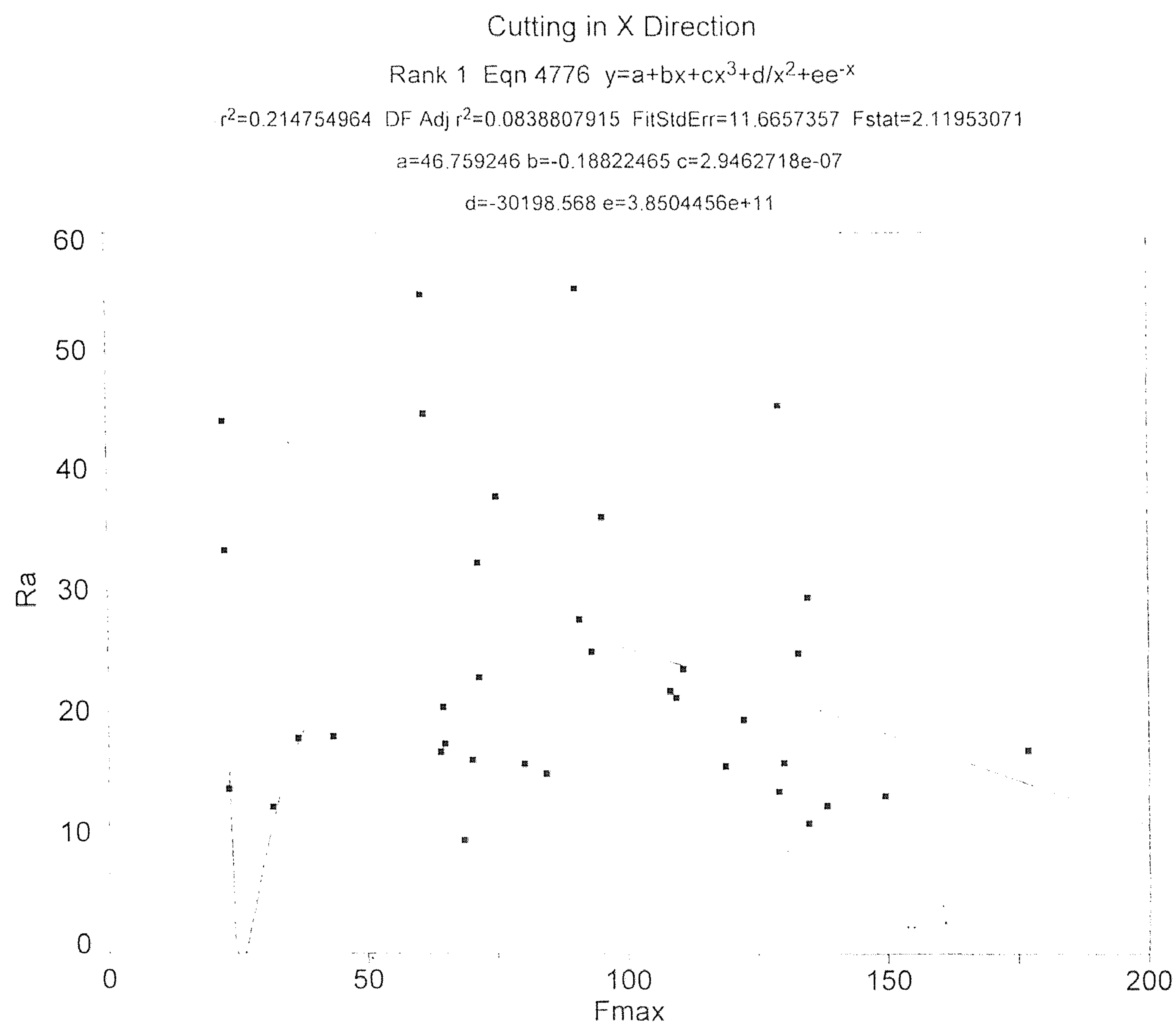
APPENDIX A

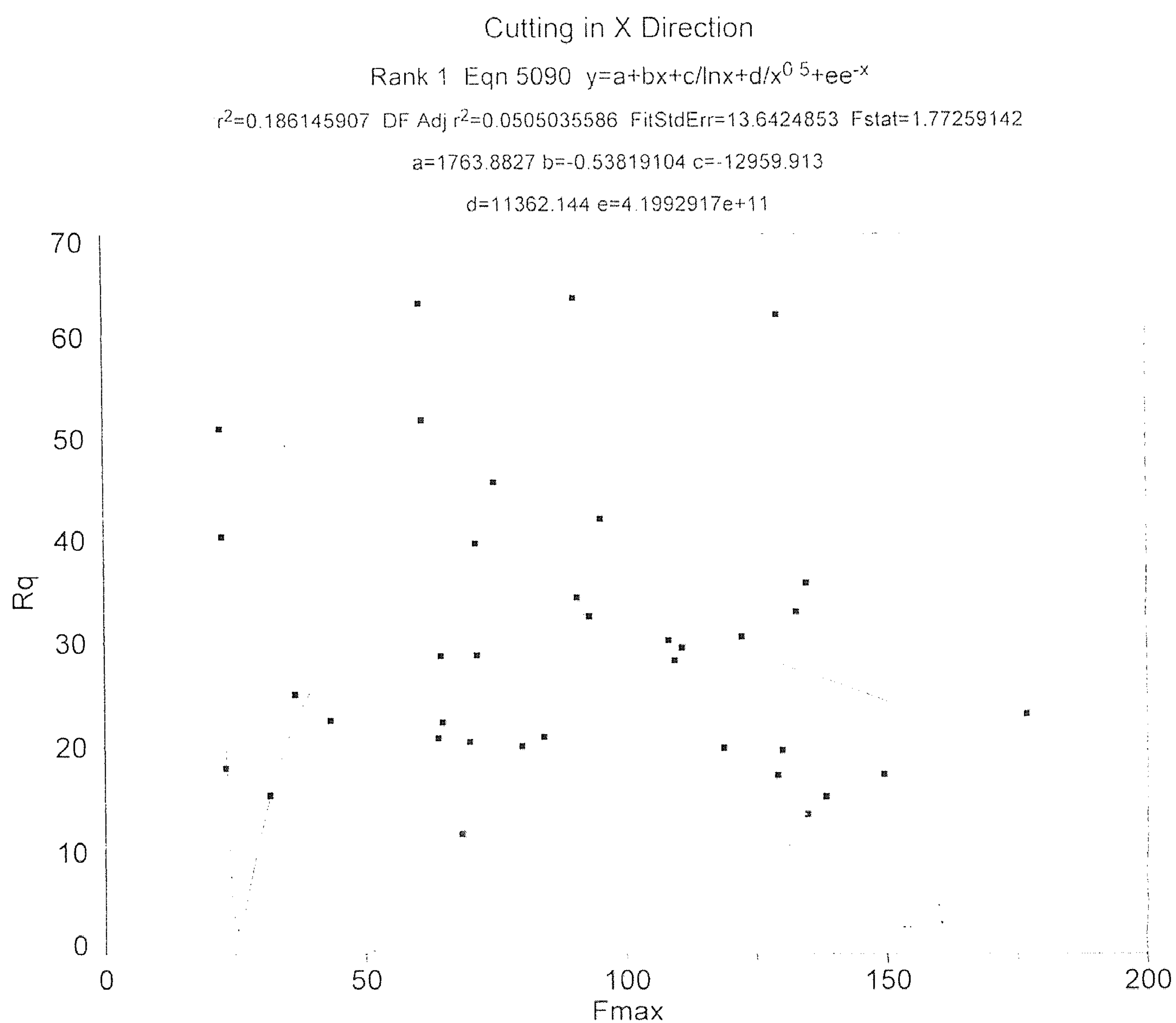
TABLE CURVE SOFTWARE RESULTS


Cutting in X Direction
Rank 1 Eqn 8005 y=a+bexp(-0.5(ln(x/c)/d)2) [Log-Normal]
r2=0.395338573 DF Adj r2=0.317317744 FitStdErr=1.00695681 Fstat=6.97405952
a=3.51925 b=38.803566
c=125.44229 d=0.011578976
Rku
Fmax
0
50
100
150
200
1
2
3
4
5
6
7
8
9


Cutting in X Direction
Rank 1 Eqn 8004 y=a+b/(1+((x-c)/d)^2) [Lorentzian]
r^2=0.251080484 DF Adj r^2=0.154445708 FitStdErr=88.8484109 Fstat=3.57607429
a=116.8581 b=25954.384
c=125.49022 d=0.28135657
Rp
Fmax
0
100
200
300
400
500
600
0
50
100
150
200


Cutting in XY Direction
Rank 1 Eqn 8014 y=a+bsin(2πx/d+c) [Sine]
r2=0.323578678 DF Adj r2=0.236298507 FitStdErr=112.519609 Fstat=5.10259772
a=228.78952 b=106.99618
c=1.1069429 d=27.818633
Rt
Fmax
0
100
200
300
400
500
600
700
50
150

