ABSTRACT

EMPIRICAL MODEL-BASED CONTROL FOR END MILLING PROCESS

by
Abdelmalak Salib

The main objective of this research is to develop an empirical model-based control mechanism to maintain a fine surface finish quality by maintaining on-line cutting force values. The proposed model has been developed to present the control model constraints, by varying the machining parameters to control the force output to be constant. To relate the surface finish and the cutting force in the end milling machining process, a design of experiment has been conducted to determine the effect of two different materials (aluminium and steel) and the machining parameters (feed rate, spindle speed) at a predefined depth of cut.

Regression model has been applied to derive an empirical relationship of the surface finish and the cutting force versus the machining parameters for the two mentioned materials. These relationships have been applied to develop the proposed mathematical simulation model, in which the cutting force is adjusted to improve the required surface finish for the end milling operation process.

The results provide means of greater efficiency by improving the surface quality, minimizing the effect of the process variability and reducing the error cost in finishing operations.

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by
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EMPIRICAL MODEL- BASED CONTROL FOR END MILLING PROCESS

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CHAPTER 1

INTRODUCTION

The end milling operation is used extensively in the machining and automotive industries for complex and costly shape machining. In recent years, automation systems have been attached to many milling machines; such automation systems have been made possible by the considerable development of micro-electronic technology. Further automation of cutting operations in milling machines will continue because of the potential for increasing productivity, reducing labor cost, avoiding operator injuries and improving product quality.

To automate the milling operation, it is necessary to monitor the machining process continuously and accurately by simple techniques. Measuring the cutting force can be proposed as a monitoring technique for the milling machine process to produce a desired surface finish. The feed rate of the tool also affects the productivity, surface finish and waviness of the product in metal cutting process. Thus, it is important to determine the proper feed rate and the spindle speed for each part of the workpiece. It is almost impossible however to determine the optimum feed rate when the initial shape of the workpiece is complex or when the cutting condition can vary because of uncertainties. In this case, the operator responsible for the task of part programming usually takes a conservative fixed value for the feed rate, which may result in lower productivity.

In order to improve the productivity in the automated manufacturing environment, it is necessary to implement sensing and corrective devices that can detect and correct the system's malfunctions.

One of the most important requirements is to obtain a relationship between the surface texture and the cutting force. Then, there should be a model control system, which would give a constant feedback of the surface texture being obtained and the cutting forces being developed. The model control system should be capable of comparing the force value and the surface texture to the required ones. These values are calculated by the equation that is derived in this research. The model control system would compare the required value with the produced one and then take corrective action by changing the feed rate and/or the spindle speed.

CHAPTER 2

LITERATURE REVIEW AND OBJECTIVES

The milling process is one of the most widely used metal cutting operations in industry with common applications including both rough and finished machining processes. The cutting force system in milling plays a central role in determining the process performance by influencing the machined surface accuracy and texture, the accurate prediction of milling forces is of fundamental concern. To further understand the milling process and to improve its efficiency, several different methodologies of the force system and surface were generated.

The different methodologies are classified under mathematical models, computer simulations, computer-assisted manufacturing and on-line sensing and monitoring. Some researchers [12,16] constructed various mathematical models of operating parameters for the milling process. They generated mathematical models that predict the forces in the milling operation and/or the surface texture. Given the current computer technology and optimization tools, these mathematical models have been implemented into computer codes that would predict the cutting forces. The sensing technology and on-line monitoring have been under continuous development for the last two decades, thus synthesized the research community to the implementation of adaptive control into the milling operation. The literature survey focus is on the different methodologies that researchers have used to understand the phenomena of the stochastic nature of forces and surface texture. Some studies have been done on forces, operating parameters and others on surface finish only. Our objective is to combine the various models together and use the knowledge and information on milling process. A summary of the research work and literature is provided in Table 1.

With the rapid development of theory, adaptive control has drawn strong interest from many researchers and industrial practitioners and subsequently has taken many different forms. Such control schemes include Model Reference Adaptive Control (MIRAC) and Self Tuning Regulations (STR). Adaptive control has been applied to metal cutting by e.g. Tae and Jonngwon [24], Pien and Tomizuka [19].

The standard MIRAC scheme deals with the control of an unknown system in the discrete domain. This scheme incorporates an on-line parameters adaptation scheme where the estimated parameters are used to determine the discrete control variables. The dynamics of the controller attempt to create pole-zero cancellations of the plant dynamics, leaving the controlled system with a deadbeat response.

Table 1. Summary of Literature review

Attributes	Applied to			Methods				AC Type		
	F	S.F	D	H	M	S	N	EBC	ACC	ACO
Sutherland,Devor (1986)	√	√		√						
Witanabe,Tohru (1986)	√				√					√
Lauderbaugh,Ulsoy (1988)	√			√						
Bucholz,Thams,Kuhn, Roman(1989)	√			√						
Kolarits,Devries (1991)	√				√				√	
Jung, Oh (1991)	√	√		√						
Kim,Huang (1992)	√				√					√
Jang, Seireg (1992)	√				√					
Pien, Tomizuka (1992)	√				√					√
Ismail, Albestawi (1993)		√			√					
Kim,Ehmann(1993)	√				√					
Kim, Kim (1994)	√				√					√
Altintas Y. (1994)	√				√				√	
Tseng, Billatos (1994)	√				√				√	
Abdou, Yien (1995)	√				√					
Tae, Jonngwon (1996)	√				√				√	
Hsu, Fann (1996)	√				√					√
Wang, Chaojung (1997)	√						√			√
Tang, cheng (1998)	√				√					√
Liu, Yanming (1999)	√						√			√
Abdou,Tereshkovich (2000)	√	√			√					
Saturley, Spence (2000)	√					√				
Salib (2000)	√	√			√	√		√		

F : Cutting Force
D: Depth of Cut
M: Mathematical Model
N: Neural Network
ACC: Adaptive Control Constrains
ACO: Adaptive Control Optimization
EBC-Empirical Model-Based Control

SF : Surface Finish
H : Heuristic Model
S : Computer Simulation

As shown in Table 1, several research papers have been published in the literature, in which different models for the cutting force and machining parameters that affect the surface finish have been proposed. Other researchers have developed adaptive controls to regulate the cutting force in the milling process. In the dissertation, empirical relationships, between surface finish and cutting force versus the milling operating parameters: spindle speed, feed rate and depth of cut have been developed. These empirical relations are used in the simulation of the control model, which generates surface finish close to user specifications. Some of the research done in this field is described, as follows.

The work of Pien and Tomizuka [19] deals with adaptive force control of two-dimensional milling processing in which the feed rate was used to control the cutting force at the desired value. Several methods are presented for softening large overshoot of cutting force caused by sudden changes in the work piece geometry.

Cho and Kim [13] developed a new on-line force control scheme for machining operation by using the Fuzzy Set Theory. Based on this new control strategy, very complex and uncertain processes can be controlled more easily and accurately compared with standard approaches for improving productivity. Experimental work, based on the end milling operation was carried out to verify that the fuzzy control schemes are applicable to the force control.

In their paper Lauderbaugh and Ulsoy [16] 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 effective 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 Albestawi [9], generated a mathematical model for surface generation in peripheral milling that includes the effect of cutter run out and flank wear. The surface finish 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 guides the numerical control in determining the proper speeds and/or the proper feed rates during the milling process as a function of factors such as work material hardness, dept of cut, spindle speed.

Abdou and Tereshkovich [1] developed a heuristic model to determine the optimal parameters in high speed milling operation applied to magnet brushless dc linear motor as a CNC feed drive. In this work, relationship has been developed between the spindle speed, the feed rate versus the cutting force and the surface finish, to incorporate practical process capabilities of high speed milling operation using a linear motor feed drive.

Smith and Tlusty [21] claim that it has been shown for many milling operations that it is desirable to set the tool 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. The authors concluded that the optimum spindle speed for milling operation is the speed where the tool frequency is equal to the natural frequency.

Tang and Cheng [25] developed an adaptive control system based on the fuzzy logic to maintain a constant cutting force under varying cutting conditions. Their experimental results show that the cutting tool travel in the cut with fast feed rate moreover, in the case of varying depth of cut, adjustable feed rates will prevent tool breakage and maintain a high metal removal rate. As a result, the developed system can significantly improve cutting performance in machining operations.

Bobe [5] employed a method, which determines the natural frequencies and vibration modes of milling machines. The method combined a finite element model and an asymmetric stiffness matrix system.

Abdou and Yien [2] described the practical effect of the operating parameters in the milling process. Experiments have been conducted to measure cutting force and tool life under dry conditions. Based on the experimental results, a mathematical model relating the cutting force to the tool life has been developed.

Jang and Seireg [10] presented models for predicting the surface finish, maximum cutting temperature, and residual stress distribution on the machined surface based on the parameters of machine tool and the cutting conditions in rotary machines. They have specified a general procedure for the selection of machine parameters for a given machine that would provide the maximum metal removal rate for any specified surface quality and tool life.

Tseng and Billatos [27] In this paper, the process measurement technique adaptive control algorithum, system identification and tool breakage detection algorithum for the milling operation have been developed using a feed back control system that can predict incipient tool failure and then retract the tool prior to significant damage needed.

Saturley and Spence [20] described the practical integration of solid modeling with milling process simulation on line monitoring and supervisory extension to the solid modeler. The NC program file, determine the tool/work piece immersion geometry for each motion. The immersion geometry is then used with machining milling process model to schedule optimal feed rates.

Liu and Elbestawi [18] developed a geometric adaptive control system for an end milling based on adaptive state tracking. The control definition is given by an external trajectory, which represents the desired surface finish. The Recursive Prediction Error (RPE) includes flexibility of both cutter and work piece and is used for joint state and parameters estimation. In this study, on line assessment of work piece geometry is considered not realizable in practice, and only the cutting force is measured.

Wang and Chaojung [34] proposed an optimal controller with two neural network of different structures for on-line determination of optimal cutting condition in milling. A back procreation neural network for modeling is used to learn the appropriate mapping between the input and output variables of the machining process.

Kolarits and Devries [15] implemented fixed and adaptive controllers for on-line feed rate manipulation to maintain a constant cutting force. The controllers have been able to increase the metal cutting efficiency. The new dynamic model of the end milling force responds to change the feed rate and/or spindle speed.

Witanabe and Tohru [35] used an adaptive control optimization scheme and applied to the physical milling process. The model is used for identifying the actual parameters calculating the temperature of the tool edges and evaluating of rate wear rate.

Tae Yong and Jonngmon Kim [24] presented an adaptive cutting force controller for the milling process. The cutting forces are measured indirectly from the use of currents drawn by A.C. feed drive servomotor.

2.1 Limitations of Literature Review

A considerable amount of research has been done in the area of unattended machining, milling operation and various means have been devised to get the desired cutting forces and surface finish on the milled products. During the course of the literature survey, despite the research performed during the past decade, a predictive theory for machinability has not yet evolved. Current test procedures do not correlate the machinability criteria, such as surface finish, cutting force with the machining parameters, and the value of cutting force that can control and get the required surface finish.

2.2 Research Objectives

The main objective of this research is to develop an empirical model-based control. The proposed model simulates the variation of the cutting force in the end milling process and provides the required surface finish. The machining parameters are adjusted in the model, in order to maintain the cutting force constant.

Interfacing the simulation model with the existing CNC machine controller, will greatly contribute towards improving the quality and productivity of the components being machined, eliminating preventive and corrective measures.

In order to achieve the main objective, the following procedures have been performed:

1. Develop a design of experiment using Taguchi's concepts for milling operation to evaluate the performance of milling process parameters in the cutting process and carrying out the most efficient combination of experimental and analytical techniques. Online force measurements using Kistler force transducer, amplifier, and United Electronics Industries (UEI) data acquisition board is made to provide force performance index relationship for each surface and set of operating parameters. Offline measurement of surface finish indices (Ra, Rku, Rq, and Rp) has been obtained using Taylor-Hobson Surtronic 3-Plus.
2. Develop an empirical model between cutting force and surface finish versus milling operating parameters namely, spindle speed, federate, and depth of cut. Simple regression (SR), Multiple regression, and peak force fitting is conducted to provide the relationships between the dependent and independent variables. The dependent variables are the cutting force and surface finish. The independent variables are spindle speed, feed rate and depth of cut.
3. Utilization of data to develop a performance rating database and significant factor/optimal level database on mean, variance, and signal-to-noise ratio for both cutting force and surface finish.
4. Develop an empirical model based control based on the above empirical modeling relationship.
5. Report final results, conclusions, and recommendations.

2.3 Dissertation Overview

The flow of the proposed research is illustrated in Figure 1. It includes the design of experiment, experimentation, force measurement, statistical technique for surface finish measurement and empirical modeling, model control algorithm and block diagram, and final results and recommendation. This research has been compiled in seven chapters as follows.

Chapter 1: Introduction. It covers all the information that is included in the succeeding chapters.

Chapter 2: Review of previous research work in the field of milling operation process such as force, surface finish, adaptive control. Statement of the objectives and overview of this research was developed.

Chapter 3: The proposed methodology, experimental setup, hardware and software that was used for this research. This chapter also describes the method of measurements for both the cutting force and the surface finish and the analysis procedure.

Chapter 4: Covers the case study that has been performed for the design of experiment, experiment results, statistical analysis such as probability plots, significant factors and peak extraction.

Chapter 5: Integrate the previous applications and analysis of the experimental results for the previous case study. Adequacy of the model has been conducted; simple regression and multiple regressions were used to drive the empirical relationship between the machining parameters versus the cutting force and surface finish.

Chapter 6: Presents the major work of the research to achieve the design of end milling empirical model base control, feed drive system, transfer function and block diagram. Simulation setup and experimental results have been presented to confirm the validity of the control model and its relevance to industry.

Chapter 7: Provides the conclusion and the recommendation for future research.

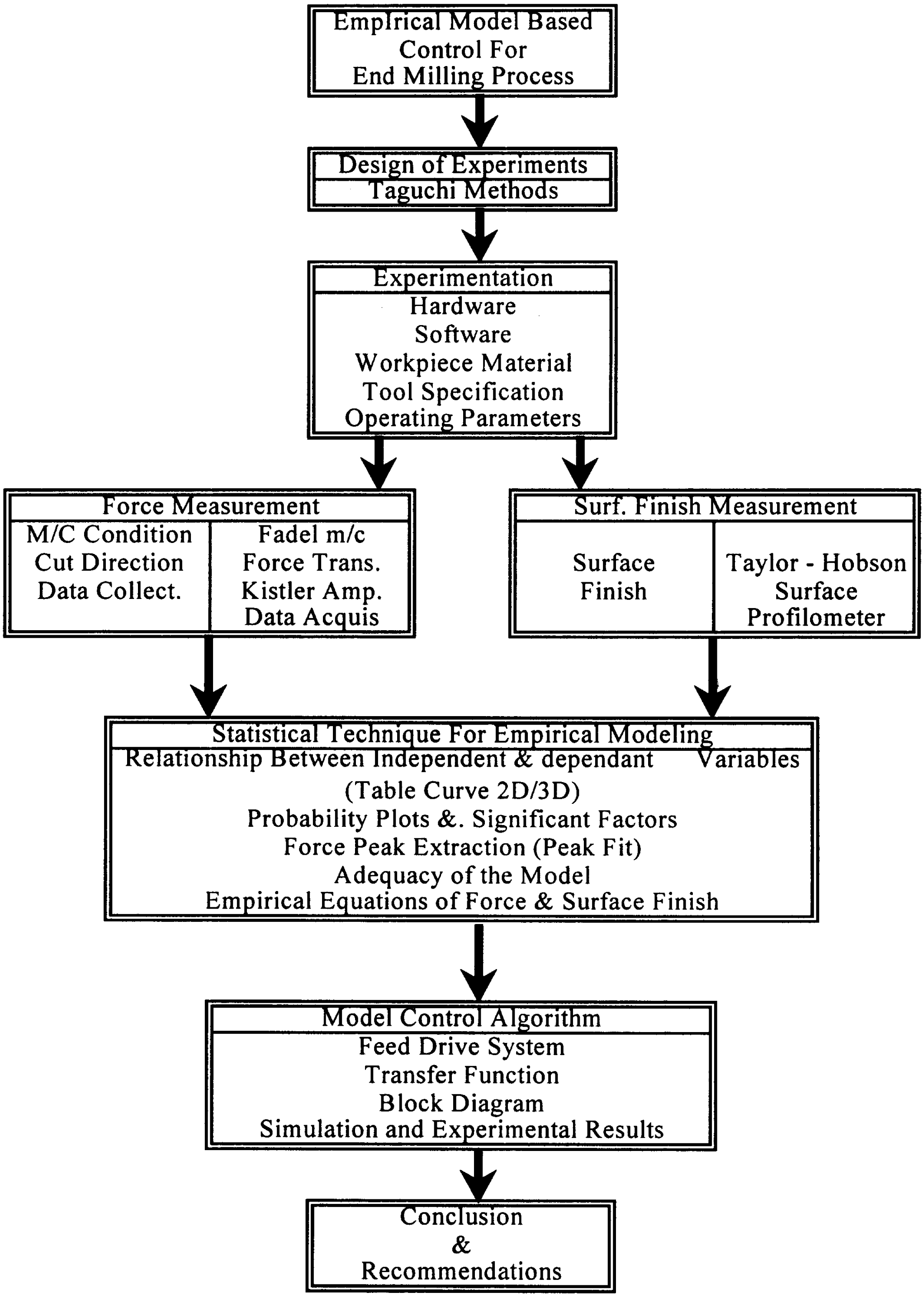


Fig. 1 Dissertation Flow Chart

CHAPTER 3

PROPOSED METHODOLOGY

In order to achieve the goals of this research, a design of experiment of the milling process under different operating parameters is conducted so that enough data can be collected to determine the system performance and optimum results.

By setting a quality characteristics for both cutting forces and surface finish, it was convenient to use Taguchi method to calculate the signal to noise ratio (S/N) since this will include both averages response and variation into a single measure. It is a method that will evaluate the impact of design parameters on the output quality characteristics and will reveal both the desirable and undesirable features of the adaptive control performance. The "signal" is the average (or mean) value representing the desirable characteristic, which will be preferably close to a specified target value. "Noise" is the measure of variability and it represents the undesirable aspects of the experimental results.

In this research, two design methods have been selected as follows:

1. <u>Nominal-is-the best</u>

This is the case where the characteristic has a nominal value, the objective being to reduce the variability around a specified target value. The S/N measure is expressed by the following equation:

$$S/N = 20\, Log_{10}\left(\frac{Y}{S}\right) \qquad \text{-------------------------------------}(3.1)$$

2. <u>Smaller-is-the best</u>

This is the case where the characteristic is optimized and the response is as small as possible, and this is expressed by

$$S/N = -10\,Log_{10}\left(\frac{Y}{S}\sum Y^2\right) \qquad \text{-------------------(3.2)}$$

Where Y is the sampling average and S is the number of samples.

The surface finish characteristics are:

Ra: Is universally used as the international parameter for surface finish. It is the arithmetic mean of the departures (from the mean line) of the surfaced finished profile. S/N smaller is better (small value provides better surface quality)

Rku: A measure of the sharpness of the surface. A spiky surface will have a high Kurtosis value and a bumpy surface will have a low Kurtosis value. Kurtosis will detect if the profile peaks are evenly distributed and is an indication of non-normality. S/N Nominal is better.