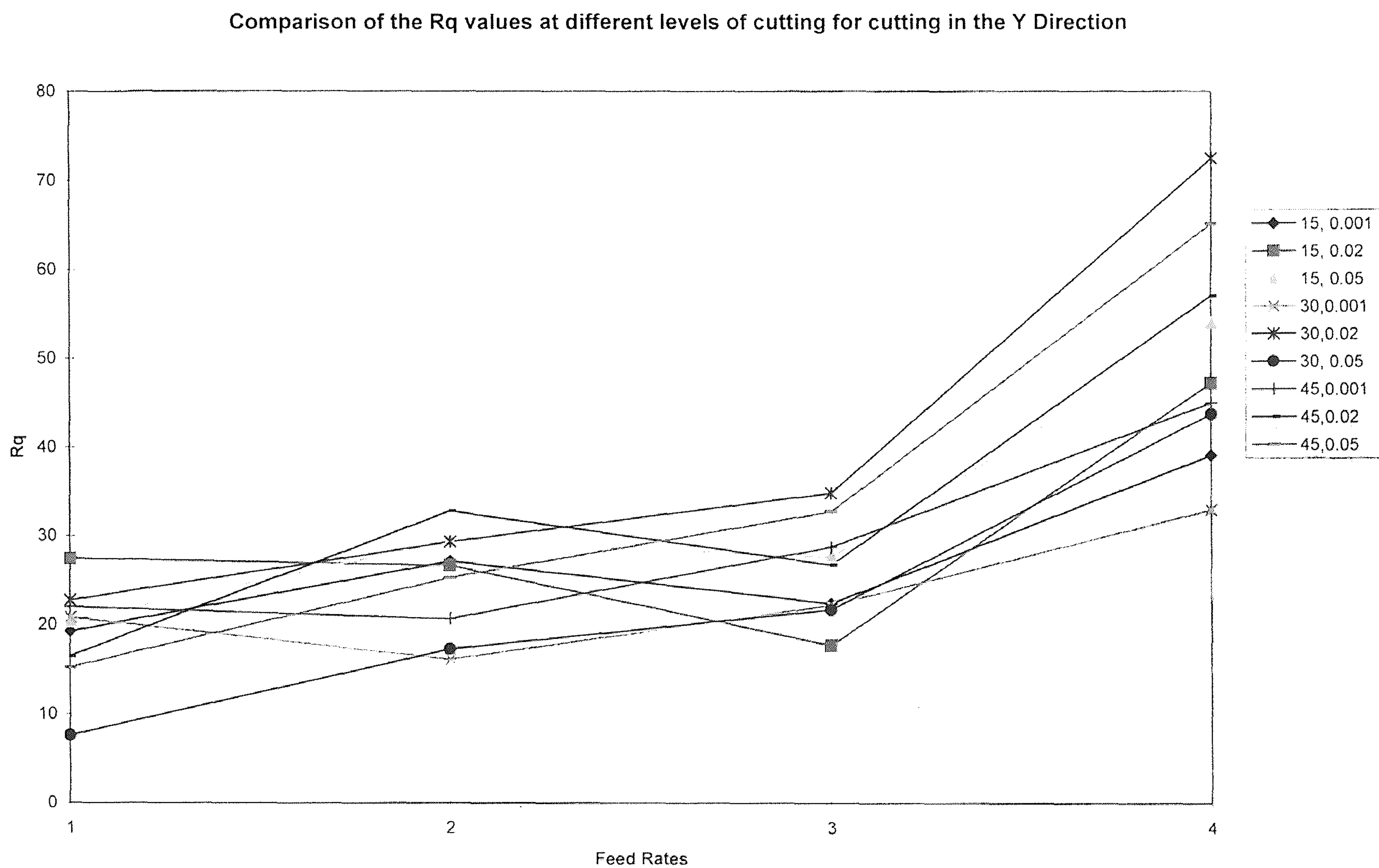

Cutting in X Direction
Rank 1 Eqn 4776 y=a+bx+cx3+d/x2+ee-x
r2=0.214754964 DF Adj r2=0.0838807915 FitStdErr=11.6657357 Fstat=2.11953071
a=46.759246 b=-0.18822465 c=2.9462718e-07
d=-30198.568 e=3.8504456e+11
60
50
40
30
20
10
0
Ra
0
50
100
150
200
Fmax

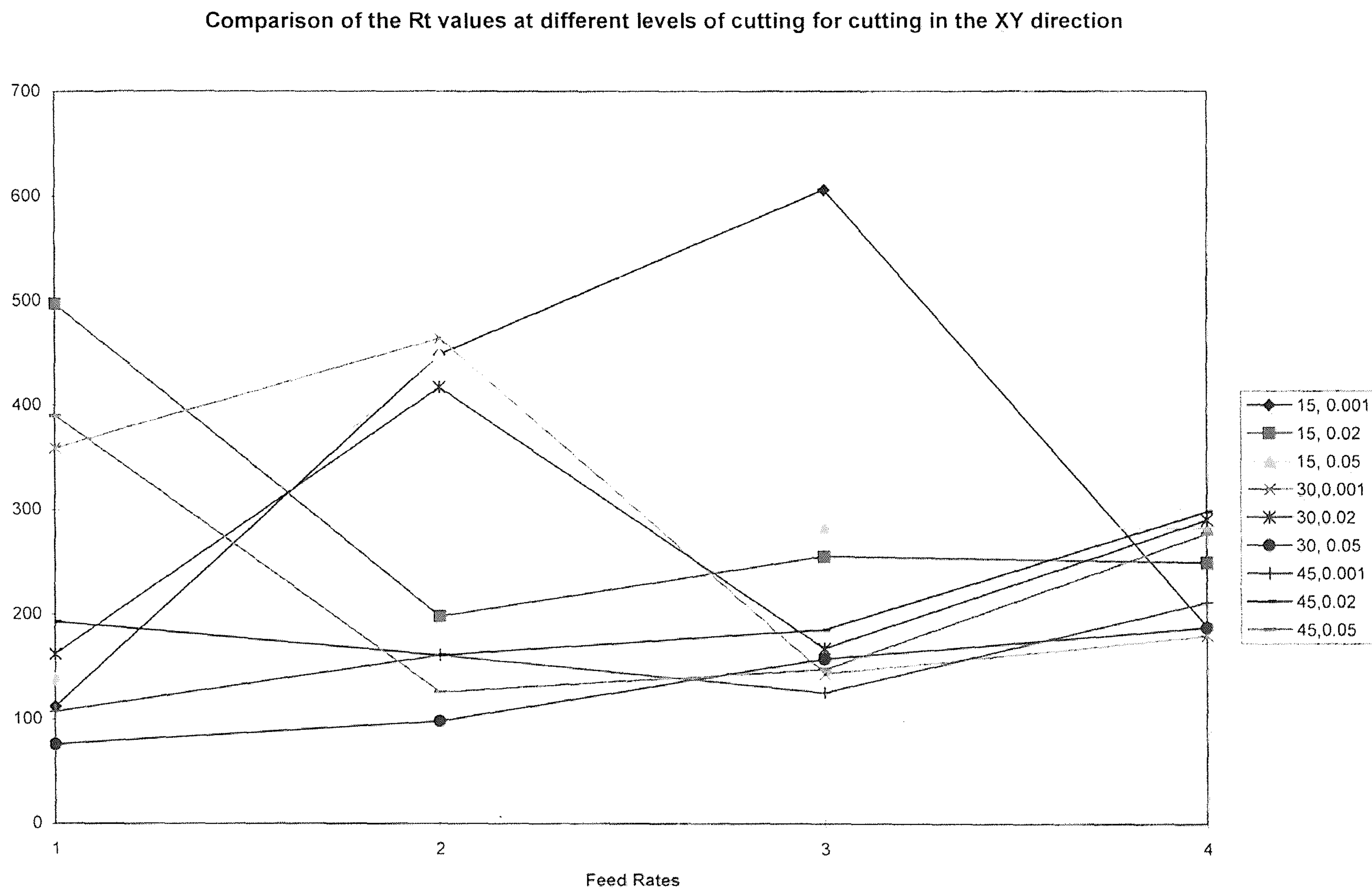


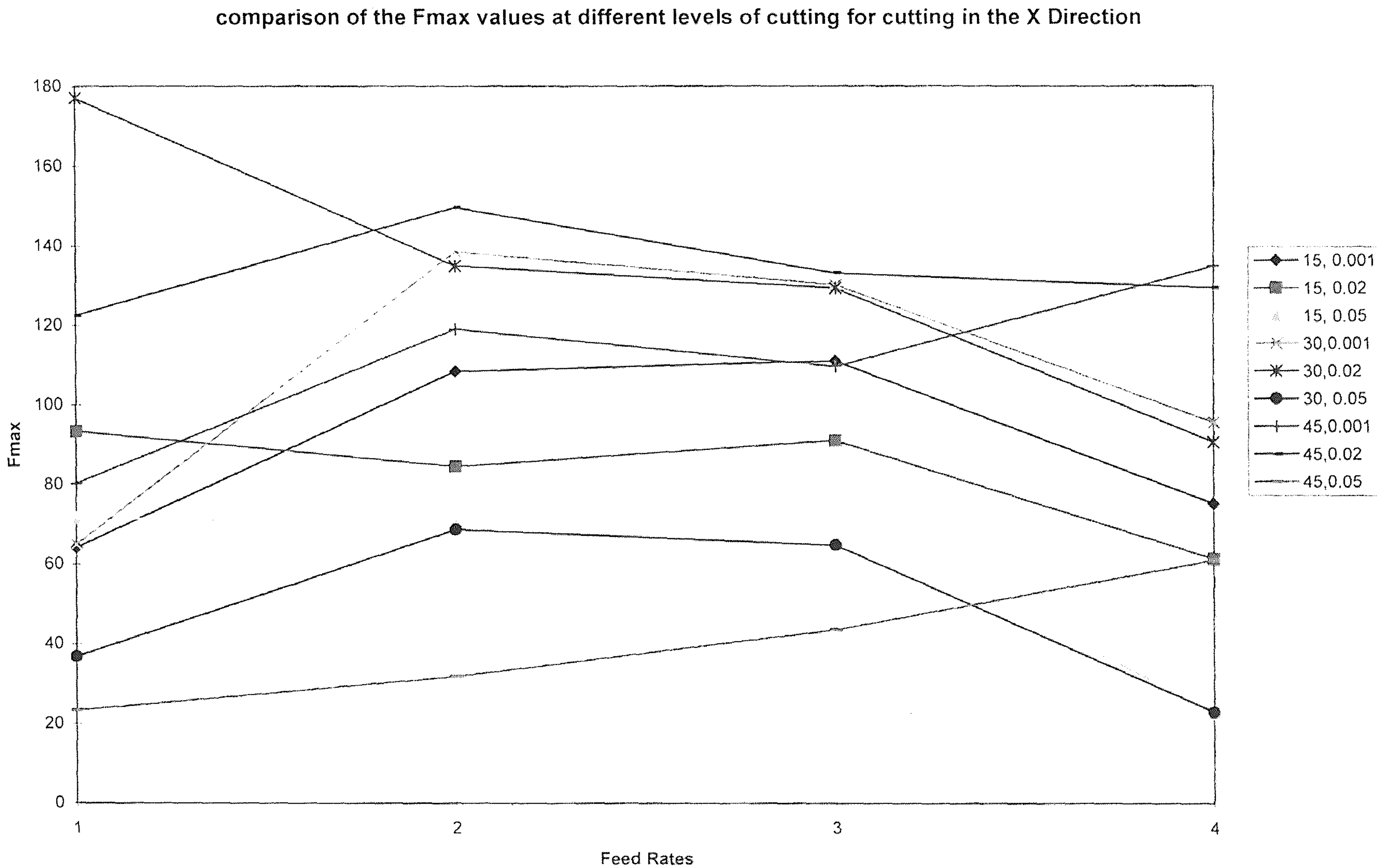
Cutting in X Direction
Rank 1 Eqn 5090 y=a+bx+c/lnx+d/x^0.5+ee^-x
r^2=0.186145907 DF Adj r^2=0.0505035586 FitStdErr=13.6424853 Fstat=1.77259142
a=1763.8827 b=-0.53819104 c=-12959.913
d=11362.144 e=4.1992917e+11
Rq
70
60
50
40
30
20
10
0
0
50
100
150
200
Fmax