Rq: A measure of the RMS parameter corresponding to Ra. S/N nominal is better. (Equal spacing between peak & valleys corresponds to equal wavelengths providing better surface quality

Rp: Measure the maximum high of the profile above the mean line within the assessment. S/N smaller is better. (Small height above the mean implies closer value to the theoretical one, hence better surface finish).

3.1 Experimental Setup

Design of experiment was necessary in order to obtain reliable results. The empirical relationships, generated for cutting forces and surface finishes, are formulated according to data collected from these results. In a milling process, there are three control parameters that affect the machining process namely, spindle speed, feed rate and depth of cut.

These three parameters are selected to be independent variables of the mathematical model for the cutting force and the surface texture. A factorial design is introduced for the formulation of the mathematical model.

Factorial designs are most frequently employed in engineering and manufacturing experiments. In a factorial design experiment, several factors are controlled and their effects upon some response are investigated at each of two or more levels. The experimental plan consists of taking an observation at each of all possible combinations of levels that can be formed from the different factors. Each different combination of factor levels is called a treatment.

The main advantage of factorial experimentation is that investigate the effects of each factor over some pre-assigned range that is covered by the levels of those factors. In other words, the objective is to obtain a broad picture of the effect of factors in addition to the interaction effects between levels, in order to maximize response.

Based on the experimental design, the milling operation is performed using three levels: low, center, and high, for each machining condition. There are three control parameters, the spindle speed, the feed rate, and depth of cut. These three control parameters are selected to be the independent variable of the mathematical models of the cutting force and the surface finish.

In the factorial design, two values of each independent variable are selected and a cubic box is formed. Within, this cubic box, the selected values of the independent variables are the vertices and the control point of this box become the set of values to be used twice.

Based on the proposed experimental design and the proposed factorial design, a total of 36 runs are defined; 12 runs are conducted at each depth of cut. Each run contains three replicates for each surface.

The proposed straight/taper design and geometry is illustrated in Figure 2. A three-step polygon deign provides 12 surfaces at three depthes of cut. There are 36 surfaces and 24 vertices.

A blank size of 4" x 4" x 1.5" allow for 0.53, 0.69, and 0.81 inch in straight cut through the x-direction and the y- direction and a 0.54, 0.86, and 1.24 inch cut for each taper direction. Figure 3 shows the tool motion for each surface at each of the operation setting as described in the proposed factorial desig

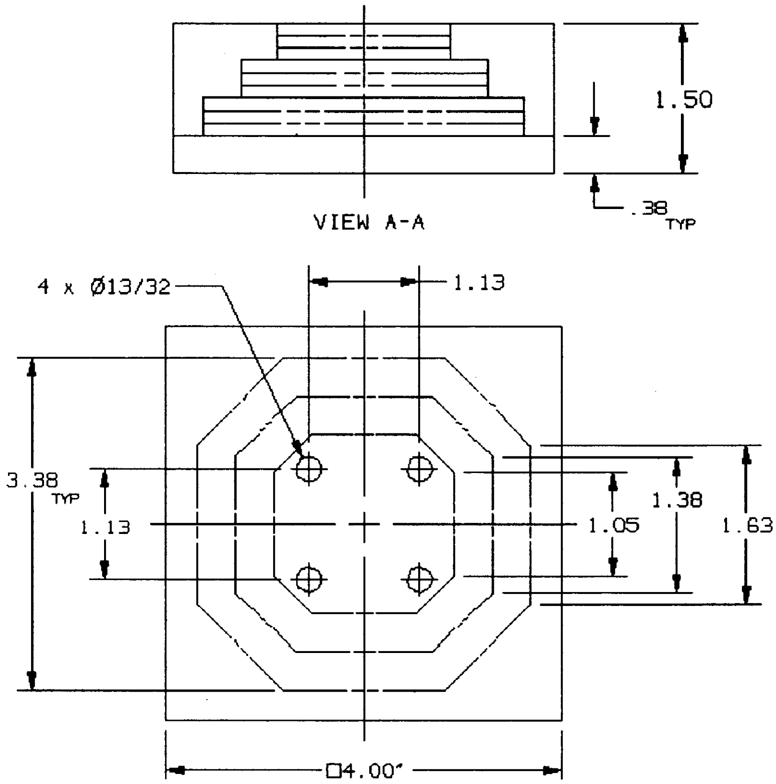


Figure 2 Workpiece Geometric Dimension

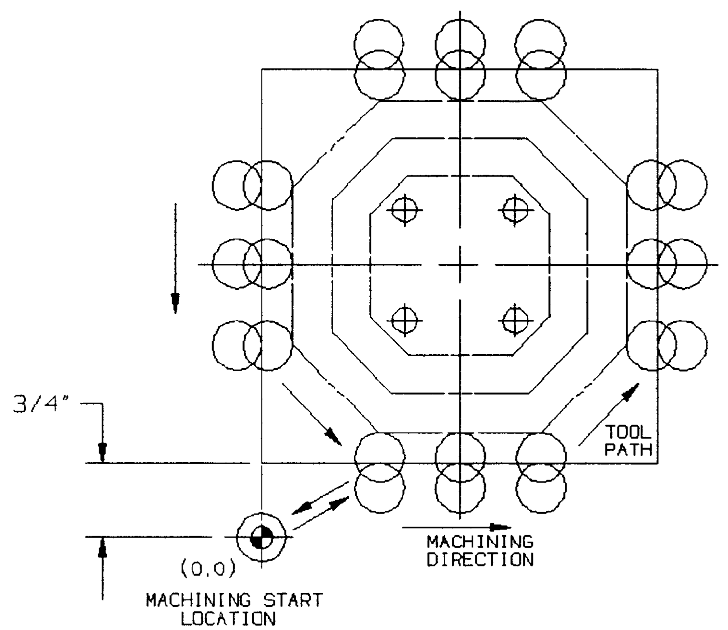


Figure 3 Workpiece Machining/Tool Path Direction

Experimental Procedure of Milling Operation

After the experiment was setup and all the equipments were integrated, the following steps were done:

1. The workpiece was fixed with the vice.
2. The data acquisition board was prepared and all the necessary information entered to the UEI-WIN30.
3. The amplifier was setup after one hour of warm-up period.
4. The CNC milling machine and the NC part program were ready for the operation.

Experimental Procedure of Surface Finish

The work piece was placed on the load cell after the milling operation is performed. The surface finish is tested and inspected by Surtronic 3+. The Surtronic 3+ is connected to a PC-pompatible computer and the surface analysis software plotted the measured surface finish.

The two graphs of the cutting force and surface finish were correlated to the same sampling workpiece. Each experiment was repeated three times under the same operating parameters in order to compare the results. Each experiment provided three values of surface finish and these three data were averaged into one value.

The force varies according to the stochastic nature of the process at each time instant, and it also leads to a variation in the surface finish at the same time. The operation parameters (spindle speed, depth of cut, feed rate) are recorded and they are known. All data is analyzed by using Table-Curve software that generates empirical relationships in which all participated data and parameters of the whole system are fit. The Table-Curve provides a correlation of coefficient parameter (R^2) that determines how well the data are fitting the mathematical function. The higher the correlation coefficients value, the more accurate is the mathematical function.

3.1.1 Hardware

The equipment used in the experiments consists of hardware and software; the hardware are included the following items:

1. A Pentium computer.
2. An analog-to-digital converter board.
3. A data acquisition board.
4. Force transducer.
5. Dual amplifier.
6. Fadal 5-axis milling machine.
7. Four-flutes carbide end mill cutter.
8. Aluminum workpieces; material 6061-T6.
9. Steel workpieces; material AISI C1020.
10. A surface measurement instrument (Surtronic 3+).

1. Microcomputer

A Pentium compatible with the speed of 120 MHz was used. It executed the software to collect, process, and store the data. As soon as the data were processed, a plot of cutting forces was displayed on the screen. Later, the data were collected for the surface finish and were plotted and displayed on the screen. It performed statistical calculation for the surface finish output.

2. Analog-to-Digital Converter Board

(ADC) is a device that converted the analog signals into digital signals. The analog signals are engaged in continuous process, and it divided into the following stages until the process is completed:

Sampling

The continuous signal is converted into periodical samples. Each sample has the same length of time, and the continuous time is broken to a series of discrete time analog signals.

Quantification

Each discrete time analog value must be assigned to one of a finite number of different amplitude levels. These amplitude levels consist of discrete values of voltage ranging over the full scale of the ADC. The different amplitude levels that were obtained must be converted into a digital code. If we use the analog-to-digital converter, we must take into consideration another three characteristics. The characteristics considered are: the sampling rate, the conversion time, and the resolution. The conversion time is the time that it takes to convert the analog signals into digital signals. During the conversion, the resolution of an ADC relates to the precision by which the analog signal is evaluated. In this research, the ADC interface with on-board memory was used and installed inside the microcomputer. The board had a conversion rate of 1 MHz and an on-board memory of 1 MB.

3. Data Acquisition Board

The WIN-30 is a full size board and has a high accuracy analog and digital I/O board for IBM-PC and compatible series of computers. It is a multi channel data acquisition for (x,y,z) cutting force directions. The cutting force data can be displayed in multiple units in either graphical or text form. A cross-hair system allows for measuring voltage and time.

The UEI WIN-30 data acquisition board is required to provide the ability to import, analyze, and store the cutting force signals. The WIN-30 board can be inserted into any 16-bit slot of a PC/AT computer and can be controlled using the STATUS software. Table 2 lists the WIN-30 data acquisition specifications board.

A/D Subsystem:

The A/D subsystem's major component is a monolithic analog to digital converter, which accepts analog voltage inputs sensors, such as pressure transducer and thermocouples, and converts them into 12 bits

Table 2. WIN-30 Data Acquisition board Specifications

Number of input Channels	16 Single-Ended
Resolution	12-bit, 1 in 4096
Total System Accuracy	+/- 0.06% (+/- 2.5 LSB)
Effective Number of Bits	11.2 (min)
Signal/Noise plus Distorsion Ratio	69 dB
Gain Error	+/- 5.0 LSB, Adjustable to 0.0
A/D Clock Divider	
Block Scan Mode	
16 Bit	2 x 50 way IDC, one Analog I/O, one Digital I/O
256 Channels per Block	0 to 27 Degrees Celsius

digital codes. This code is transmitted to the host processor, which processes it according to the software in use at the time.

The A/D may be operated in either single conversion or continuous conversion mode. In single conversion mode the board performs as a single conversion on the selected input channels and stops on completion of this conversion. In continuous conversion mode conversions are performed continuously at a set rate. Programming the WIN-30's internal timer or an external clock source sets this rate.

A/D conversions may be monitored by polled I/O, DMA or by interrupts. In polled I/O mode the software continuously polls the boards' status resister to check for completion of the current A/D conversion. DMA (Direct Memory Access) is used to transfer data direct from the A/D to memory. In interrupt mode, the board automatically generates a hardware interrupt on completion of each conversion.

4. Force transducer

A transducer is a sensor that converts one type of physical quantity to another type. In this research, the transducer was used for the purpose of converting the vibration of the cutting forces to analog signals. The transducer measured each separate components of the force at the same time. The transducer has three wires that are connected to the charge amplifier. Each channel correlated to one component of the measured force (Fx, Fy, Fz). There are two types of transducers; one is covert into digital signals and the other convert into analog signals. The analog transducer is used in the case of continuous process when the electrical voltage is measured. The signal can be interpreted as the value of the measured variable. In order for getting an accurate reading, calibration procedure is required. The calibration procedure establishes a relation between the variable to be measured and the output signal.

A Kistler 9067 force transducer was used to measure the three orthogonal components of the cutting forces in an arbitrary direction. The force transducer contains three pairs of quartz rings that were mounted between two steels blades in the transducer case. Two quartz pairs were sensitive to shear and were used to measure the horizontal force components. The remaining quartz pair, which was sensitive to pressure, measured the vertical components of the force acting in an arbitrary direction. The work piece was an eight-side polygon that was connected with four screws to the fixture as shown in Figure 4. It should be noted that the transducer should be calibrated with the fixture as a preload.

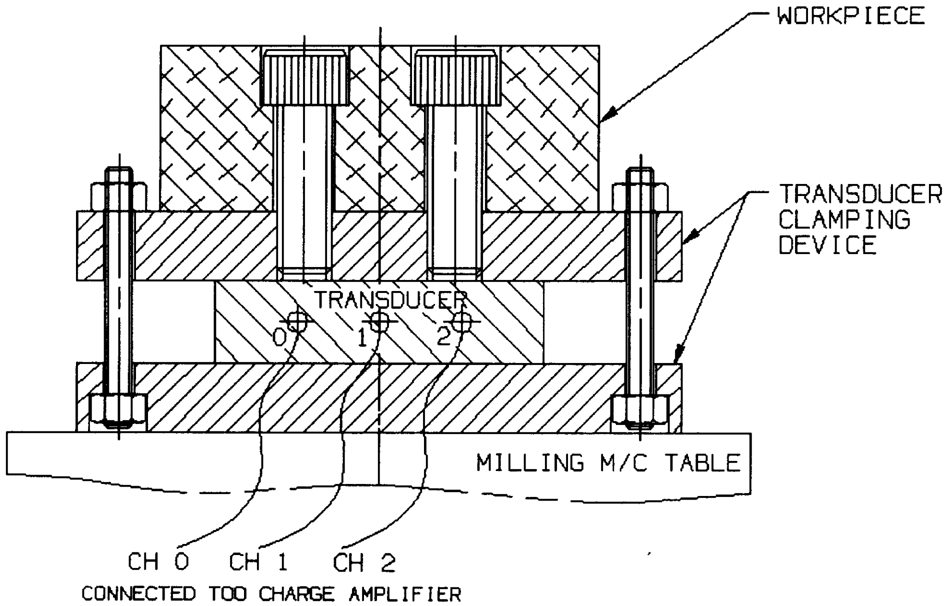


Figure 4.Workpiece/Transducer setup

Dual Amplifier

Kistler model 5004 dual mode amplifier was selected. It was used to filter the cutting force signals and to amplify the signals before processing. This amplifier is a single charge amplifier and constant current supply. The unit converts a piezoelectric transducer signal into a proportional output voltage. The dual mode allows the 5004 to be used with either a charge (high impedance) or a voltage (low impedance) mode transducer; the dual mode amplifier can be used with either charge mode or voltage mode transducer. In either case, the Kistler amplifier conditions the transducer signal for proper operation with the users readout or measurement equipment.

When operated in the 'charge' mode, the Kistler amplifier operates as a charge amplifier that converts the transducer charge signal into a useable low impedance voltage signal. The output voltage has a range up to +10 volts. This relatively high voltage and low impedance provides a signal useable with most readout and analysis equipment.

In the voltage mode, the Kistler amplifier provides the necessary constant current excitation to the low impedance transducer. An input capacitor C1 decouples the DC power from the amplifier input. The decoupling capacitor also serves to convert the low impedance transducer output into a charge signal that is fed into a charge amplifier input. Once the voltage signal is converted into a charge signal, the unit functions in the manner described above. Filtering is also possible with the 5004 amplifier, Table 3 lists the Kistler amplifier specification and Table 4 lists the amplifier setup parameters for the proposed experiment.

Table 3. Amplifier Specifications

Parameters	Units	Value/Type
Measuring Range	pC	±10 to 999000
Transducer Sensitivity	PC/Mu or mV/MU	0.01 to 9990.0
Scale	MU/V	0.002 to 1000000
Accuracy	%	<=0.5
Time Constant	Long (sec)	Up to 100000
	Medium (sec)	1 to 10000
	Short (sec)	0.01 to 100
Time constant Resistor	Long □	1E14
	Medium □	1E11
	Short □	1E9
Noise	PCrms/pF	<2E-5
Filter Type		One Pole Passive
Cutoff Frequency	Hz	180K
Impedance	Ohm	100
Voltage Range	V	±10.0
Current Limit	mA	± 5.0
Operating Temp. Range	^{0}C	0 to 50

Table 4. Amplifier Setup Parameters

Parameters	Units	Value/Type
Filtering (low pass)	Hz	10.0 KHz
Mode	V	Voltage
Transducer Sensitivity	mV/MU	10.0
Scale	MU/V	50.0
Voltage Range	V	-10.0V to +10.0V
Time Constant	Short (s)	0.10
Operating Temperature	°C	Room Temperature
Time Before operation	Hour	1.0

Fadal CNC Machine

The Fadal CNC machine was used to perform the milling process. The Fadal CNC milling machine is a five axis-milling machine. The Model 32MP control is equipped with multiple processors to expand machine capabilities. There are processors for each axis, the keyboard, the spindle, the main CPU, the video screen, and a built-in computer for the user.

The operator may switch between computer, using a DOS platform, and machine operation. The machine operation has been enhanced with the addition of the 1400-3 high speed processor, and macro capabilities. The DOS platform allows full PC computer function.
With this control, the DOS platform may be used while executing a machine program. 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 M function and command capabilities. The macro capability provides the programmer with full mathematical calculations within a program.

Applications for the DOS platform vary according to user requirements. Any DOS application software for a PC computer may be used. The control is supplied with MS-DOS FADAL CNC Memory manager, and the FADAL emulator software, DOS applications may include disk management, menus, communications, and computer aided manufacturing (CAM) software. Table 5 shows the technical specification for Fadal milling of machine.

These software applications may allow the operator to perform program editing, program creation, and file management, while executing on a program on the machine. The Fadal CNC memory manager is used to transfer data between the DOS platform and the machine memory, and

Table 5. Technical Specifications for Fadal Milling Machine

Specifications	VMV40/VMC 40TH
Table Size	39" x 16"
Floor to Table Surface	30"
T-Sots (No. x Width x Span)	3 x 5.62" x 4.33"
Cutting feed Rate (X/Y/Z)	0.01"-250" (375"at 150%
Rapid Feed Rate (X/Y/Z)	700 imp (X,Y) 600 imp (Z)
Max. Weight on Table	1,000 lbs.
Axis Drive Motor (X/Y/Z)	DC, 1,800 Lb. Continuous Trust 3,500 Lb. Peak
Ball Screw Size	40mm Dia. X/Y/Z
Longitudinal (X Axis)	22"
Cross (Y Axis)	16"
Vertical (Z Axis)	20" (Optional 28")
Spindle Nose to Table	4"-24" (4"-32" With Z option)
Spindle Center to Column Ways	16"
Main Motor	15 HP,11.2KW/22.5HP
HT,	16.8 KW
Torque	16 Ft-lbs./220 Ft-lbs
Accuracy, Axis Positioning	$\pm$ 0.0002"
Accuracy, Axis Repeatability	$\pm$ 0.0001"
Glass Scale (X/Y/Z)	Optional
Spindle Speed	75-10,000 RPM / 10-10,000 RPM
Spindle Orientation	electromechanical
Spindle Taper	No. 40

Table 5. Continued	
Specifications	**VMV40/VMC 40TH**
ATC, Nomber of Tools	21
ATC, Tool Selection	Random/Bi-directional
Max. Tool Diameter	3”
(without Adjacent Tools)	4.5”
Max. Tool Length	15”
Max. Tool Weight	15Lbs
Machine width x Depth	98” W x 77”D
Machine Height	94”H
Machine Weight	8,300 Lbs
Air Pressure Requirement (Momentary)	80 PSI, 15 SCFM
Power Requirement (3-phrase)	40/45 Amps, 230 VAC
Single Phase (Optional)	Amps, 230 VAC / N.A.
Servo Motor	FANOC A06B-0502-B
Servo Drive	FANOC T084/03-A20B-1003-008/02A

DNC operations. The Fadal emulator is used to simulate the machine operation, while it is on the DOS platform. The graphic display is useful in checking a program for errors.