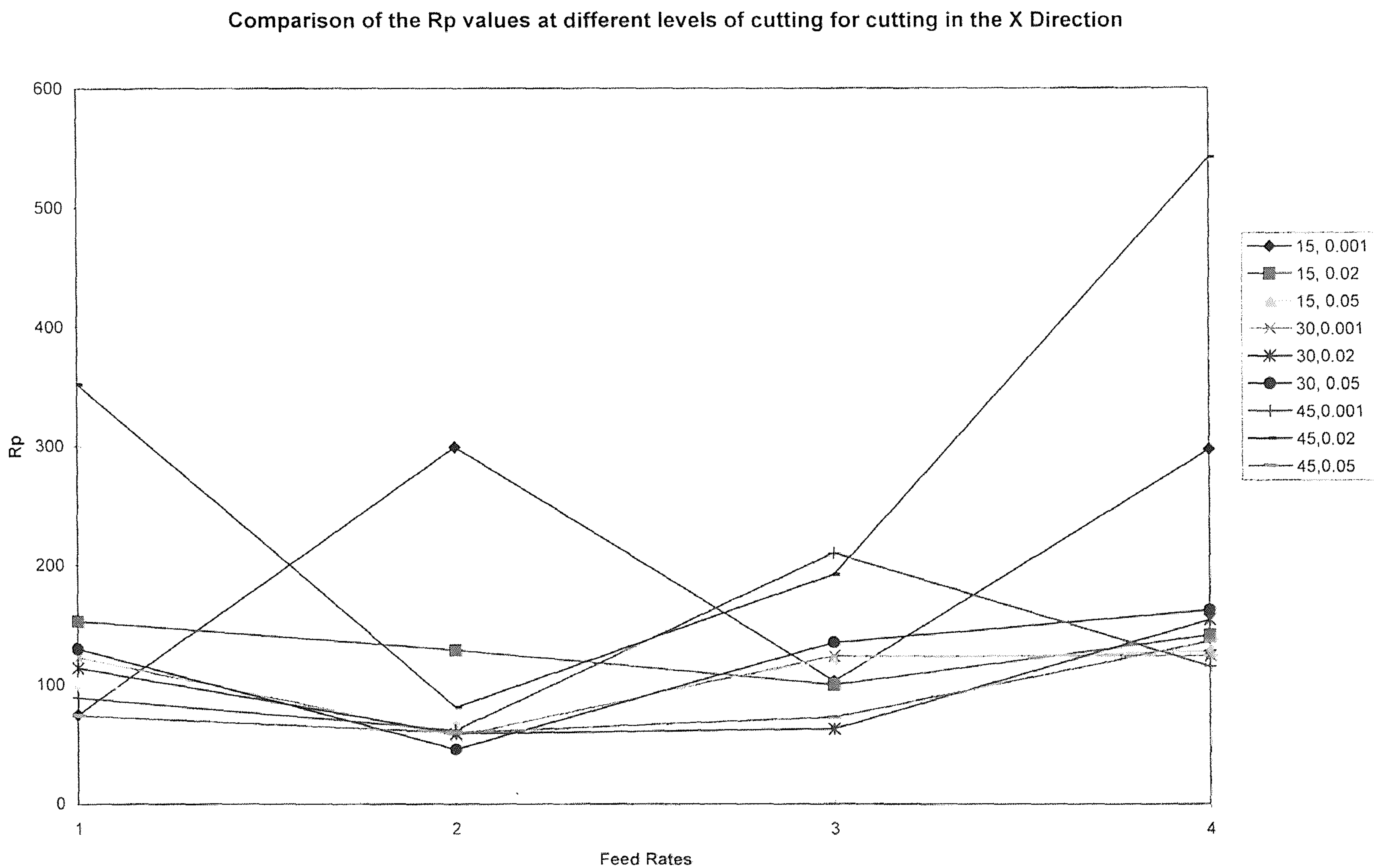
APPENDIX B

PLOTTINGS OF THE COMPARISONS OF THE DIFFERENT OPERATING PARAMETERS AT DIFFERENT LEVELS OF CUTTING

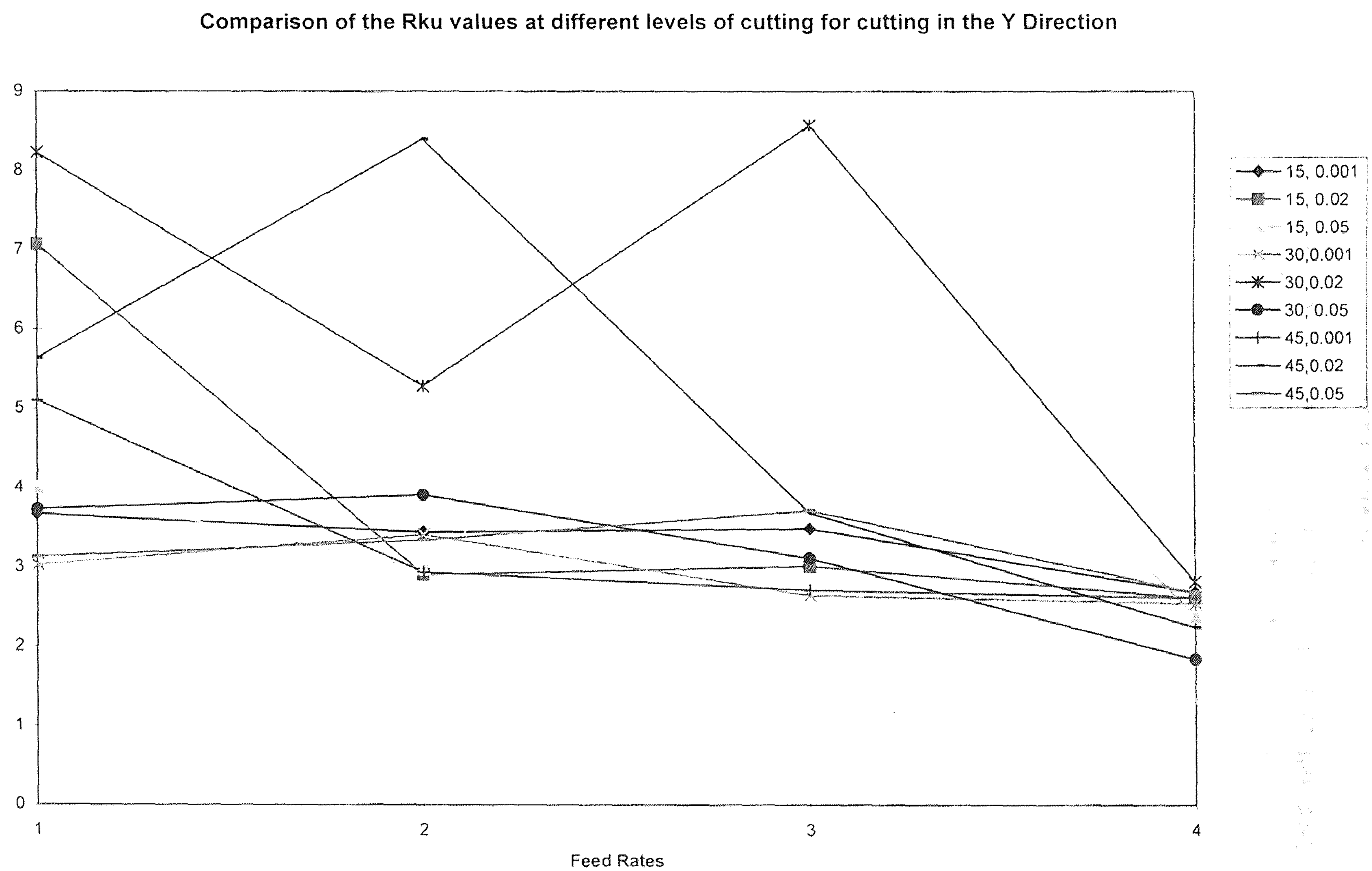

Comparison of the Rq values at different levels of cutting for cutting in the Y Direction
Rq
80
70
60
50
40
30
20
10
0
1
2
3
4
Feed Rates
15, 0.001
15, 0.02
15, 0.05
30,0.001
30,0.02
30, 0.05
45,0.001
45,0.02
45,0.05


Comparison of the Rt values at different levels of cutting for cutting in the XY direction
700
600
500
400
300
200
100
0
1
2
3
4
Feed Rates
15, 0.001
15, 0.02
15, 0.05
30,0.001
30,0.02
30, 0.05
45,0.001
45,0.02
45,0.05


comparison of the Fmax values at different levels of cutting for cutting in the X Direction
180
160
140
120
100
80
60
40
20
0
Fmax
1
2
3
4
Feed Rates
15, 0.001
15, 0.02
15, 0.05
30,0.001
30,0.02
30, 0.05
45,0.001
45,0.02
45,0.05