5. Milling Cutter and Work Piece

Four ½ inch diameter, flute carbide end mills were used to perform the cutting operations. First, the roughing operation was performed, then the finishing, was performed and data were collected. Each experiment consists of three different paths as follows: X direction, XY direction, and Y direction, all under the same conditions.

6. Surface Measurement Instrument (Surtronic 3+)

Surtronic 3+ measured the surface finish off-line. The data were dumped into Surface Analysis Software, and the data were plotted to a graph that describes the profile of the surfaced texture.

The Surtronic 3+ is a portable instrument for surface texture, and it can be used in laboratory and workshop. The surface measurement that is given by this instrument is very accurate, and it highly used in the industry for measurement of different kinds of metal. The parameters that available for the evaluation of surface texture are: Ra. Rq, Rku.

The parameter evaluations and other functions of the instruments are microprocessor based. The measurement results are displayed on an LCD screen and can be output to an optional printer or another computer for further evaluation. An alkaline non-rechargeable battery normally powers this instrument. If performed, a NiCad rechargeable battery can be used.

<u>Display- Traverse unit</u>

The top panel, of the display-traverse unit, carries a membrane type control panel and a liquid crystal display. The unit houses the electronics for controlling the measurement sequence, computing the measurements data and outputting the results to the display, or to the RS 232 port for use with a printer or to a computer, for further analysis.

The unit also contains a drive motor that traverses the pickup across the surface to be measured. The measuring stroke always starts from the extreme outward position ready for the next cut-off (Lc) or Length (Ln).

Specifications for Surtronic 3+

<u>Alkaline battery:</u>

minimum 600 measurements of 4mm measurement length

<u>NiCad:</u>

Minimum 200 measurements of 4mm measurement length

Size: 6 LR 61 (USA/ Japan), 6 F 22 (IEC)

Fixed Battery / external charger

External charger (NiCad only):

110/240V RTH No. 112/1591

50/60 Hz

<u>Traverse unit:</u>

Transverse speed: 1mm/sec

<u>Measurement units:</u>

Metric/Inch preset by DIP-switch, deselect by menu

<u>Cut-off values:</u>

0.25mm, 0.8mm, and 2.50mm (0.01in, 0.03in and 0.1in)

Display

LCD-matrix.2 linesX16 characters, alphanumeric

Keyboard:

Membrane switch panel tactile

Filter:

Digital Gauss filter or 2CR filter (ISO) selectable by DIP-switch

3.1.2 Software

The softwares that were used consist of the following:

1. UEI (United Electronic Inc.) to record graphs of these force components.
2. Taylor-Hobson Surtronic 3-plus
3. Softwares used to perform data analysis include Excel, Table Curve 2D, Table Curve 3D, MathCad, Peak Fit and Part Programming.

3.2. Experiment Data Collection

The data collection is the most important phase in this research. The data collection is divided into two procedures:

- Force data collection
- Surface finish data collection

The detailed procedures for data collection are as follows:

1. The force transducer measures the analog signals equivalent to the cutting forces in the three planes.
2. These signals are then transferred to the amplifier to be filtered and amplified.
3. The three signals of the different components are then transferred to the ADC interface board.
4. The signals are digitalized, and collected with the help of the UEI software.
5. The digital signals are transferred to an array and stored in the computer memory as an ASCII file.
6. The data in the array are then processed and plotted on the screen immediately.

In the surface finish data collection; the Surtronic 3+ was calibrated as follows:

1. I placed the reference specimen on a flat surface and I set up the instrument to make the traverse across it. I made sure that the Traverse unit body is parallel to the surface of the standard and that the stylus traverses at right angles to the lay of the grooves.
2. I selected the 0.03-inch cut-off and the Ra parameter.
3. I compared the Ra value reading with the Ra value of the reference specimen.

4. If it differed by more than 2%, I used the small screwdriver to turn the sensitivity adjuster. This is located through the hole, which is located in the front panel of the display unit.
5. I calibrated the Surtonic 3+, each time that I began a new set of measurement for the day.

The instrument Surtonic 3+ was connected to the computer. In the computer, the surtonic 3+ software was installed and displayed the output graphs of the measured surface finish. The setting of the Surtonic 3+ is as follows:

Parameter:	Ra
Lc:	0.03 inch
Ln:	0.15 inch
Range:	---.-2
Vv:	x1000
Vh:	x100
Data Dump Ln:	400 inch
Data dump range:	200 inch

The Surtonic was set to the above setting, and measurements of the surface texture were taken. The stylus was laid perpendicular to the surface to be measured. I activated the software to pick up the necessary measurements. Each time that data was collected, it was stored as an ASCII file. I measured the X, XY, and Y directions for each experiment.

Each measurement was repeated three times in different places for each direction. The final output was an average of the three measurements as it is tabulated in the results chapter.

3.3 Experimental Measurements

3.3.1 Cutting Force Measurement

Control and storage of online force measurement is performed using the United Electronic Inc.(UEI) STATUS for windows, STATUS is a data acquisition software for the WIN-30 data acquisition board. Utilizing of UEI STATUS is due to the following reasons:

1. Cutting force data can be acquired from the UEI WIN-30 board for which multi-channel data acquisition (X,Y, and Z direction cutting force) is fully supported.

2. The acquired cutting force data can be displayed in multiple units in either graphical or text form, a cross-hair system allows the measurement of voltage and time.

3. The acquired cutting force data can be processed by FFT or chirp-z method to yield frequency domain representations.

4. The cutting force data can be stored for recall and can be written as an ASCII text file for use with spreadsheet or graphical problems.

The STATUS software setting used for cutting force acquisition for this research experimentation is listed in Table 6 also a sample of STATUS output is provided in Figure 5.

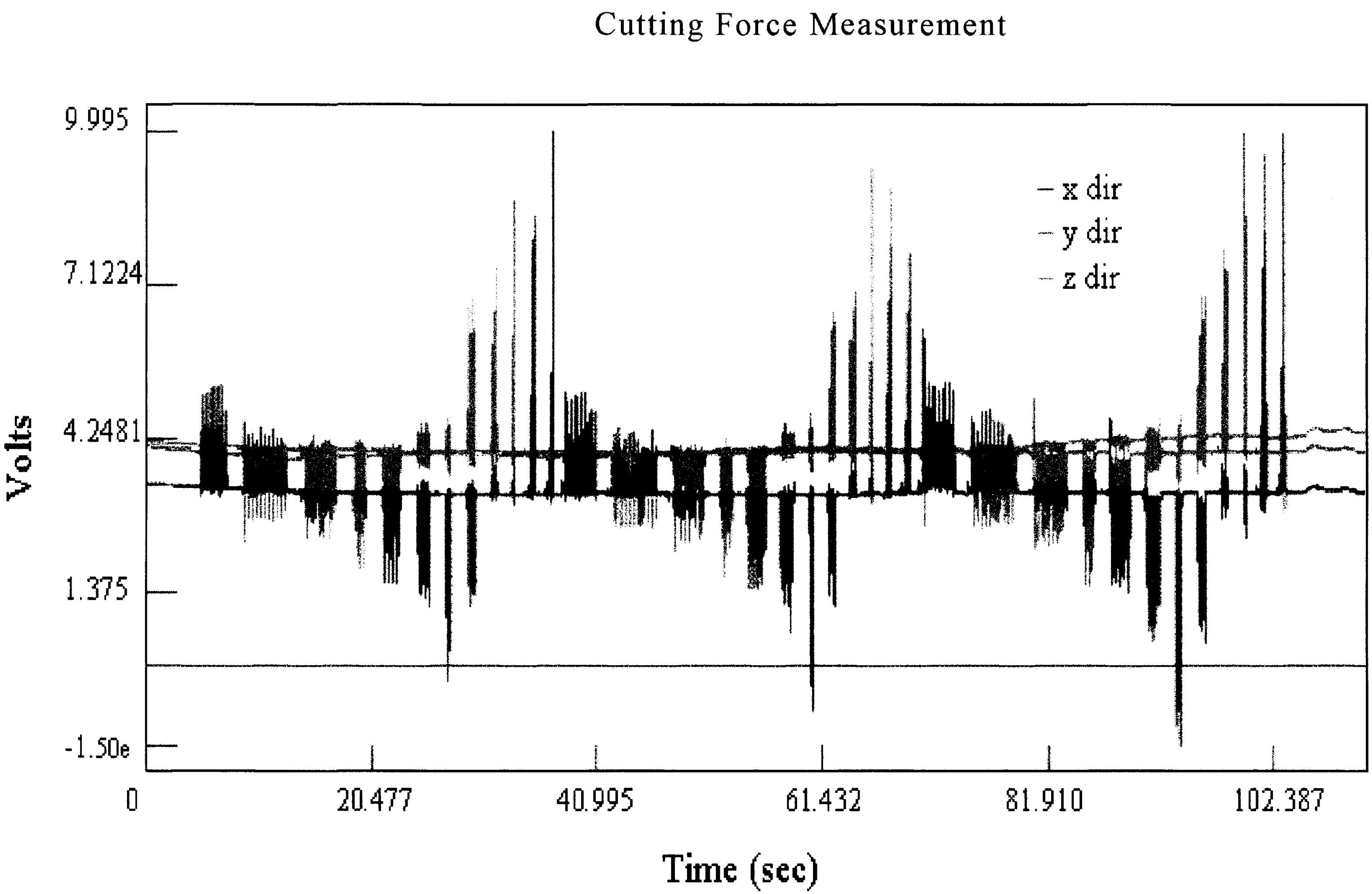


Figure 5. Cutting Force Sample STATUS Signal Output

Table 6 Experiment STATUS Software Setup

Channels	2,1,0 (X,Y,Z)
Range (Volts)	-10 to +10
Gain	1.0
Sampling Rate	200 Hz
Samples/Channel	22600
Total number of Samples	245200
Sampling Clock	Internal
Data Transfer	Smart Cache
Interrupt Level	11
Analog Input	Single Ending
Base Address	700

3.3.2 Surface Finish Measurement

Surface finish measurement was measured off-line using Surtronic 3+. The data were dumped into surface analysis software and plotted onto a graph that described the profile of the surface finish. The raw data of the measurement is processed by the software package using the surface relationship.

1. Surface Skewness $$R_{SK} = \frac{1}{nR_q^3}\sum_{i=1}^{i=n}(Y_i)^3 \quad (3\text{-}3)$$

2. Mean spacing $$S_m = \frac{1}{n}\sum_{i=1}^{i=n}S_i \quad (3\text{-}4)$$

3. Peak-to-Valley Height $$R_{tm} = \frac{1}{n}\sum_{i=1}^{i=n}R_{ti} \quad (3\text{-}5)$$

4. Surface Kurtosis $$R_{Ku} = \frac{1}{nR_q^4}\sum_{i=1}^{n}(Y_i)^4 \quad (3\text{-}6)$$

5. Surface Wavelength $$\lambda_q = \frac{2\pi R_q}{\Delta_q} \qquad (3\text{-}7)$$

6. Roughness Average $$R_a = \frac{1}{l}\int_0^l |y(x)|dx \qquad (3\text{-}8)$$

Where

R_q = RMS of roughness average

Y_i = Profile area

S_i = Peak Spacing

n = Number of Peaks

Δ_q = RMS slope of the profile

R_{ti} = max peak to valley height of the surface profile in one sampling length

l = sampling length

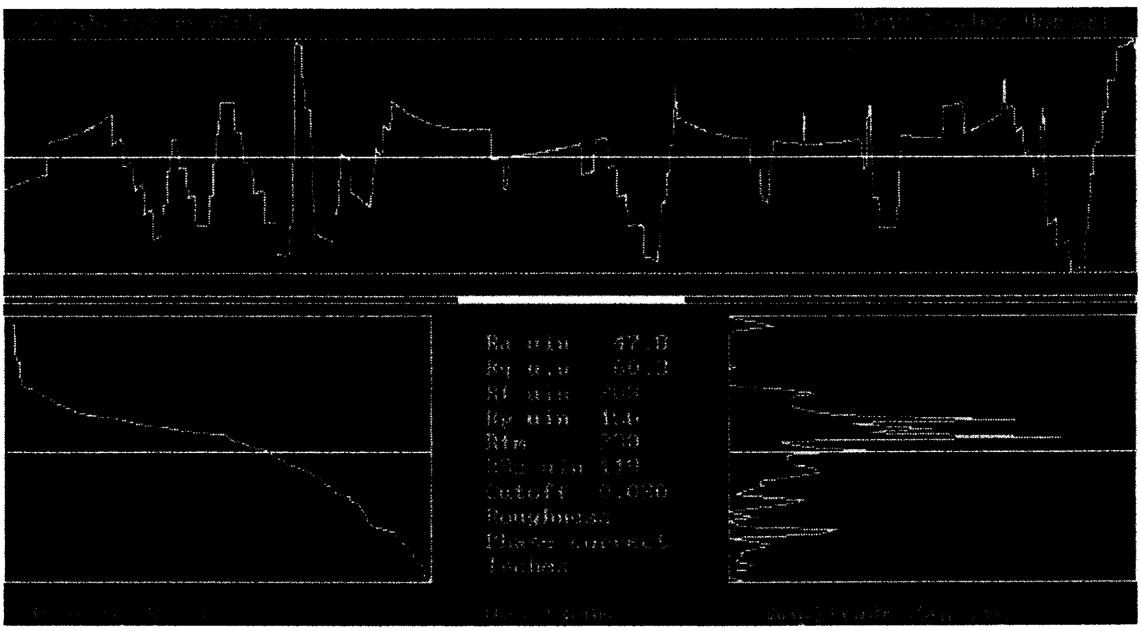


Figure 6. Surface Finish Sample Profile Output

As shown in the surface finish profile output graph, roughness consists of the finer irregularities of the surface texture, which usually includes those irregularities resulting from the inherent action of the production process. These are considered to include traverse feed marks and other irregularities within the limits of the roughness sampling length.

Waviness is the more widely spaced component of surface texture. Unless, otherwise noted, waviness is to include all irregularities whose spacing is greater than the roughness sampling length and less than the waviness sampling length. Waviness may result from such factors as machine or work deflections, vibration, chatter, heat treatment or warping stains. Roughness may be considered superposed on a 'wavy' surface.

Lay is the direction of the predominant surface pattern, ordinarily determined by the production method used.

Flaws are unintentional irregularities, which occur at one place or at relatively infrequent or widely varying intervals on the surface. Flaws include such defects as cracks, blowholes, inclusions, checks, ridges, scratches etc.

A peak is the point of maximum height on that portion of a profile, which lies above the centerline and between the two intersections of the profile and the centerline. A valley is the point of maximum depth of that portion of a profile, which lies below the centerline and between two intersection of the profile and centerline. The roughness sampling length is the sampling length within which the roughness average is determined. This length is chosen, or specified, to separate the profile irregularities, which are designated as roughness from those irregularities, designated as waviness. The cutoff is the electrical response characteristics of the roughness average measuring instrument, which is selected to limit the spacing of the surface irregularities to be included in the assessment of roughness average. The cutoff is rated in millimeters. In most electrical averaging instruments, the cutoff can be selected. It is a characteristic of the instrument rather than of the surface being measured. In specifying the cutoff, care must be taken to choose a value, which includes all the surface irregularities, which desires to be measured.

Roughness Average (R_a)

This roughness, also known as arithmetic average (AA) and centerline average (CLA), is the arithmetic average of the absolute values of the measures profile height deviations taken within the sampling length and measured from the graphical centerline. For graphical determinations of roughness average, the height deviations are measured normal to the chart centerline. Roughness average is expressed in microinch. A microinch is one millionth of an inch, (0.000001 inch). For written specifications or reference to surface finish requirements, microinch may be abbreviated as □in. It should be understood that the reading, which is considered significant, is the mean reading around which the needle tends to dwell fluctuate under small amplitude.

The peak-to-valley height is the maximum excursion below the centerline plus the maximum excursion below the centerline within the sampling length. This value is typically three or more times the roughness average. The waviness height is the peak-to-valley height of the modified profile from which roughness and flaws have been removed by filtering, smoothing, or other means. The measurements are to be taken normal to the nominal profile within the limits of the waviness sampling length and expressed in microinches.

The surface measurements are taken using a Taylor-Hobson Surtronic 3+ profilometer and the data is recorded on a Pentium 120 Mhz data desktop computer, each value of the measurement represent the average of three reading of each replicates (9 readings). As shown in Figure 7, each surface measurement is taking opposite of the cutting direction. The Stylus is placed 2 mm from the center line to provide a central traverse distance of 4 mm.

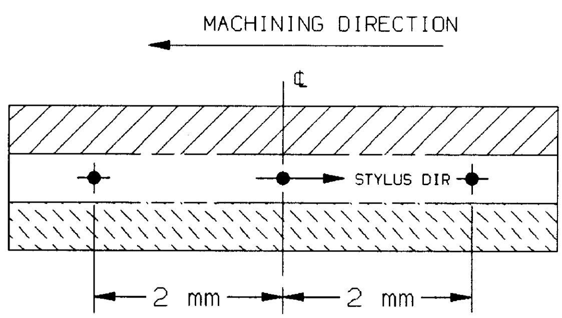


Figure 7 Workpiece Surface Finish Measurement

3.3.3 Procedures of Analysis

The analysis of the experimental results has been performed using many statistical techniques to determine the system performance and the optimum levels, also to come up with the empirical models that achieved the object of this research. The data analysis for cutting force and surface finish using the mean, standard deviation and signal-to-noise ratio has been performed using the following analysis:

- Single Regression Software (SR).
- Multiple Regression Software (MR).
- Peak Force Extraction (Peak Fit).
- Generated Probability Plots.

The spreadsheets statistical features were used to generate and test the probability plot and the operating levels for significant factors effect.

<u>Single Regression (SR)</u>

Single regression was used to find the relationship between two parameters as follows:

- Cutting Force vs Feed Rate
- Cutting Force vs Speed
- Surface Finish vs Cutting Force

Each of the above relationship was performed using the equation discovery Table-Curve 2D, which was developed by Jandel Scientific [30]. This software is ideally used when one has to determine the relation between two variables, in which one is dependent and the other is independent. This software has a file Menu that allows the user 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, Bessel's function and various other desired mathematical and algebraic calculations. Next it has a process menu 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 spreadsheet, 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 them. To use the table curve software, the entire data 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 and y)

The data is transformed into mathematical models after the analysis and thereby conclusions can be made. With the help of the empirical relations obtained for 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 Curve 2D automatically tests 3665 built-in equations. 2D empirical relationships with the best ideal fit are sorted in descending order. Once the process is completed, Table Curve presents a statistically ranked list of the best-fit equations and provides graphic capabilities. The adequacy of the fit is determined by the R-Square value, a value of 1.0 indicates a perfect fit, and a value close to zero indicates that there is no relationship between the independent and the dependent values. Figure 8 shows an example of the table curve 2D graph of the relationship between the cutting force and the surface finish. The graph also shows the rank of the equation and the estimator parameters. The relationship in this graph was taken for the aluminum work piece at low depth of cut with the machining parameter of spindle speed 2500 revolution per minute and a feed rate of 40 inch per minute. As explained previously, the graph shows the adequacy of the fit by R-Square value, as well as the relationship between the dependent and the independent variables.

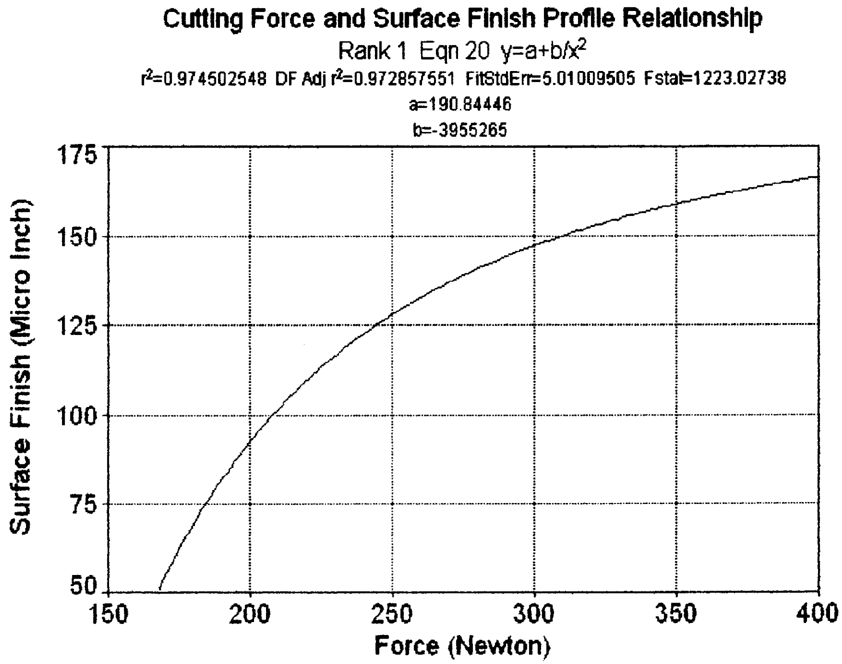


Figure 8. Single Regression for Surface Finish vs Force graph

Multiple Regression (MR)

Multiple regressions are one of the most recent and useful software discoveries, to determine the relationship between three variables in which two are independent and the other is the dependent variable. In this research, multiple regression software is used to determine the relationship for the following variables: Spindle Speed, Feed Rate, Surface Finish, and Cutting Force at a fixed depth of cut.

A relationship can be obtained by using the cutting force and surface finish that obtained from the proposed design of experiment function. The goodness of the fit is determined by the R-Square value. In this research, the spindle speed and the feed rate are considered the independent variables and the cutting force and the surface finish were used as the dependent variables. Table curve 3D software [31] combines a surface fitter with the ability to find the ideal equations that describes three-dimensional empirical data. Table-curve 3D uses a selective subset procedure to fit 36,000 of its 453,697,387 built-in equations from all disciplines to find the one that provides the ideal and best fit. Figure 9 shows an example of the Table–curve 3D graph for the relationship between speed, feed and cutting force at low depths of cut. It can be noticed from Figure 9. That the Table-curve 3D presents a statistically ranked list of the best-fit equation. It also provides graphic capabilities.

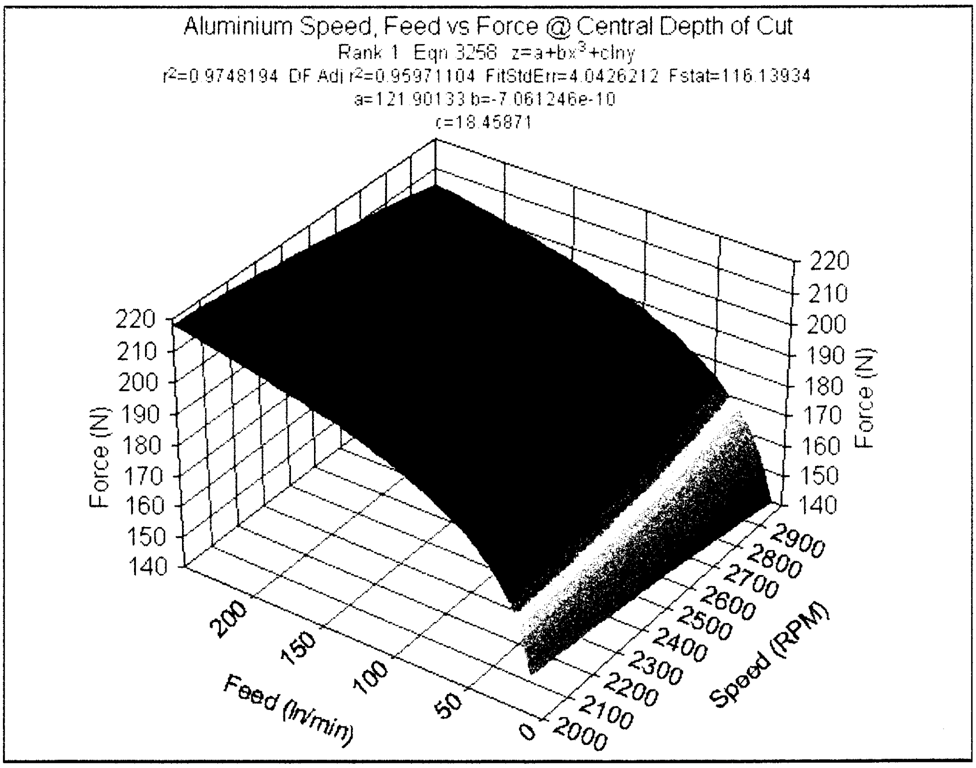


Figure 9. Table-Curve 3D Graph

Peak Extraction (Peak Fit) [33]

For each surface, force measurement taken according to the proposed design of the experiment, the component of the resultant force signal for each direction of cut is separated using the Peak fit software package. Each component of force data obtained during the experimentation is separated into three criteria such as:

- Peak Force Amplitude (a_0).
- Force center (a_1).
- Force width (a_2)

The (a_3) and (a_4) components are shape distortion indices for the force center. The strength and goodness of the fit are measured by the R-Square value, the number of peaks is determined for each surface. The best fit is close to R-square of 1.00, and a weedy fit is indicated with a value close to zero. Figure 10 shows a sample of a peak fit output for Aluminum work piece machine cut. The cutting force data that obtain from the experiment results are imported via an ASCII text file, into peak fit where the force signal is best fit and separated into peaks revealing amplitude, widths, and height. For the proposed methodology, statistical peak function family is selected with in peak-fit and fitted using the residual method. Using the best-fit beta amplitude function represented by the following equation.

$$y=\frac{\left[\dfrac{x-a_1+\dfrac{a_2(a_3-1)}{a_3+a_4-2}}{a_2}\right]^{(a_3-1)}\left[1-\dfrac{x-a_1+\dfrac{a_2(a_3-1)}{a_3+a_4-2}}{a_2}\right]^{(a_4-1)}}{\left[\dfrac{a_3-1}{a_3+a_4-2}\right]^{(a_3-1)}\left[\dfrac{a_4-1}{a_3+a_4-2}\right]^{(a_4-1)}}$$

Where a_0 is the amplitude, a_1 is the center, and a_2 is the width as previously explained, were obtained for each treatment replicate.

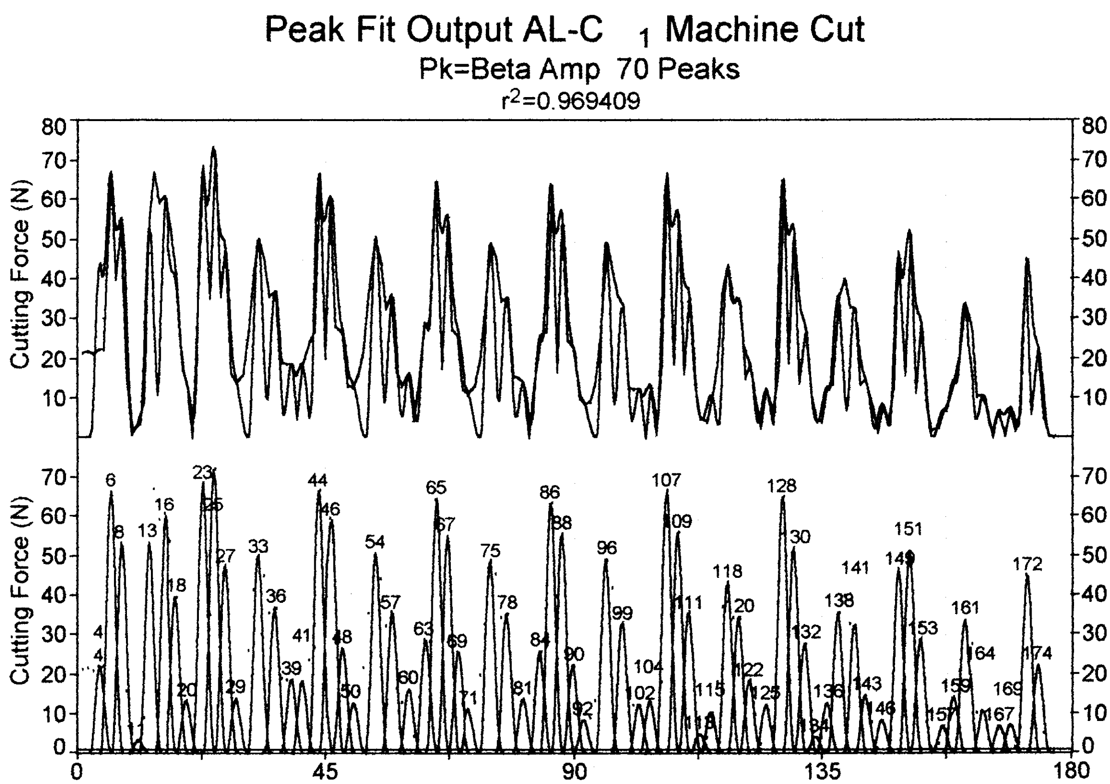


Fig 10 peaks fit sample output

CHAPTER 4

CASE STUDY AND ANALYSIS

4.1 Method of Experiment, Set up and Procedure

Based on the experimental design, the capacity of the milling machine used three levels (lower, center, and upper) whichwere selected for each cutting condition. There are three control parameters, the spindle speed, the feed rate, and depth of cut. These three control variables are selected to be the independent variables of the mathematical models of the cutting force and the surface roughness.

In the factorial design, two values of each independent variable are selected and a cubic box is formed. Within this cubic box, the selected values of the independent variables are the vertices and the control points of this box are the set of values to be used twice.

Tables 7 and 8 show the operating parameters for both Aluminum and Steel materials that are used in this research.

Table 7. Aluminum work piece operating parameters

<table>
<tr><th rowspan="3">Levels</th><th colspan="4">Variables</th></tr>
<tr><th rowspan="2">Speed RPM</th><th colspan="2">Feed Rate</th><th rowspan="2">Dept of Cut In</th></tr>
<tr><th>In/tooth</th><th>In/min</th></tr>
<tr><td>Low</td><td>2000</td><td>0.002</td><td>16</td><td>0.01</td></tr>
<tr><td rowspan="2">Central</td><td rowspan="2">2500</td><td>0.004</td><td>40</td><td rowspan="2">0.03</td></tr>
<tr><td>0.01</td><td>100</td></tr>
<tr><td>High</td><td>3000</td><td>0.02</td><td>240</td><td>0.06</td></tr>
</table>

Table 8. Steel work piece operating parameters

Levels	Variables			
	Speed RPM	Feed Rate In/tooth	Feed Rate In/min	Dept of Cut In
Low	3500	0.001	14	0.01
Central	4000	0.002	32	0.03
		0.005	80	
High	4500	0.01	180	0.06

Based on the proposed experimental design, the proposed factorial design for the Aluminum and the Steel workpiece, a total of 36 runs are defined; 12 runs are conducted at each depth of cut. Each runs contains three replicates for each surface of both the Aluminum and Steel workpieces. The tool motion for each surface setting was described in the proposed factorial design. The proposed straight/taper design and machining procedures is illustrated in Figure 11 .for the Aluminum work piece and in Figure 12. for the steel work piece. A 3-step polygon deign provides 12 surfaces at three depth of cut. There are 36 surfaces and 24 vertices. The blank size of the work piece geometry and the machining dimension were illustrated previously in Figure 2. Figure 3 shows the cutter machining direction for each surface finish for all the operating parameter setting as described in the proposed factorial design. ½ inch diameter-four flutes carbide, mill tool cutter was used in this machining operation.

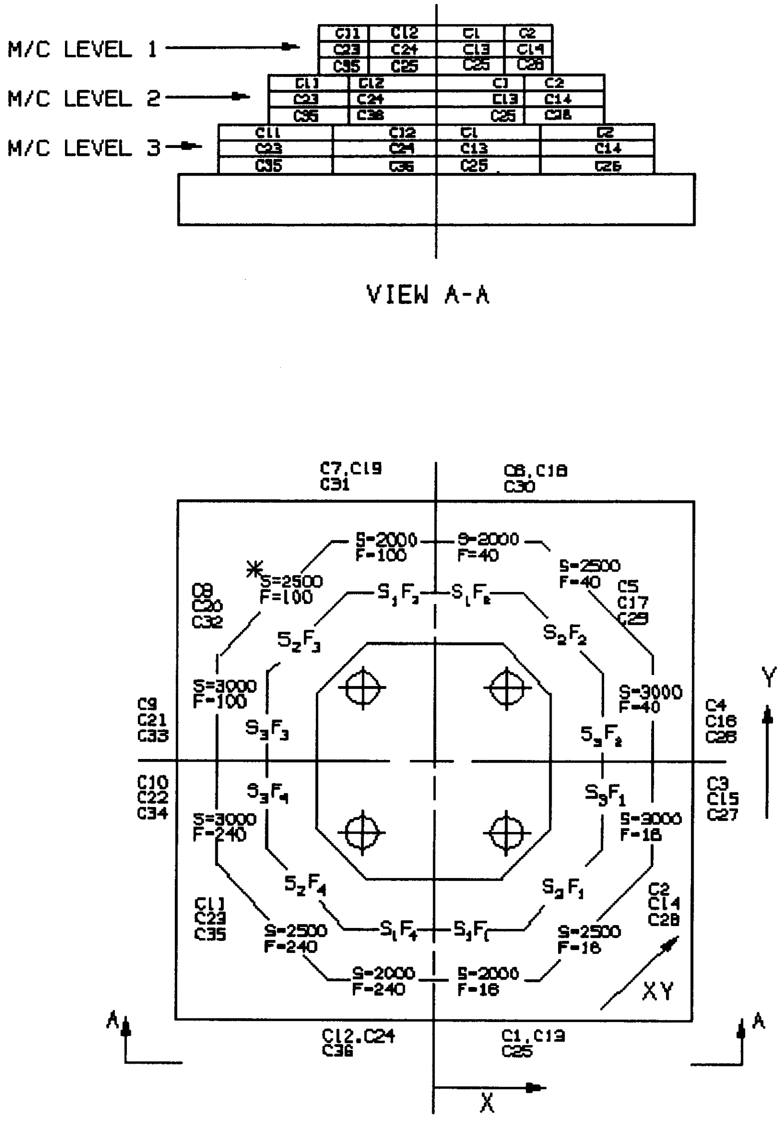


Figure 11. Aluminum Workpiece Machining Process
Material: Aluminum 6061-T6

In the above Figure
Level 1 : Machined with .0.01 inch depth of cut
Level 2 : Machined with .0.03 inch depth of cut
Level 3 : Machined with .0.06 inch depth of cut
S : Speed (rpm)
F : Feed rate (ipm)
M/C : Machined surface

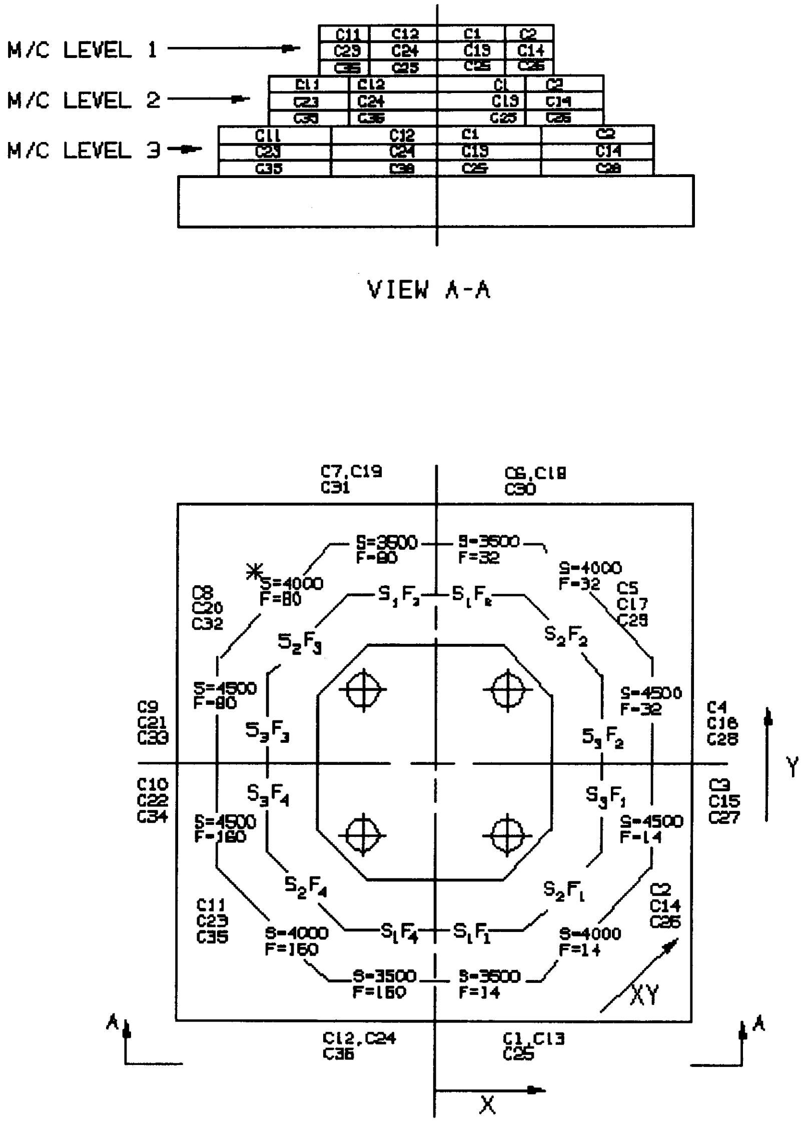


Figure 12. Steel Workpiece Machining Process
Material: Carbon Steel C1020

4.2 Experimental Results

All the data that were obtained in the Fadal CNC milling machine software was in form of thousands of numbers. These data were organized so that the mathematical model could be derived, the surface finish data was imported in Excel spreadsheets, the surface parameter was averaged or maximized or minimized to obtain the 36 values for the cutting process, Ra, Rku, Rq and Rp values were averaged as the average value would give optimum results. The cutting force data was spl/it into the maximum and average values so that we can obtain optimum results, for these purpose also the Excel spreadsheets was used, before performing all the functions, the data files had been converted from .dat format to .xls format as mentioned in previously in the experiment design, Taguchi method was used to calculate the S/N ratio. Table 9 and Table 10 list the mean, standard deviation, and Signal-to-Noise ratio of the cutting force and the surface finish. These cutting force results have been performed for both the two types of materials that have been used in this research (Aluminum and Steel). The average of the cutting forces has been performed using the excel software. The surface finish reading is the average of six surface finish experiment measured for each replicate machining process. Tables for cutting force and surface finish averaging results are included in the appendix of this research. The results in Tables 9 and 10 also include the operating parameter.