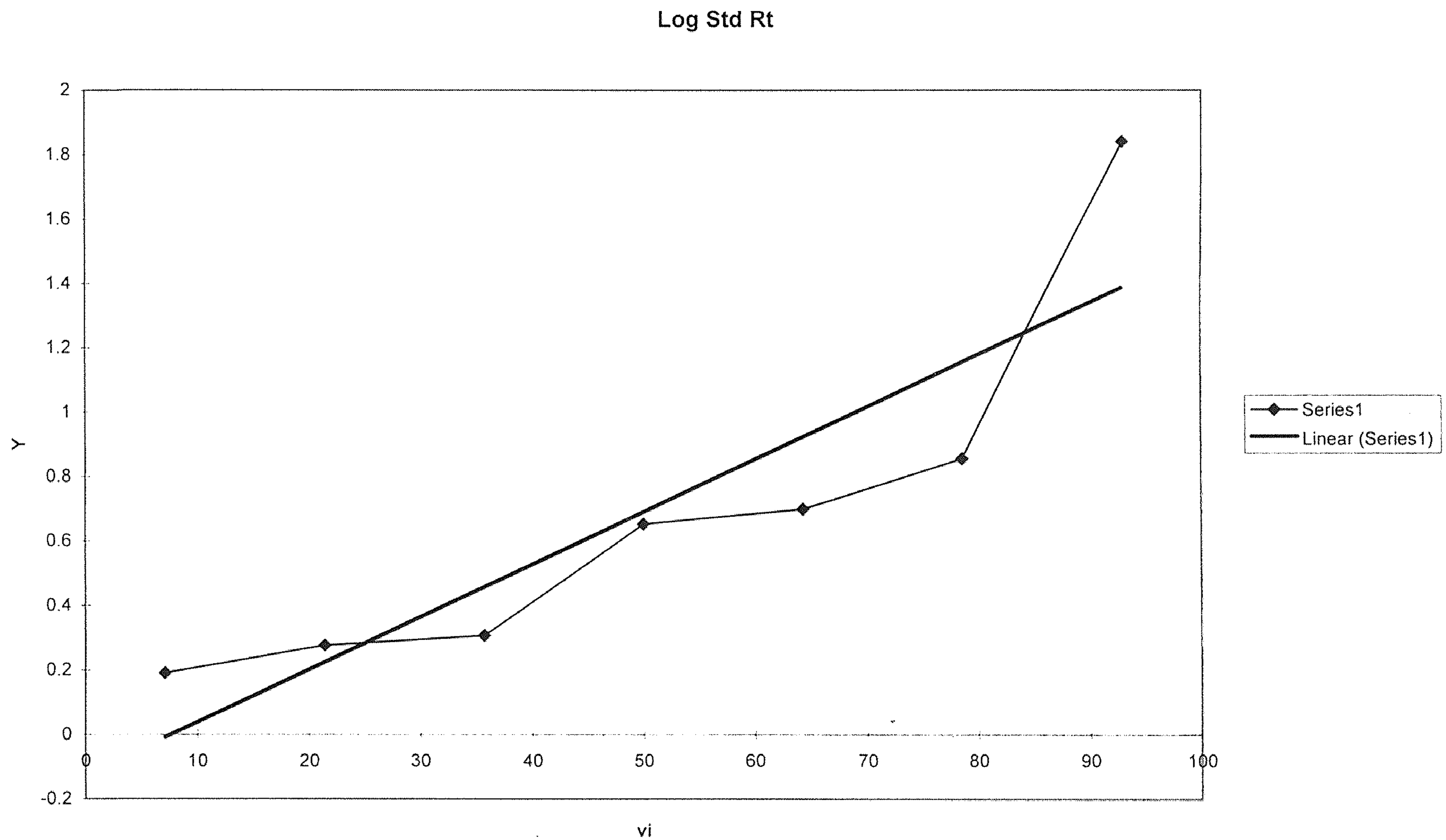


Comparison of the Rp values at different levels of cutting for cutting in the X Direction
600
500
400
300
200
100
0
Rp
1
2
3
4
Feed Rates
15, 0.001
15, 0.02
15, 0.05
30,0.001
30,0.02
30, 0.05
45,0.001
45,0.02
45,0.05