Table 9. Aluminum Experimental Results																						
Surface	Speed	Feed	Depth	Cutting Dir	Cutting force			Ra			Rku			Rq			Rp			Rt		
					Mean Force	Force stdev	Force S/N	Ra	Stdev Ra	S/N Ra	Rku	Stdev Rku	S/N Rku	Rq	STDEV Rq	S/N Rq	Rp	STDEV Rp	S/N Rp	Rt	STDEV Rt	S/N Rt
1	2000	16	0.01	X	172.9	16.114	10.729	18	1.020	17.238	4	0.622	6.130	23	1.159	19.583	77	8.467	9.108	136	14.700	9.282
2	2500	16	0.01	XY	165.1	24.746	6.673	17	1.171	14.601	3	0.855	3.952	22	1.364	15.863	83	11.590	7.152	130	35.397	3.679
3	3000	16	0.01	Y	147.9	23.213	6.371	11	0.638	17.778	13	1.834	6.893	16	0.556	28.688	79	8.797	9.018	136	8.885	15.256
4	3000	40	0.01	Y	151.8	16.537	9.182	27	4.569	5.965	4	1.034	3.805	36	5.978	5.981	118	29.597	4.002	243	25.285	9.624
5	2500	40	0.01	XY	184.6	15.679	11.777	36	1.696	20.950	5	0.365	12.339	47	1.540	30.624	188	10.357	18.163	312	13.361	23.335
6	2000	40	0.01	X	196.8	18.102	10.870	46	1.081	42.214	4	0.146	29.143	62	1.028	60.261	153	8.146	18.797	317	14.418	21.970
7	2000	100	0.01	X	198.1	22.36	8.859	75	1.796	41.726	3	1.215	2.626	91	2.066	44.066	207	12.174	16.966	504	11.643	43.270
8	2500	100	0.01	XY	194.6	31.268	6.225	71	4.556	15.483	3	0.141	23.127	90	4.994	17.952	231	23.820	9.716	472	22.281	21.174
9	3000	100	0.01	Y	190.0	40.954	4.639	58	0.661	87.569	3	0.077	32.620	65	8.343	7.838	177	7.402	23.854	336	10.523	31.960
10	3000	240	0.01	Y	205.1	67.32	3.046	90	1.349	66.641	3	0.122	21.499	113	1.450	77.884	278	19.329	14.405	515	31.084	16.554
11	2500	240	0.01	XY	211.7	68.692	3.083	92	1.790	51.497	3	0.072	38.830	115	2.068	55.783	297	15.516	19.156	595	16.233	36.634
12	2000	240	0.01	X	216.3	58.929	3.670	122	4.606	26.595	4	0.714	4.915	162	2.376	68.369	402	13.830	29.082	878	10.299	85.215
13	2000	16	0.03	X	179.1	14.172	12.636	28	2.254	12.391	4	0.331	11.900	37	3.030	12.151	113	19.894	5.669	227	11.931	18.999
14	2500	16	0.03	XY	173.1	16.968	10.203	20	2.030	9.617	5	0.575	8.922	26	2.833	9.293	95	10.557	8.989	185	18.986	9.750
15	3000	16	0.03	Y	149.7	19.009	7.877	14	1.457	9.854	4	0.731	4.816	18	1.262	14.093	43	5.025	8.512	103	9.874	10.477
16	3000	40	0.03	Y	154.8	13.146	11.775	31	2.698	11.661	3	0.344	7.820	39	4.653	8.367	117	26.891	4.355	196	40.938	4.793
17	2500	40	0.03	XY	186.9	12.4521	15.009	42	2.005	21.117	3	0.233	12.429	53	2.482	21.384	140	7.321	19.182	248	34.383	7.210
18	2000	40	0.03	X	196.0	15.627	12.542	52	0.658	79.346	2	0.103	19.969	125	9.439	13.250	160	19.649	8.166	274	31.127	8.803
19	2000	100	0.03	X	207.3	19.405	10.684	92	1.079	85.635	2	0.058	40.415	110	1.212	90.361	252	7.085	35.538	524	4.934	106.233

20	2500	100	0.03	XY	194.2	29.623	6.555	87	1.350	64.273	2	0.077	29.156	99	1.046	94.988	205	6.684	30.689	528	13.596	38.811
21	3000	100	0.03	Y	181.4	32.034	5.664	65	0.557	117.456	6	0.229	24.749	90	8.218	11.004	277	4.916	56.395	627	14.752	42.533
22	3000	240	0.03	Y	196.2	58.471	3.356	100	1.207	82.809	3	0.058	49.075	125	1.173	106.986	299	4.448	67.164	601	14.891	40.368
23	2500	240	0.03	XY	211.1	49.676	4.249	115	1.646	69.770	3	0.108	24.101	142	1.562	91.176	347	18.385	18.892	606	28.150	21.527
24	2000	240	0.03	X	216.8	53.18	4.077	131	1.466	89.335	3	0.058	59.660	166	1.035	160.771	383	6.570	58.261	1012	9.524	106.236
25	2000	16	0.06	X	186.3	10.432	17.854	37	1.872	19.967	2	0.184	11.327	44	2.085	21.031	82	5.911	13.853	181	15.712	11.513
26	2500	16	0.06	XY	181.2	11.054	16.391	32	1.101	28.810	4	0.375	11.501	42	3.177	13.366	128	10.184	12.612	282	35.675	7.905
27	3000	16	0.06	Y	158.1	15.642	10.110	22	1.332	16.509	8	0.873	9.610	33	1.508	21.929	136	17.018	8.011	278	15.467	17.973
28	3000	40	0.06	Y	162.1	10.382	15.613	46	2.387	19.385	4	0.637	6.434	57	2.851	20.050	155	11.711	13.255	245	41.972	5.845
29	2500	40	0.06	XY	190.0	10.266	18.504	53	0.688	77.484	2	0.058	38.298	63	0.660	96.117	155	4.861	31.911	293	8.387	34.894
30	2000	40	0.06	X	194.5	11.504	16.903	64	1.560	41.077	2	0.058	31.754	74	2.113	34.988	149	8.660	17.232	287	25.576	11.204
31	2000	100	0.06	X	207.6	14.983	13.857	109	0.993	109.347	3	0.089	29.329	130	0.987	131.381	377	9.900	38.037	555	19.433	28.548
32	2500	100	0.06	XY	194.7	18.34	10.616	100	0.428	232.786	3	0.058	48.305	126	0.907	138.460	329	4.229	77.716	567	5.606	101.187
33	3000	100	0.06	Y	176.0	18.234	9.655	76	1.321	57.244	2	0.072	26.454	88	1.627	53.993	172	5.508	31.185	318	10.406	30.561
34	3000	240	0.06	Y	181.3	31.49	5.756	115	3.983	28.979	3	0.058	55.811	141	0.461	305.553	445	2.488	178.788	616	4.463	138.053
35	2500	240	0.06	XY	205.0	35.391	5.792	123	2.708	45.303	3	0.072	38.675	156	2.031	76.973	397	12.797	31.005	732	21.306	34.366
36	2000	240	0.06	X	210.4	45.115	4.665	138	3.288	42.109	3	0.155	16.599	169	3.579	47.141	419	23.345	17.939	716	26.412	27.100

Table 10. Steel Experiment Results

Surface	Speed	Feed	Depth	Cutting Dir	Cutting force			Ra			Rku			Ra			Rq			Rp			Rt		
					Mean Force	Force stdev	Force S/N	Ra	STDEV	S/N	Rku	STDEV	S/N	Ra	STDEV	S/N	Rq	STDEV	S/N	Rp	STDEV	S/N	Rt	STDEV	S/N
1	3500	14	0.01	X	197.0	21.358	9.2252	31	2.572	12.081	6	2.562	2.277	31	2.572	12.081	41	5.049	8.196	199	63.757	3.125	323.222	88.499	3.652
2	4000	14	0.01	XY	186.7	34.296	5.4437	25	1.099	22.296	4	0.439	8.181	25	1.099	22.296	31	1.810	17.187	102	23.097	4.411	201.778	23.812	8.474
3	4500	14	0.01	Y	161.0	41.944	3.8374	23	0.895	25.672	5	0.124	43.944	23	0.895	25.672	33	1.497	21.909	114	6.486	17.627	233.778	11.188	20.895
4	4500	32	0.01	Y	169.9	30.808	5.515	38	2.106	18.169	3	0.219	12.112	38	2.106	18.169	47	2.340	20.156	113	4.413	25.659	231.111	13.412	17.231
5	4000	32	0.01	XY	209.0	30.573	6.8353	42	9.467	4.419	5	0.316	14.755	42	9.467	4.419	60	2.402	24.901	190	14.508	13.073	384.667	19.681	19.545
6	3500	32	0.01	X	222.5	27.331	8.1393	57	1.387	41.277	4	0.222	16.104	57	1.387	41.277	71	9.417	7.563	224	8.721	25.658	431.778	14.988	28.809
7	3500	80	0.01	X	242.2	34.371	7.0466	99	1.303	75.794	3	0.058	45.033	99	1.303	75.794	118	1.248	94.501	307	9.820	31.308	579.333	11.026	52.543
8	4000	80	0.01	XY	232.8	70.699	3.2935	92	1.115	82.697	3	0.096	28.059	92	1.115	82.697	116	0.949	121.692	282	10.560	26.674	527.889	16.755	31.507
9	4500	80	0.01	Y	217.0	74.797	2.9012	77	1.199	64.641	2	0.072	29.084	77	1.199	64.641	92	1.187	77.098	202	8.673	23.328	377.111	12.152	31.033
10	4500	180	0.01	Y	237.9	118.171	2.0133	121	1.997	60.698	3	0.122	23.777	121	1.997	60.698	156	2.218	70.524	397	18.717	21.234	735.444	29.745	24.725
11	4000	180	0.01	XY	240.5	109.025	2.2058	134	0.712	188.187	3	0.058	49.075	134	0.712	188.187	163	1.120	145.823	420	12.903	32.558	680.889	13.455	50.606
12	3500	180	0.01	X	246.1	76.2377	3.2286	148	2.036	72.520	3	0.173	14.562	148	2.036	72.520	179	3.459	51.656	494	66.535	7.418	876.778	30.191	29.041
13	3500	14	0.03	X	195.1	13.266	14.71	44	1.970	22.566	3	0.146	18.046	44	1.970	22.566	54	2.256	24.074	157	20.259	7.772	269.778	17.258	15.632
14	4000	14	0.03	XY	185.6	26.239	7.0717	34	1.385	24.564	4	0.509	7.938	34	1.385	24.564	44	1.321	33.221	156	6.184	25.171	289.667	12.047	24.044
15	4500	14	0.03	Y	159.9	36.657	4.3608	24	1.468	16.453	5	1.856	2.837	24	1.468	16.453	32	1.135	28.235	100	33.483	2.993	213.889	36.766	5.818
16	4500	32	0.03	Y	165.7	26.172	6.3315	51	0.985	51.417	3	0.091	27.818	51	0.985	51.417	61	0.962	63.629	142	11.199	12.670	301.444	11.299	26.678
17	4000	32	0.03	XY	191.7	94.256	2.0339	72	1.759	41.019	6	0.184	30.833	72	1.759	41.019	97	0.953	101.748	287	27.737	10.351	629.667	27.046	23.282
18	3500	32	0.03	X	209.9	22.837	9.1933	72	1.759	41.019	6	0.184	30.833	72	1.759	41.019	97	0.953	101.748	287	27.737	10.351	629.667	27.046	23.282
19	3500	80	0.03	X	220.0	23.62	9.3141	133	3.042	43.871	3	0.072	44.863	133	3.042	43.871	166	3.234	51.341	491	27.602	17.801	847.333	31.998	26.481

20	4000	80	0.03	XY	198.8	24.747	8.0336	109	0.375	289.877	2	0.058	39.260	109	0.375	289.877	129	0.455	282.566	295	8.007	36.801	547.444	8.078	67.771
21	4500	80	0.03	Y	173.0	58.156	2.9748	86	1.449	59.709	2	0.091	27.086	86	1.449	59.709	108	2.051	52.672	255	11.278	22.619	488.333	18.557	26.315
22	4500	180	0.03	Y	223.6	93.385	2.3943	137	4.711	29.061	3	0.205	13.521	137	4.711	29.061	169	4.628	36.605	434	28.630	15.144	756.444	34.863	21.698
23	4000	180	0.03	XY	223.9	94.256	2.3758	146	2.169	67.360	3	0.173	15.011	146	2.169	67.360	177	3.280	54.075	442	66.650	6.637	890.111	42.367	21.009
24	3500	180	0.03	X	240.9	69.543	3.4636	156	0.679	230.329	3	0.058	56.580	156	0.679	230.329	197	1.686	116.739	593	117.580	5.041	1154.778	12.964	89.075
25	3500	14	0.06	X	201.1	15.217	13.214	53	0.612	86.139	2	0.058	39.067	53	0.612	86.139	63	0.786	79.669	137	7.037	19.530	258.556	12.185	21.219
26	4000	14	0.06	XY	192.7	25.557	7.5419	42	1.113	37.703	4	0.362	10.508	42	1.113	37.703	54	1.181	45.757	153	13.841	11.038	316.889	11.859	26.721
27	4500	14	0.06	Y	159.9	33.219	4.8123	30	0.484	61.607	4	0.146	30.152	30	0.484	61.607	41	0.731	55.845	144	5.991	23.960	262.333	15.205	17.253
28	4500	32	0.06	Y	165.7	24.736	6.699	59	2.427	24.395	3	0.203	14.675	59	2.427	24.395	75	2.974	25.142	205	7.885	25.958	375.778	15.304	24.554
29	4000	32	0.06	XY	198.6	22.585	8.7929	71	7.426	9.627	2	0.086	27.418	71	7.426	9.627	86	8.364	10.297	201	40.282	5.001	389.556	39.717	9.808
30	3500	32	0.06	X	203.1	18.743	10.836	82	2.155	37.888	2	0.109	22.191	82	2.155	37.888	100	2.090	47.970	246	8.954	27.461	442.889	18.960	23.359
31	3500	80	0.06	X	206.8	18.086	11.435	146	2.169	67.360	3	0.173	15.011	146	2.169	67.360	177	3.280	54.075	442	66.650	6.637	890.111	42.367	21.009
32	4000	80	0.06	XY	206.9	43.085	4.8032	130	2.437	53.424	3	0.914	3.682	130	2.437	53.424	162	7.558	21.434	449	87.597	5.127	832.111	93.297	8.919
33	4500	80	0.06	Y	199.4	32.655	6.1058	101	0.617	163.000	3	0.038	75.633	101	0.617	163.000	127	0.722	175.861	372	7.389	50.378	584.333	113.005	5.171
34	4500	180	0.06	Y	223.6	53.121	4.2093	134	0.793	168.958	3	0.058	56.580	134	0.793	168.958	168	1.875	89.837	488	117.387	4.161	1010.111	12.592	80.219
35	4000	180	0.06	XY	224.8	83.869	2.6802	156	0.679	230.329	3	0.058	56.580	156	0.679	230.329	197	1.686	116.739	593	117.580	5.041	1154.778	12.964	89.075
36	3500	180	0.06	X	230.8	61.805	3.7337	177	0.663	266.247	2	0.072	31.095	177	0.663	266.247	207	0.881	235.367	410	4.737	86.485	856.111	10.962	78.100

The Units of the data in the above table are as follows:

Speed:	(Revolution per Minute)
Feed:	(Inch per Minute)
Deep of Cut	(Inch)
Cutting Force:	(Newton)
Ra, Rku, Rq, Rp, Rt	(µin)

CHAPTER 5

ANALYSIS AND EMPIRICAL RELATIONSHIP

Statistical analysis is applied to the previous experimental results, such as probability plotting, significance of factors, peak force extraction. Single regression and multiple regression provide data to develop the empirical relationship for both applications of aluminum and steel work piece machining operation.

5.1 Generated Probability Plots

The results that were obtained from the number of experiments performed for aluminum and steel work pieces were analyzed using a very useful technique called the probability plotting. These probability plotting were plotted on excel, by using the 36 values of surface finish and cutting forces obtained for cutting process, on each x, y, z directions. This technique is used to check the normality of the sample data and identify the significant factors that cause variability. It used for determining whether the sample data confirms the hypothesized normal distributing based on the visual examination of the data. This plots also helped in determining if there was a particular combination of speed, feed, and depth of cut that would have any significant effect on the cutting force parameters and/or the surface finish parameters. The plotting shows the effect Vs, Vi values calculated for each plot. The method of calculation was performed as follows for the results of the cutting force and surface finish experimental data. The S/N, Log (s) and mean values are

- Ranked from smallest to largest
- Plotted against the cumulative frequency Vi where

$$V_i = \frac{(i - 0.5)}{n}$$

Where Vi = Accumulative frequency at number i

n = The total number of combination

As the Vi values and the effect are calculated, then the graph of the effect versus the Vi is plotted. After the graph is plotted, a linear trend line is established to check whether all the points follow the trend or not, is any point does not seem to follow the trend it should be separated and the graph should be plotted again, theses procedures should be carried out until a linear trend is observed. These probability plotting determine any significances of any particular operating parameters as main effect.

5.2 Significant Factors

For the experimental data, three depths of cut for each surface is checked for significant factors using the method previously explained, single, dual, and triple interaction effects are determined for the cutting force and surface finish these three effects indicates the following

- Main effect (single), speed (S), feed (F), depth of cut (D).
- Two-way effect (dual), which are (S x F), (S x D), (F x D).
- Three way effect (triple) which are (S x F x D).

These probability plotting were plotted on excel by using the 36 values of cutting force and surface finish obtained for machining in each x, y, z directions. Due to the hundreds of graphs that made for the probability plotting technique, all graphs are included in the Appendix on a CD. Tables 11 and 12 show the analysis of the probability plotting for the surface finish and cutting force parameters. For each of aluminum and steel work piece experiment these values have been imported from Microsoft excel after summarizing the entire data from probability plotting.