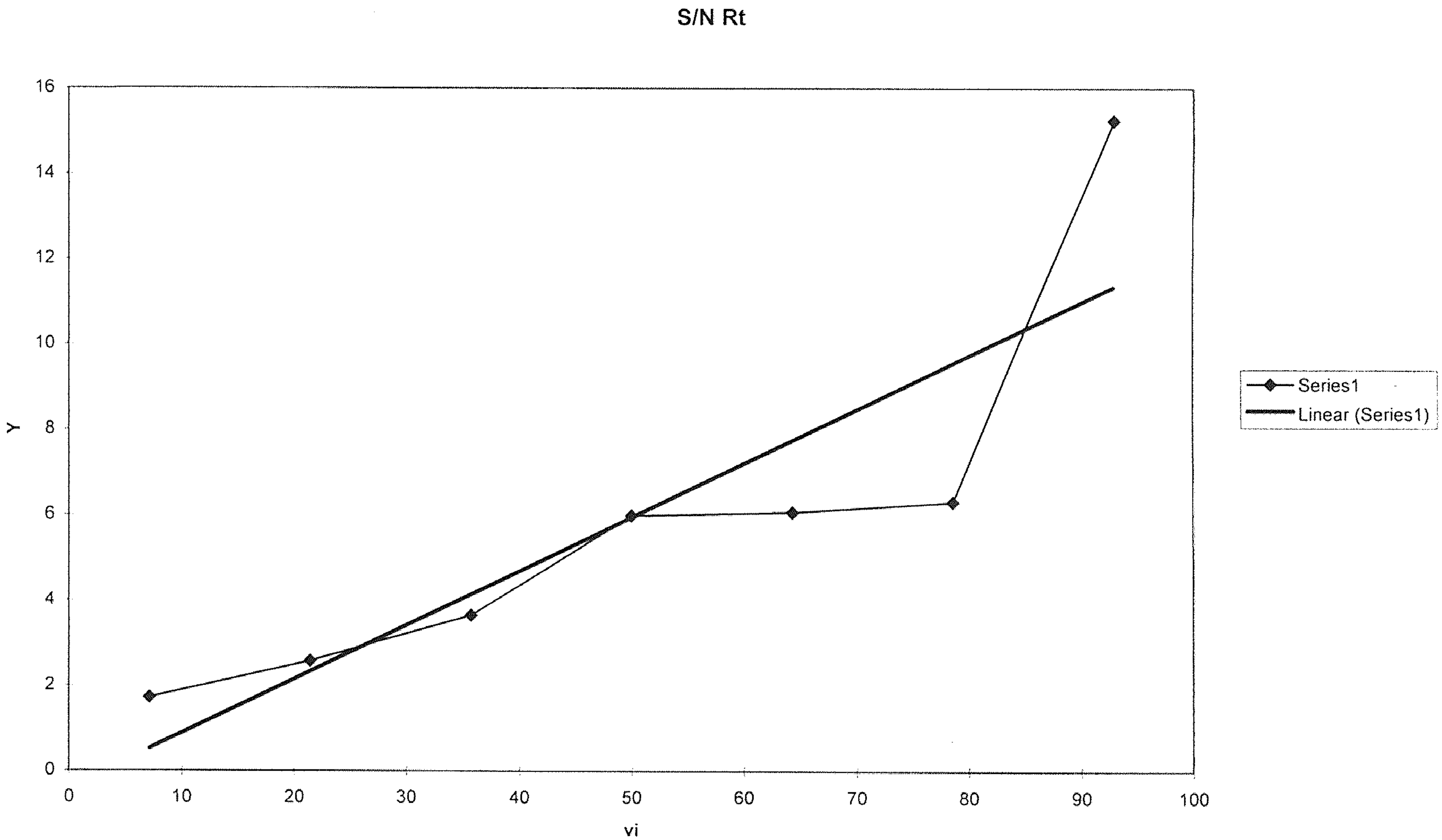

Comparison of the Rku values at different levels of cutting for cutting in the Y Direction
9
8
7
6
5
4
3
2
1
0
1
2
3
4
Feed Rates
15, 0.001
15, 0.02
15, 0.05
30,0.001
30,0.02
30, 0.05
45,0.001
45,0.02
45,0.05

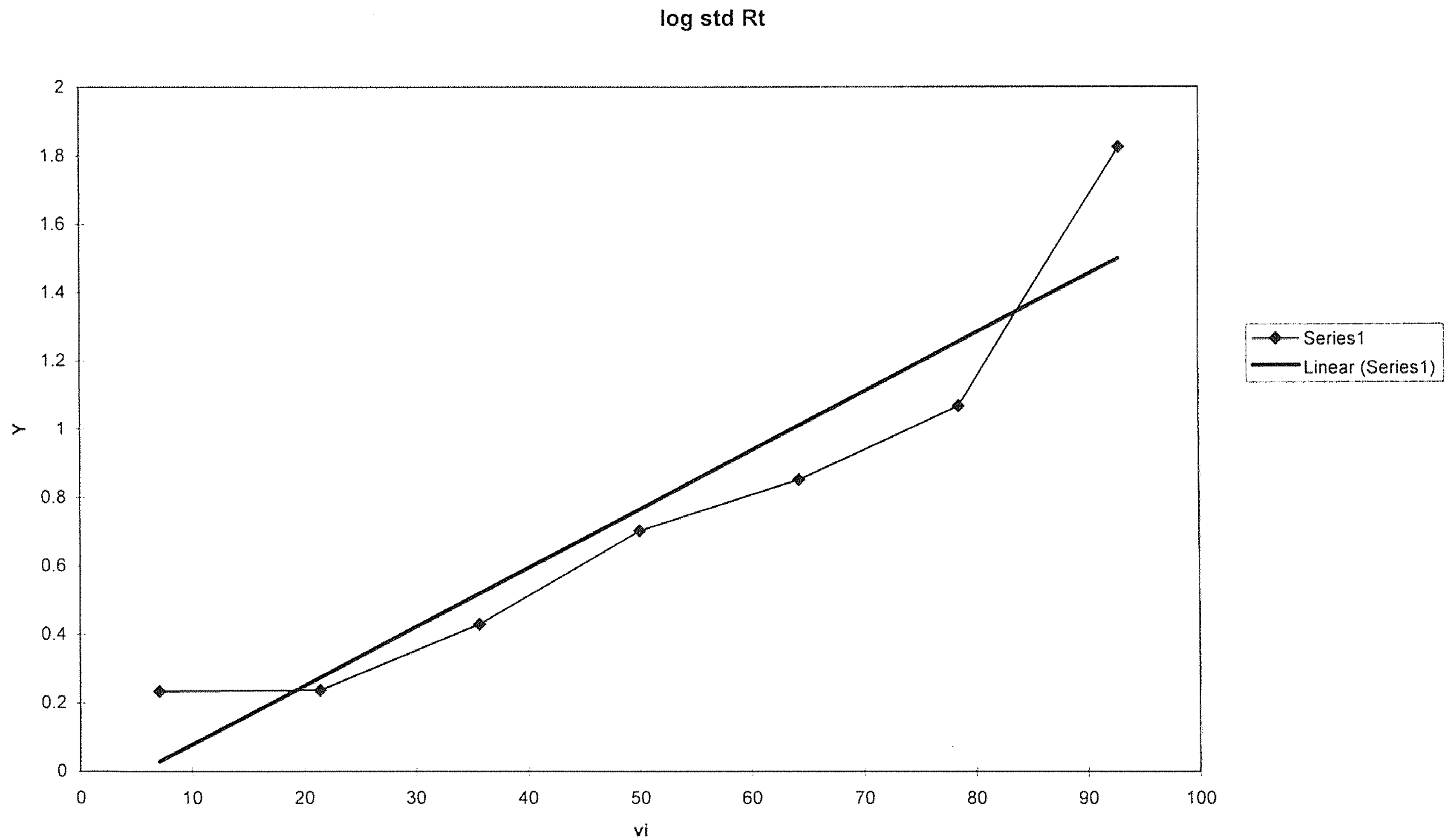
APPENDIX C

PLOTTINGS OF THE VARIATIONS OF THE SURACE TEXTURE AND THE CUTTING FORCE PARAMETERS AT DIFFERENT LEVELS OF CUTTING



Log Std Rt
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
Y
0
10
20
30
40
50
60
70
80
90
100
vi
Series1
Linear (Series1)


S/N Rt
16
14
12
10
8
6
4
2
0
Y
0
10
20
30
40
50
60
70
80
90
100
vi
Series1
Linear (Series1)


log std Rt
Y
vi
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
10
20
30
40
50
60
70
80
90
100
Series1
Linear (Series1)

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