Table 11 Aluminum Workpiece Significant Factors at Low Depth of Cut														
Run	Variable		Significance Factor	Force			Ra		Rku		Rp		Rt	
	Speed	Feed		Mean	Stdev	S/N	Stdev	S/N	Stdev	S/N	Stdev	S/N	Stdev	S/N
1	2000	16	"FXD"	-	-	-	-	-	2.133	-	-	-	-	-
2	2500	16	(S)	-	1.431	-	-	-	-	-	-	-	-	-
3	3000	16	"SXF"	-	-	-	0.183	-	-	-	-	-	-	-
4	3000	40	(SXFXD)	-	-	-	-	-	-	5.512	-	-	-	-
5	2500	40	"SXFXD"	-	-	-	-	-	-	-	2.531	-	-	-
6	2000	40	"FXD"	-	-	-	-	-	-	-	-	-	-1.620	-
7	2000	100	(S)	-	2.131	-	-	-	-	-	-	-	-	-
8	2500	100	"SXF"	-	1.891	-	-	-	-	-	-	-	-	-
9	3000	100	"S", "SXFXD"	-	-	-	0.243	-	-	-	-	-	-	-18.31
10	3000	240	"F", "SXFXD"	-	-	-	-	-	3.022	-	0.593	-	-	-
11	2500	240	"FXD"	-	-	-	-	-	-	-	0.5931	-	-	-
12	2000	240	"SXFXD"	-	-	-	-	-	-	-	-	-	0.321	-

Central Depth of Cut														
13	2000	16	“FXD”	-	-	-	-	-	2.712	-	-	-	-	-
14	2500	16	-	-	-	-	-	-	-	-	-	-	-	-
15	2500	16	“SXFXD”	-	-	-	0.289	-	-	-	-	-	-	-
16	3000	40	“F”, “SXD”	-	-	-	-	-	-	6.127	-	1.231	-	-
17	3000	40	“SXFXD”	-	-	-	-	-	-	-	-	-	4.159	-
18	2000	40	“FXD”	-	-	-	-	-	-	-	-	-	-1.933	-
19	2000	100	“SXFXD”	-	1.998	-	-	-	-	-	-	-	-	-
20	2500	100	“SXF”	-	2.311	-	-	-	-	-	-	-	-	-
21	3000	100	“S”, “SXFXD”	-	-	-	0.354	-	-	-	-	-	3.445	-
22	3000	240	(SXFXD),D	-	-	-	-	-	4.193	-	0.823	-	-	-
23	2500	240	“FXD:	-	-	-	-	-	-	-	0.593	-	-	-
24	2000	240	“SXFXD”	-	-	-	-	-	-	-	-	-	0.499	-

High Depth of Cut															
25	2000	16	“FXD	-	-	-	-	-	4.831	-	-	-	-	-
26	2500	16	“SXF”	-	-	8.100	-	-	-	-	-	-	-	-
27	3000	16	“SXF”	-	-	-	0.183	-	-	-	-	-	-	-
28	3000	40	-	-	-	-	-	-	-	-	-	-	-	-
29	2500	40	“F”, “SXD”	-	-	-	-	-	-	-8.152	-	1.937	-	-
30	2000	40	“FXD”	-	-	-	-	-	-	-	-	-	-5.335	-
31	2000	100	“SXFXD”	-	-	-	-	-	0.834	-	-	-	-	-
32	2500	100	“SXF”	-	3.516	-	-	-	-	-	-	-	-	-
33	3000	100	s,“SXFXD	-	-	-	0.843	-	-	-	3.141	-	-	-
34	3000	240		-	-	-	-	-	3.433	-	-	-	-	3.151
35	2500	240	“FXD”	-	-	-	-	-	-	-	1.836	-	-	-
36	2000	240	“SXFXD”	-	-	-	-	-	-	-	-	-	2.339	-

Table 12 Steel Workpiece Significant Factor at Low Depth of Cut														
Run	Variable		Significance Factor	Force			Ra		Rku		Rp		Rt	
	Speed	Feed		Mean	Stdev	S/N	Stdev	S/N	Stdev	S/N	Stdev	S/N	Stdev	S/N
1	3500	14	“FXS”	-	-	-	-	-	-	-	4.903	-	-	-
2	4000	14	S,”FXD”	-	-	-5.311	-	-	-	-	-	-	-	3.139
3	4500	14	“SXFXD	-	-	-	-	-	0.2801	-	-	-	-	-
4	4500	32	S, “SXFXD”	-	-	-	-	-	-	-3.340	-	-2.510	-	-
5	4000	32	“SXFXD”	-	-	-	-	-	-	-	4.153	-	-	-
6	3500	32	“FXD”	-	-	-	-	-	-	-	-2.039	-	-	-
7	3500	80	“S”	-	-	0.341	-	-	-	-	-	-	-	-
8	4000	80	“SXFXD”	-	-	-	4.381	-	-	-	-	-	-	-
9	4500	80	“SXFXD, F	-	-	-	-	1.809	-	-	-	-	-	-1.305
10	4500	180	F, SXFXD	-	-	-	-	-	5.395	-	1.507	-	-	-
11	4000	180	“SXFXD”	-	-	-	-	-	-	-	-	3.157	-	-
12	3500	180	“SXF”,”SXFXD”	-	-	-	-	-	-	-	-	-	2.451	-

Central Depth of Cut														
13	3500	14	“SXD”	-	-	-	-	-	3.153	-	-	-	-	-
14	4000	14	“SXF”	-	-	-	-	-	-	-	2.103	-	-	-
15	4500	14	“SXFXD”	-	-	-	1.005	-	-	-	-	-	-	-
16	4500	32	“SXF”, “SXD”	-	-	-	-	-3.452	-	-	-	1.408	8.1331	-
17	4000	32	“SXFXD”	-	-	-	-	-	-	-	-	-	-	-2.333
18	3500	32	“FXD”	-	-	-	-	-	-	-	-	-	-	-
19	3500	80	“SXFXD”, D	-	2.810	-	-	-	-	-	4.058	-	-	-
20	4000	80	“SXF”	-	-	-	3.003	-	-	-	-	-	-	-
21	4500	80	S, “SXFXD”	-	-	1.889	-	-	-	-	-	-	-	-5.307
22	4500	180	“SXFXD”, D	-	-	-	8.754	-	-	-	4.381	-	-	-
23	4000	180	“FXD”	-	-	-	-	-	-	-	-	-	0.9901	-
24	3500	180	“SXFXD”	-	-	-	-	-	-	4.001	-	-	-	-

High Depth of Cut														
25	L	L	“FXD”	-	-	-	-	-	-	-	2.7791	-	-	-
26	C	L	“SXD”	-	2.356	-	-	-	-	-	-	-	-	-
27	H	L	“SXF”,D	-	-	-	.829	-	-	-	-	-12.310	-	-
28	H	SL	FX ”SXD”	-	-	-	-	-	-	-3.098	-	-	4.992	-
29	C	SL	-	-	-	-	-	-	-	-	-	-	-	-
30	L	SL	“FXD”	-	-	-	-	-	-	-	-	-	-	13.451
31	L	SH	“SXFXD”	-	-	-	-	-	1.405	-	-	-	-	-
32	C	SH	“SXF”	-	-	-	3.671	-	-	-	-	-	-	-
33	H	SH	F, “SXFXD”	-	-	-	-	-	-	-1.209	-	4.075	-	-
34	H	H	“SXFXD”, F	-	-	-	-	-	-	-	-	-	2.350	-
35	C	H	“FXD”	-	-	-	-	-	-	-	2.156	-	-	-
36	L	H	“SXFXD”	-	-	-	-	-	-	-	-	-	-	-12.382

The analysis of the probability plots in table 11 and 12 shows that the speed, feed, and depth of cut, by themselves have no significant effect on most of the surface finish values, whereas the two ways (dual) interaction has a significant effect on the value of the surface finish. It was also observed that the three way interaction effect (triple) for the three parameters (S x F x D) did have a significant effect in some cases as shown on table 11 and 12. It has been also observes that the same effect and significant factors for both aluminum and steel cutting parameters are very similar.

It has also been observed the following at the low depth of cut:

- The two-way effect (dual) interaction of "F X S" has an effect on the measure of the maximum high of the surface profile (R_p) standard deviation with a high optimum level.
- Spindle speed (S) and two way effect (dual) interaction "F X S" has an effect on the mean force and the RMS parameter (R_q) signal to noise ratio respectively. The significant optimum levels are low for the S/N force and high for the R_q.
- Three-way effect (triple) interaction "S X F X D" has a significant effect on the sharpness of the surface (R_{ku}), the significant optimum level is low.

- Two way effect (dual) interaction "F X D" has a significant effect on the measure of the maximum high of the surface profile (R_p) with a low optimum level.
- The spindle speed is significant on the mean force signal to noise ratio with a low optimum level.
- Three way effect (triple) interaction "S X F X D" has a significant effect on the standard deviation of the surface roughness (R_a) with a high optimum level.

For the central depth of cut the following observations have been perceived:

- The two way effect (dual) interaction of "F X D" has an significant effect on the standard deviation of the (R_{ku}) with a low optimum level.
- Three way effect (triple) interaction "S X F X D" has a significant effect on the standard deviation on the surface roughness (R_a) with a low optimum.
- Feed rate (F) and two way effect (dual) interaction "S X D" has an significant effect on the standard deviation and the signal to noise ratio for the R_{ku} and R_p respectively. The significant optimum level are high for the S/N force and low for the standard deviation.
- Three way effect (triple) interaction "S X F X D" has a significant effect on the standard deviation on the mean cutting force with a low optimum level.

- Feed rate (F) and three-way effect (triple) interaction "S X F X D" has an significant effect on the standard deviation for both the surface roughness and the R_t. The significant optimum level are low for the surface finish and high for the R_t.
- Three way effect (triple) interaction "S X F X D" and main effect (D) has a significant effect on the standard deviation Rku and R_p respectively. The optimum level are high for the first and low for the second effect.
- The two-way effect (dual) interaction of "F X D" has an significant effect on the standard deviation of the (R_p) with a low optimum level.

For the high depth of cut the following observations have been perceived:

- The two way effect (dual) interaction of "F X D" has an significant effect on the standard deviation of the (R_{ku}) with a high optimum level.
- The two-way effect (dual) interaction of "S X F" has an significant effect on the signal to noise ratio on the mean force with a high optimum level.
- Feed rate (F) and two way effect (dual) interaction "S X D" has an significant effect on the signal to noise ratio for both the R_{ku} and R_p respectively. The significant optimum level is low on both effect.

- The two-way effect (dual) interaction of "F X D" has an significant effect on the standard deviation of the (R_t) with a low optimum level.

It has been observed that the steel work piece material has contributed the same significant effect as it has been observed in the aluminum work piece material. All other similar results are included in the CD.

5.3 Regression and Parameter Estimates

Single regression, Multiple regression, and Peak Force curve fitting is conducted to provide functional relationship with the controllable factors such as spindle speed, feed rate, and depth of cut, with the surface finish and cutting force. Single regression was used to determine the relationship between cutting force and surface finish or feed rate, multiple regression is used to determine the relationship with operating parameters and the proposed cutting force and surface finish, peak separation of the force data is also used to determine the peak force, force center, and force width.

5.3.1 Peak Extraction

For each surface measurement taken according to the proposed design of experiment, the component of the force signal for each direction of the cut is separated using the peak fit software package. Each component force signal is separated in three criteria such as peak fit amplitude (a_0), force center (a_1), and force width (a_2), the (a_3) and (a_4) component are shape distortion indices for the force center and width, the strength of the fit is measured by the R-square value, a strong fit is indicated with a value close to 1.0. A weak fit is indicated a value close to zero. For each surface, the number of peaks is also determined. Table 13 lists the peak values for the proposed design if experiment for the aluminum work piece at each depth of cut also table 14 lists the peak value for the steel proposed design of experiment at each depth of cut.

5.3.2 Adequacy of the model

The adequacy is examined by using the previous analysis methods, single and multiple regression, Peak Fit extraction and generated probability plot performed to analyze the data of the results and to establish the relationship of the main objective of this research. The residual was also applied to the model to determine if there is any pattern or if there is any relationship between the cutting force and the surface finish for the proposed design of experiments. The surface finish was extracted at the same operation parameters and was measured as described in section 3.3.2, at the same sampling time of the cutting force to analyze the force pattern and compare it with the surface finish profile. Figure 13 and Figure 14 shows the best profiles for the cutting force and surface finish. The Table curve 2D software has been used to find different profile equations between the cutting force and the surface finish, sorted in descending order based on the value of the R-Square. The correlation coefficient was one of the most important measures for checking the adequacy of these models. It confirms that the independent and the dependent variables are greatly close to each other and established that they are truly significant

Table 13 Aluminum Peak Values at Low D.O.C.

n	a0	a1	a2	A3	a4	# Peaks	R Square
1	16.819	80.356	4.070	2.091	5.586	70	0.987
2	44.498	27.234	3.804	2.199	4.404	100	0.969
3	35.716	110.067	3.365	2.235	2.2349	88	0.913
4	73.241	6.042	4.513	3.355	3.553	28	0.961
5	33.314	15.697	3.039	1.939	2.311	53	0.953
6	55.314	4.510	4.863	4.937	4.659	25	0.832
7	24.597	17.205	7.958	3.024	3.524	6	0.721
8	69.021	32.737	2.333	1.568	2.109	32	0.999
9	87.547	21.456	3.672	4.795	5.363	24	0.937
10	99.666	4.287	3.483	5.436	3.494	7	0.996
11	154.001	27.855	2.439	4.428	5.291	24	0.989
12	67.390	15.931	3.921	2.930	6.875	12	0.863
Central D.O.C.							
n	a0	a1	a2	a3	a4	# Peaks	R Square
13	55.613	44.843	3.913	3.853	7.651	88	0.714
14	47.414	43.926	4.251	2.229	5.347	100	0.806
15	17.638	40.080	3.558	4.132	5.451	100	0.354
16	25.916	5.694	3.819	2.079	3.448	35	0.662
17	23.140	15.444	2.404	3.509	4.520	66	0.260
18	23.220	28.412	3.629	2.318	2.029	28	0.823
19	24.803	18.733	6.821	4.717	2.008	12	0.829
20	14.384	2.181	14.384	31.224	0.080	34	0.799
21	78.695	39.198	2.928	4.588	5.394	19	0.948
22	89.341	4.103	3.390	4.618	3.956	10	0.897
23	107.619	29.216	2.332	4.7522	5.004	20	0.941
24	58.949	16.090	4.045	2.618	6.876	9	0.948
High D.O.C.							
n	a0	A1	a2	a3	a4	# Peaks	R Square
25	48.720	95.458	3.525	3.005	6.934	89	0.954
26	47.933	43.113	4.058	2.390	5.930	112	0.877
27	63.964	11.738	5.481	3.468	4.850	97	0.789
28	43.730	42.517	4.150	2.080	3.028	34	0.792
29	15.638	128.771	2.296	4.019	6.290	79	0.850
30	19.4604	37.929	4.147	3.976	4.173	36	0.863
31	23.916	35.439	5.212	2.612	4.954	10	0.889
32	37.618	3.122	2.196	5.124	4.847	32	0.812
33	44.761	6.942	2.695	4.269	5.149	24	0.979
34	52.843	14.491	2.502	4.792	5.693	9	0.951
35	41.184	25.440	2.516	3.573	5.112	19	0.976
36	12.282	22.028	3.589	2.381	3.242	9	0.973

Table 14 Steel Peak Values at Low D.O.C

n	a0	a1	a2	a3	a4	# Peaks	R Square
1	4.815	128.920	3.119	4.774	6.143	99	0.961
2	64.238	5.075	4.428	3.657	8.193	100	0.877
3	31.509	102.161	3.184	3.370	6.239	92	0.963
4	99.810	43.401	3.101	3.975	4.186	75	0.899
5	89.835	118.442	3.524	3.683	2.076	65	0.864
6	24.392	35.272	3.436	4.150	4.981	46	0.862
7	47.376	1.487	4.016	2.573	8.111	13	0.841
8	147.968	42.886	2.062	4.277	5.289	28	0.944
9	139.483	18.939	3.339	4.321	2.693	26	0.985
10	93.947	6.674	3.458	3.279	8.728	6	0.850
11	152.010	3.359	2.392	2.573	1.651	19	0.990
12	100.329	6.019	3.707	4.697	3.246	18	0.931
Central D.O.C.							
n	a0	a1	a2	a3	a4	# Peaks	R Square
13	4.238	135.658	4.092	3.998	5.833	98	0.949
14	43.035	237.373	8.079	4.604	8.016	100	0.884
15	94.320	178.573	7.573	5.643	2.076	70	0.833
16	101.326	39.739	2.654	3.730	4.304	47	0.950
17	41.935	38.602	4.058	5.894	2.754	61	0.807
18	25.968	90.096	3.406	7.314	5.572	50	0.925
19	29.268	34.497	2.554	5.496	6.918	18	0.766
20	71.478	36.732	3.263	4.691	2.713	28	0.894
21	103.651	8.128	2.318	5.366	5.585	29	0.869
22	41.492	17.110	1.997	5.784	5.442	12	0.906
23	63.315	29.923	2.498	2.727	2.187	15	0.734
24	24.721	26.777	2.714	3.487	5.223	16	0.995
High D.O.C.							
n	a0	a1	a2	a3	a4	# Peaks	R Square
25	48.733	93.330	3.025	7.849	9.634	100	0.922
26	68.395	113.127	7.513	5.713	6.739	100	0.953
27	48.146	159.247	7.030	4.792	12.599	100	0.842
28	196.061	48.569	3.875	3.878	1.763	56	0.958
29	57.124	122.747	4.918	6.511	4.965	68	0.810
30	36.768	100.151	3.410	5.385	7.410	56	0.806
31	24.462	41.246	2.356	5.647	5.861	25	0.903
32	36.267	53.843	2.180	3.786	5.331	29	0.940
33	43.044	5.638	3.208	5.287	4.882	22	0.798
34	149.614	10.897	2.450	4.548	3.511	12	0.993
35	121.215	34.443	2.679	2.517	3.291	15	0.980
36	103.870	24.370	2.190	4.544	4.831	12	0.993

to the model. As it is shown from the two Figures (13 and14), there is a strong correlation between the force and the surface finish. Although it looks that there is a linear relationship between them, the practical application and the majority of the results of our experiment has proven the opposite. These relationships are established in section 5.3.4 [equations 5.7-5.9] for the Aluminum and [5.10-5.12] for Steel material. These empirical relationships were developed based on the results of 36 reading of the design of experiment.

p

Figure 13 Cutting Force and Surface Finish Profile at High Depth of Cut with Spindle Speed 2000 RPM and Feed Rate of 240 in/min

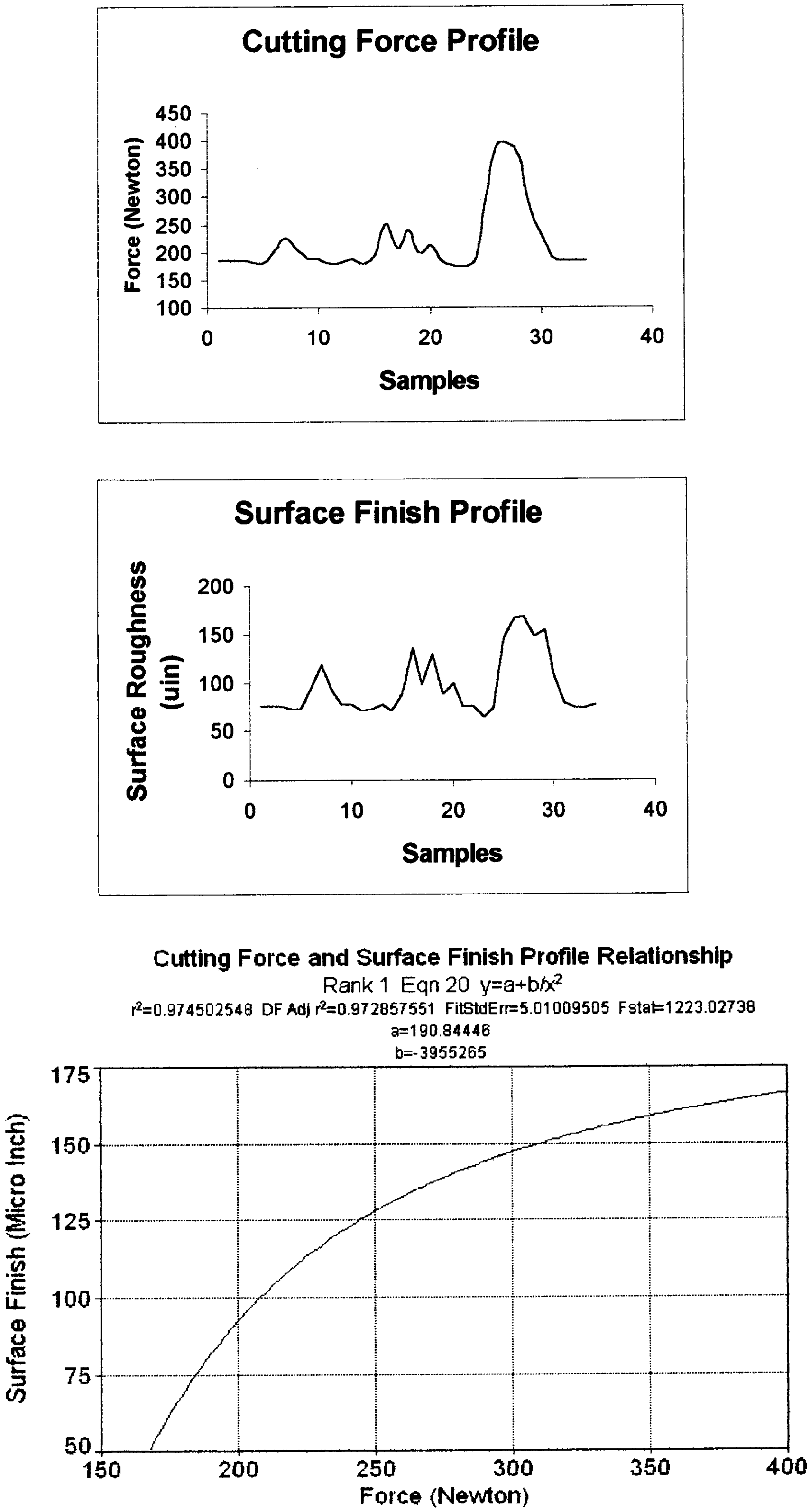
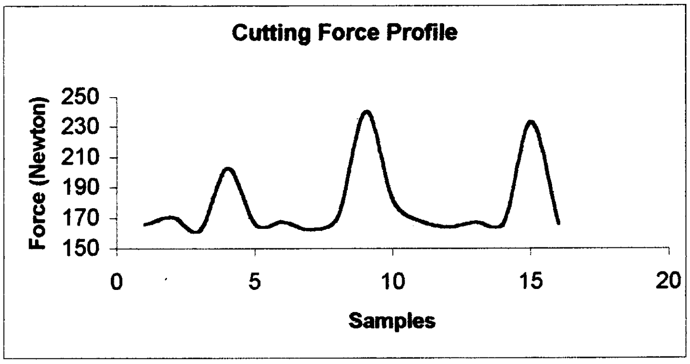
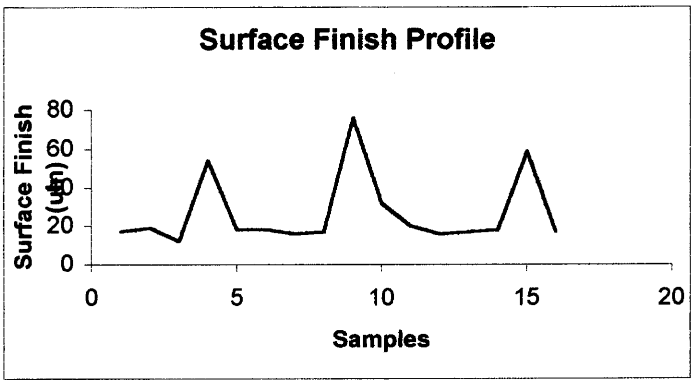
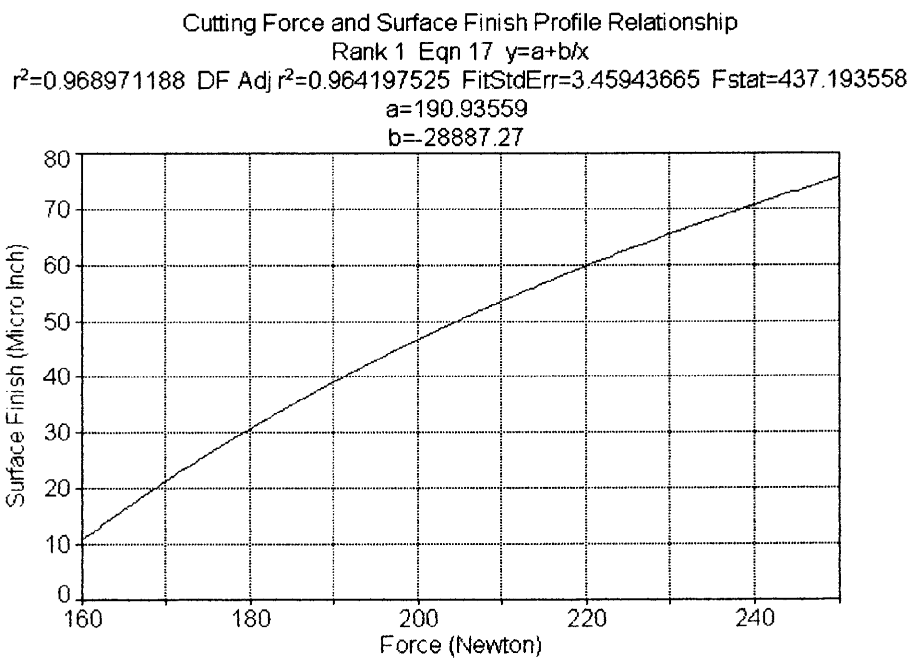


Figure 14 Cutting Force and Surface Finish Profile at Low Depth of Cut with Spindle Speed 3000 RPM and Feed Rate of 24in/min







Similarly, other graphs have been performed to determine the variation of the machining parameters with respect to the direction of the cutting forces and the surface finish.

These graphs were plotted to determine the relationship of these operating conditions and the trend of the cutting force and the surface finish. It was observed that a similar pattern variation for the surface finish versus the spindle speed for the three different depths of cut at the same feed rate. The same observation has been found for the cutting force and the feed rate. These graphs are plotted in Figures 15, Figure 16, and Figure 17 for the aluminium work piece. By examining the machining operation for these patterns, it is also observed that all the machining operations follow the same trend at the same machining parameters. Figure 17 shows that the surface finish decreases when the spindle speed increase, and it has the same trend at the same feed and depth of cut. On the other hand, Figure 16 shows that the cutting force decreases when the spindle speed increase, at the same feed rate and depth of cut.

Both graphs confirm the relationship between the cutting force and the surface finish, which have the same trend at the same operating parameter, as shown in Figure 17. Thus, the first objective of the research is fulfilled. That is, if the cutting force is regulated to a constant value during the operation, then a fixed surface finish could be obtained. Other graphs have been plotted to confirm the adequacy of the model is submitted in the CD Appendix.

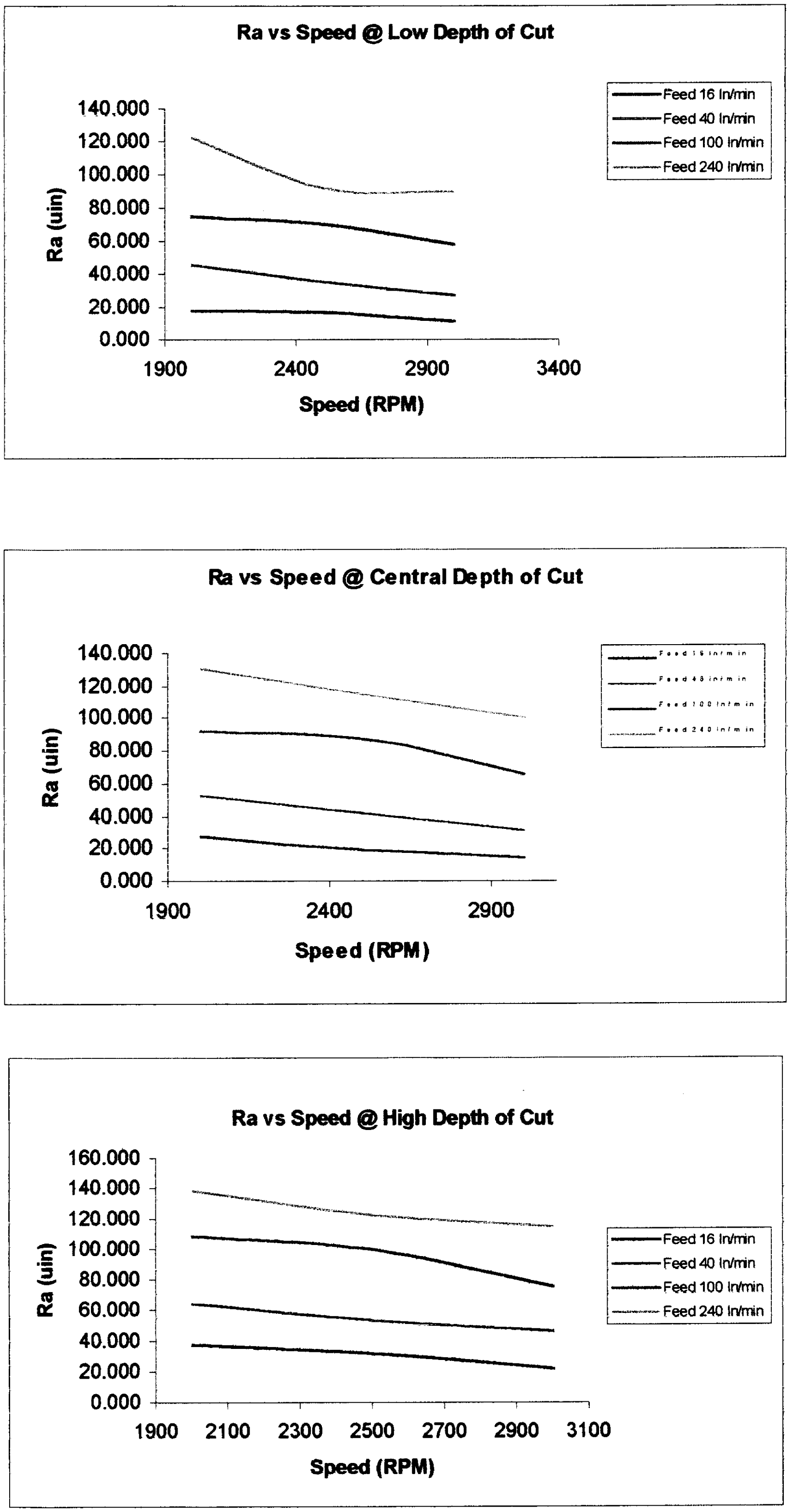
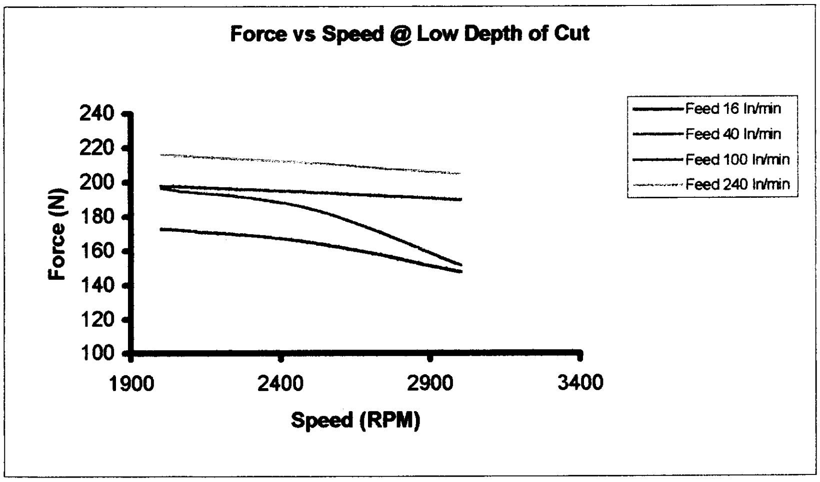
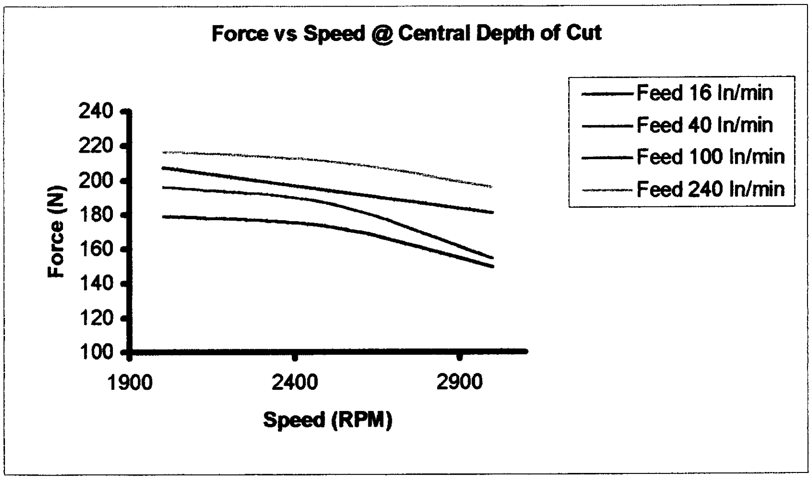


Figure 15. Pattern of Surface Finish vs Speed
For the Aluminum





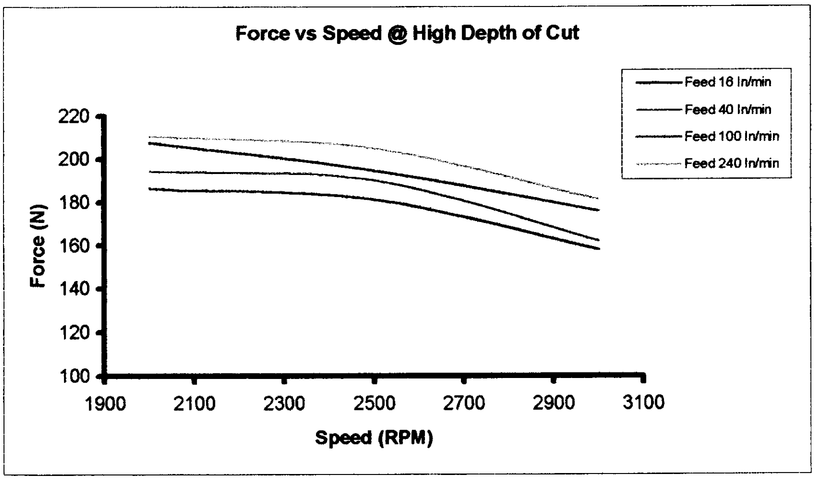
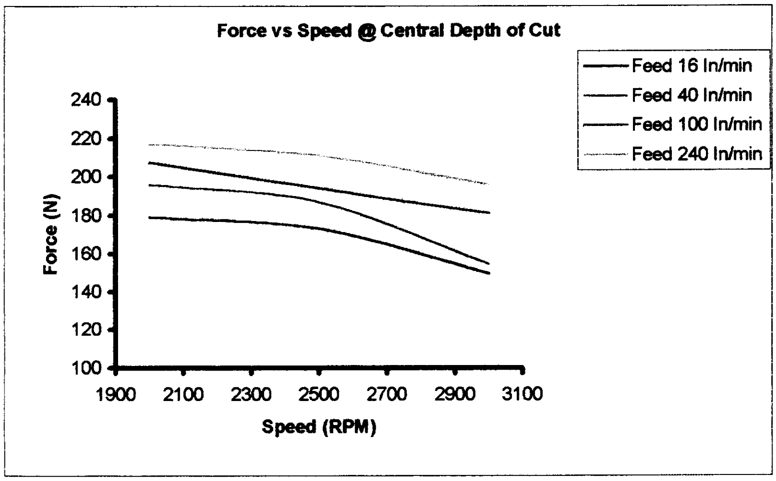


Figure 16. Pattern of Cutting Force vs Speed
For the Aluminum



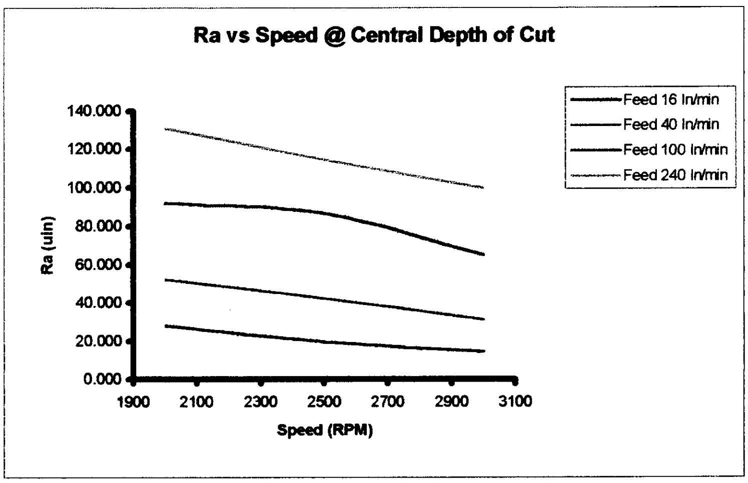


Figure 17. Pattern of Force and Surface Finish vs Speed For the Aluminium

Similar graphs show that the cutting force decreases when the feed rate decreases, and the relationship are close to linear trend. The feed rate-speed has an interaction effect on the cutting force. The cutting force minimizes when the feed rate is low and the spindle speed is high, at the same time decreases the surface finish (fine surface finish). On the other hand, the feed rate- speed interaction maximizes the force when the feed rate is high. And the spindle speed is low, and in this case, the surface finish increases (rough surfaced finish). Other graph pattern that shows more of the adequacy of the model is in the Appendix on the CD.

Finally, the above heuristic process was used to determine a good solution and find an empirical relationship between the input parameters of the machining operations (speed, feed rate, and depth of cut) with respect to the output results (cutting force and surface finish). All the above functional relationship has been found by the strongest and popular software discovery, single regression and multiple regressions. In this research, the single regression functional relationship was used to determine the cutting force as the dependent variables and the surface finish as the independent variables. These variables were controlled by the cutting speed, feed rate, and depth of cut. In the multiple functional relationships, the spindle speed, and the feed rate was use as the independent variables. The cutting force and the surface finish were the dependent variable. All the above relationships and equations were determined by the goodness and the strength of the R-square values. Multiple regressions functional are most appropriate, since it associate three different variables. In our work to come, it is very useful to use both single and multiple regression functional relationship to complete this research.

5.3.3. Single Regression and Empirical Relationships

Using the Table-Curve 2D software performs single regression; by using the force data and surface finish data obtained from the proposed design of experiment. Function relationship determined the goodness of the fit is determined by the R-square value. A value of 1.0 indicates a perfect fit, and a value close to zero indicated that there is no relationship between the independent and dependent variables. In this research the dependent variables for this proposed modeling is the cutting force (x-direction), and the independent variables is the surface finish (y-direction).

a) <u>Aluminum work piece / Single Regression Equations</u>

Listed in Table 15 the aluminum work piece relationship between the cutting force obtained form the proposed design of experiment at each depth of cut and the proposed surface finish indices. The R-square value is also listed to indicate the strength of the relationship

Cutting Force vs Surface Roughness 2D		
Level	Function	R-Square
Low	y = a + b exp (-x/c) [Exponential]	0.953792
Central	y = a + b exp (-x/c) [Exponential]	0.974403
High	y = a + b exp (-x/c) [Exponential]	0.931662

Table 15 Single Regression Aluminum Work Piece Empirical Relationship

Table 16 lists the single regression parameters estimates for each relationship at each of the depth of cut level.

Cutting Force Parameters Estimates 2D			
Parameters	Low	Central	High
a	-0.9636	13.8339	21.4558
b	0.0439	0.0019	0.0002
c	-27.3184	-19.6380	-16.2552

Table 16 Single Regression Parameter Estimate Aluminum

Using the estimate parameters in the above table, with the empirical relationship in table 15 gets the following empirical equations.

Low Depth of Cut Equation

$$R_a = 0.043e^{F/27.3} - 0.963 \quad \text{--------------------------------(5.1)}$$

Central Depth of Cut Equation

$$R_a = 0.001e^{F/19.6} + 13.83 \quad \text{--------------------------------(5.2)}$$

High Depth of Cut Equation

$$R_a = 0.0003e^{F/16.25} + 21.45 \quad \text{-----------------------------(5.3)}$$

Where

R_a = Surface Finish (□in)

F = Cutting Force (Newton)

b) Steel work piece / Single Regression Equations

The empirical relationship for the steel work piece has been established by using the same procedures that has been done previously for the aluminum work piece and the results were as follows:

Low Depth of Cut Equation [R-Square value= 0.9843]

$$R_a = 0.006e^{F/24.5} - 12.61 \quad \text{--------------------------------(5.4)}$$

Central Depth of Cut Equation [R-Square value= 0.8705]

$$R_a = 2.29e^{F/54.7} - 15.84 \quad \text{--------------------------------(5.5)}$$

High Depth of Cut Equation [R-Square value= 0.9678]

$$R_a = 0.016e^{F/25} - 16.76 \quad \text{--------------------------------(5.6)}$$

5.3.4 Multiple Regression and Empirical Relationships

Multiple Regressions was utilized to determine the relationship between spindle speed and feed rate with the proposed surface finish and cutting force at a fixed depth of cut. By using the surface finish and the cutting force data at the proposed levels obtained from the proposed design of experiment, functional relationship are determined, the goodness of the fit is determined by the value of the R-square. A value of 1.0 indicates a perfect fit a value close to zero indicates that there is no relationship between the independent and the dependent variables. For the proposed multiple regression the independent variables are spindle speed (x-axis), and feed rate (y-axis). The dependent variable is cutting force or the surface finish (z-axis).

a) <u>Aluminum work piece / Multiple Regression Equations</u>

Listed in Table 17 the aluminum work piece relationship between the cutting forces obtained form the proposed design of experiment at each depth of cut and the proposed speed and feed rate. The R-square value is also listed to indicate the strength of the relationship.

Cutting Force vs Surface Roughness 3D		
Level	Function	R-Square
Low	$z = a + b\,x^3 + c \ln y$	0.97157
Central	$z = a + b\,x^3 + c \ln y$	0.97481
High	$z = a + b\,x^3 + c \ln y$	0.96278

Table 17 Multiple Regression Aluminum Work Piece Empirical Relationship

Table 18 lists the multiple regression parameters estimates for each relationship for the above empirical relationship at each of the depth of cut level.

Cutting Force Parameters Estimates 3D			
Parameters	Low	Central	High
a	159.35055	121.90133	177.35006
b	-1.80978e-09	-7.06124e-10	-1.63077e-09
c	13.75882	18.45871	9.048537

Table 18 Multiple Regression Parameter Estimate for Aluminum work piece empirical relationship

Using the estimate parameters in the above table, with the empirical relationship in table 17 gets the following empirical equations.

Low Depth of Cut Equation

$$F_c = 159.35 - \frac{1.81}{10^9} S^3 + 13.76 \ln(f) \quad \text{----------------------(5.7)}$$

Central Depth of Cut Equation

$$F_c = 121.90 - \frac{7.06}{10^{10}} S^3 + 18.45 \ln(f) \quad \text{---------------------(5.8)}$$

High Depth of Cut Equation

$$F_c = 177.35 - \frac{1.63}{10^9} S^3 + 9.05 \ln(f) \quad \text{-------------------- (5.9)}$$

b) Steel work piece / Multiple Regression Equations

The empirical relationship for the steel work piece has been established by using the same procedures that has been done previously for the aluminum work piece and the results were as follows:

Low Depth of Cut Equation [R-Square value= 0.9844]

$$F_c = 286.44 - \frac{5.82}{10^{10}} S^3 - 353.27 \ln f / f \qquad \text{------------------------}(5.10)$$

Central Depth of Cut Equation [R-Square value= 0.9861]

$$F_c = 232.16 - \frac{8.77}{10^{10}} S^3 + 1.34 f / \ln f \qquad \text{---------------------} (5.11)$$

High Depth of Cut Equation [R-Square value=0.8761]

$$F_c = 208.04 - \frac{5.88}{10^{10}} S^3 + 3.83 f^{0.50} \qquad \text{--------------------} (5.12)$$

Adequacy of the model have been conducted, single regression and multiple regression were used to drive the empirical relationship between the machining parameters versus the cutting force and surface finish.

The above equations provided a suitable mathematical basis for defining the behaviour of both the cutting forcer and the surface finish versus the end milling machining parameters. It is possible to obtain a discrete transfer function, develop block diagram, and use the above technique for manipulating the operating parameters to design the necessary empirical model based control to realize the objective of this research as been illustrated in the following chapters.

Comparison of above empirical relationship to other previous work

Similar empirical relationship between the cutting force and the milling operating parameters (speed, feed, and depth of cut) has been developed as Abdou and Yien [2], Abdou and Tereshkovich [1] and Tseng and Billatos [27].

The proposed relationships in section 5.3.4 [equations 5.7-5.9] for the Aluminum and [5.10-5.12] for Steel material are different from the published models that were previously stated. Illustrated in Table 19, the comparison between them

Table 19. Comparison of the different relationships

Attributes	**Proposed Model**	**Abdou& Yien**	**Tseng& Billatos**	**Abdou& Teroshkovich**
Modeling	Multiple regression	Predefined regression model	Predefined regression model	Multiple regression
Independent variable	F, S (D is pre-specified)	S, F, D	F, D (S is not considered)	S, F, D
Milling machine used	CNC Fadal	CNC Mazak	CNC Siber-Hegner	High speed
Work piece Material	Aluminum Steel	Aluminum	Aluminum Steel	Aluminum

As expected, the proposed model that was developed by the previous work is different in functions and parameters estimates. Otherwise, it is a coincidence if they look exact.

CHAPTER 6

EMPIRICAL MODEL BASED CONTROL

An empirical model based control is a regulator that can modify its behavior in response to change in the dynamics of the process and the disturbances. From the last application methods and previous analysis. The first objective of this research has been achieved. If the cutting force maintained constant during the process of the machining process, then the surface finish can also remain stable. In the previous research work the cutting force resultant is obtained using a Kistler force Transducer, which provides of three orthogonal components of dynamic forces F_X, F_Y, F_Z and these forces were measured on-line using the UEI for windows. These measured cutting forces signals can be used in the model controller to regulate the cutting force. The second objective of this research work is to develop an empirical model based control, which can solve such practical drawbacks. The proposed control model main objective is to regulate the milling process operation parameters such as the feed rate and the spindle speed, and maintain the cutting force constant, to achieve on line the required value of the surface finish.

The basics structures of the proposed control model consists of CNC feed drive controller, model parameters, and adjustable mechanism. The Fadal CNC Milling machine was used in connection with the feed drive controller.

6.1 CNC Machine Feed Drive Controller

The Fadal CNC milling machine was used to perform the milling process. This CNC milling machine is a five axes machine. It moves on X, Y, and Z axes and rotates in both directions of rotation, more information's of the machine were explained in chapter 3. A Fanuc CNC system model 15M, is used with the Fadal CNC system. The feed axes of the machine, have ball screw drives and directly driven by permanent magnet synchronized AC serve motor. The serve motors are identical to each other. The model number of the serve driver is Fanuc T084/03-A20B-1003-008/02A.

Based upon the technical data provided from Fanuc Ltd. (KOGA). The block diagram of the feed drive system can be derived as shown in Figure 18. The technical data of this block diagram of this drive system listed in Table 20, as provided by the Fanuc Ltd. At the input channel of this system, there is an interval time delay of the feed rate command, when the command signal is processed at the programmable machine controller of the CNC machine system. The transfer function between the variation of the feed rate command signals (f_c) and the variation of the actual feed rate (f_a) is as follows:

$$\frac{f_a(S)}{f_c(S)} = \frac{K_i K_{ip} K_t e^{-sT}}{J_e L_a S^3 + J_e\left(R_a + K_H K_{ip}\right)S^2 + K_t\left(K_p K_{ip} + K_b\right)S + K_i K_t K_{ip}} \quad \text{---(6.1)}$$

Substituting the values from Table 1 yields to

$$\frac{f_a}{f_c} = \frac{497000e^{-0.08s}}{(s+14.0)(s^2+155s+35500)} \quad \text{-------------------- (6.2)}$$

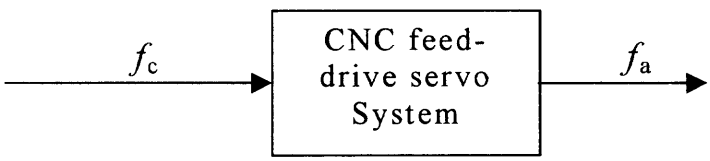
Equation (2) can be approximate

$$\frac{f_a}{f_c} = \frac{14.0e^{-0.08s}}{s+14.0}$$ ---------------------------------------(6.3)

t =0.08 Sec.

The time delay for the system to respond form the signal of the command until it proceeds at the programmable machine controller

s = sample number This controller consists of CNC feed drive mechanism and the cutting process. It main objective is to generate series of feed rate command signals (f_c) and cutting speed (S_c) in which they both regulate the cuttting force (F_c) So that the force output maintain constant to achieve the surface finish value (R_a) that is required by production.



The CNC feed drive system Eqution 6.3 is used for the feed drive servo system

$$\frac{f_a}{f_c} = \frac{14.0e^{-0.08s}}{s+14.0}$$ ---------------------------------------(6.4

Where

f_a = feed rate command (In/min).

f_a = actual feed rate (In/min).

Data Value of the Fanuc drive system		
Data	Description	Value
f_c	Feed rate command (mm/min)	-
$\square_c$	Angular velocity command (rad/min)	-
K_i	Velocity integral gain [V/(rad/sec)]	8.2
K_p	Velocity proportional gain [V/(rad/sec)]	0.4944
V_{ic}	Current command (f)	-
K_H	Current feedback gain (f/A)	0.007
R_a	Armature coil resistance (ohms)	0.15
K_t	Torque constant (kgf. m/A)	.0165
T_m	Motor drive torque (kgf. m)	-
J_e	Equivalent feed-drive inertia (kgf. m. sec^2)	0.0146
f_a	Actual feed rate (mm/min)	-
$\square_a$	Actual ang. Velocity (rad/min)	-
K_F	Ang. Velocity gain [(rad/sec)/(mm/min)]	0.0105
V_{if}	Feedback current (f)	-
K_{ip}	Current proportional gain (-)	7.5429
L_a	Armature coil inductance (mH)	1.20
I_q	Actual current (A)	-
K_b	Back EMF constant [V/(rad/sec)]	0.38
T_d	Disturbance torque (kgf.m)	-
$\square$	Angular velocity of motor shaft rad/sec)	-

Table 20 Fanuc Ltd. Data for the Feed Drive System

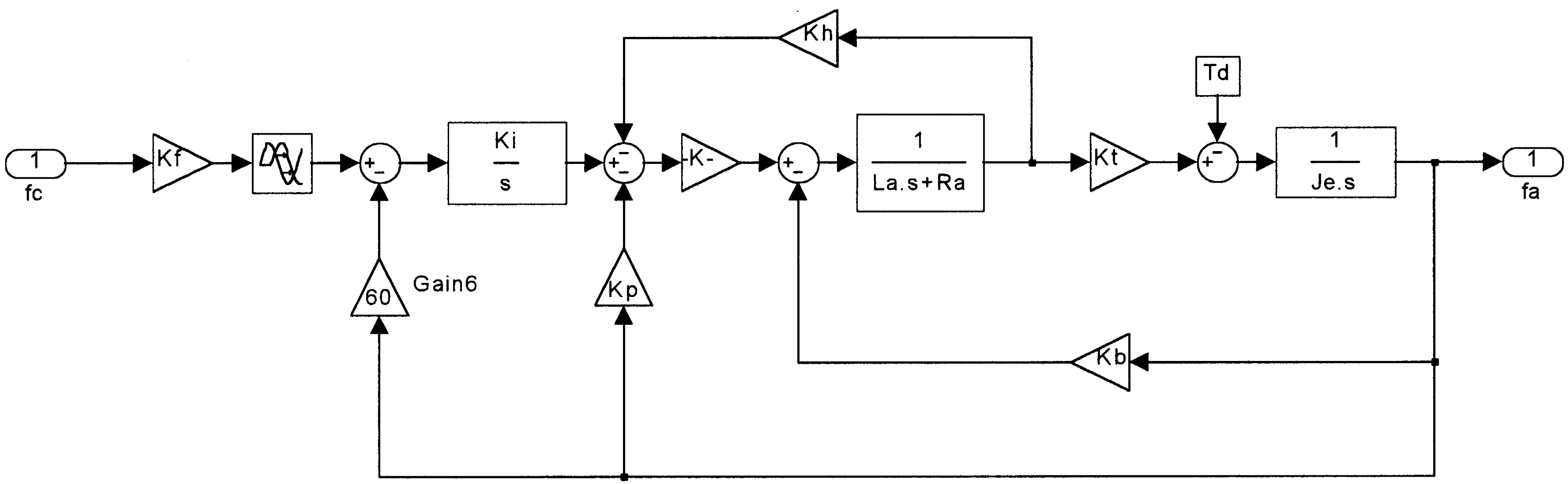


Figure 18 Feed Drive System Block Diagram

6.2 Parameter Estimator Algorithm

The model parameter estimator algorithm used in this research was based on the results of the previous proposed experiments data and design of experiment the Single and Multiple regression has been conducted to provide functional relationship with the controllable factors such as, Spindle Speed (RPM), Surface Finish (□in) and Cutting Force (N). The Multiple regression modeling is conducted to determine an empirical relationship between the spindle speed and Feed Rate, Cutting Force and Surface Finish. Using these two models lead us to a very useful empirical modeling that help to establish the parameter algorithm for both materials application Aluminum and Steel.

6.2.1 Aluminum Estimator Algorithm

Any machining process starts with requested surface finish (R_a). Using the single regression formula for aluminum machining at low depth of cut

$$F_a = 71 + 45.2(R_a)^{0.24} \quad \text{-------------------------------------} \quad (6.5)$$

Appling the above equation with the requested and known surface finish gives the cutting force to achieve and reach the surface finish value. In order to get the best operating parameters the following equations are used:

$$\ln f = \frac{1.15}{5.6 - \ln F} \qquad \text{------------------------------------ (6.6)}$$

$$S^2 = 17601629 - 2.6F^3 \qquad \text{------------------------------------ (6.7)}$$

The above Equations can establish the best machining parameters Speed and Feed rate required to produce a cutting force that control this surface finish as requested. The objective of the control model is to regulate the feed rate and speed to maintain the cutting force constant. The following multiple regression equation is used for this purpose.

$$F = 159 - \frac{1.8}{10^{10}} S^3 + 13.8 \ln f \qquad \text{----------------------------(6-8)}$$

The purposed surface finish is tested by the following equation

$$R_a = \left(\frac{F - 71}{45.2} \right)^4 \qquad \text{----------------------------(6-9)}$$

Where

R_a = Surface Finish (□in)

F = Cutting Force (Newton)

6.2.2 Steel Estimator Algorithm

Similar to the application of aluminum material, the machining parameters can be established by using the same previous methods. The following steel work piece model parameters is as follows

$$F_a = 293 - \frac{593}{R^{1/2}} \quad \text{-------------------------------- (6.10)}$$

$$f_a = 189 - \frac{5926160}{F^2} \quad \text{-------------------------- (6.11)}$$

$$S = \left(30064193 - 2.28F^3\right)^{1/2} \quad \text{---------------------------(6.12)}$$

S = Spindle Cutting Speed (RPM)

f = Feed Rate (In/min)

The above equations can establish the best speed and feed rate required to produce the controlled cutting force.

$$F_c = 286.44 - \frac{5.82}{10^{10}} S^3 - 353.27 \frac{\ln(f)}{f} \quad \text{-------------(6.13)}$$

The purposed surface finish is tested by the following equation

$$R_a = \left(\frac{593}{293 - F}\right)^2 \quad \text{---------------------------------- (6-14)}$$

6.3 Simulation Block Diagram

6.3.1 Aluminum Work Piece Block Diagram

The block diagram of the proposed control model based on the model parameters that illustrated in 6.2, was established as shown in Figure 20. This control model provide a closed loop control for the cutting force and produce a specific and desired surface finish. The parameters model was used to manipulate the feed rate and the spindle speed for the machining process. The feed rate command as long as the spindle speed was regulated by the Fanuc feed drive system as was explained in equation 6.3. This system has an inner velocity loop which included in the mechanism of the feed drive shown in Figure 19. The objective of the drive system is to minimize the error and give the suitable and actual feed rate and spindle speed for this kind of machining process.

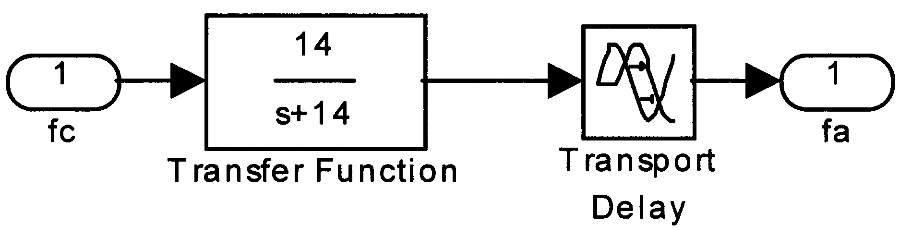


Figure 19 Feed Drive System Transfer Function

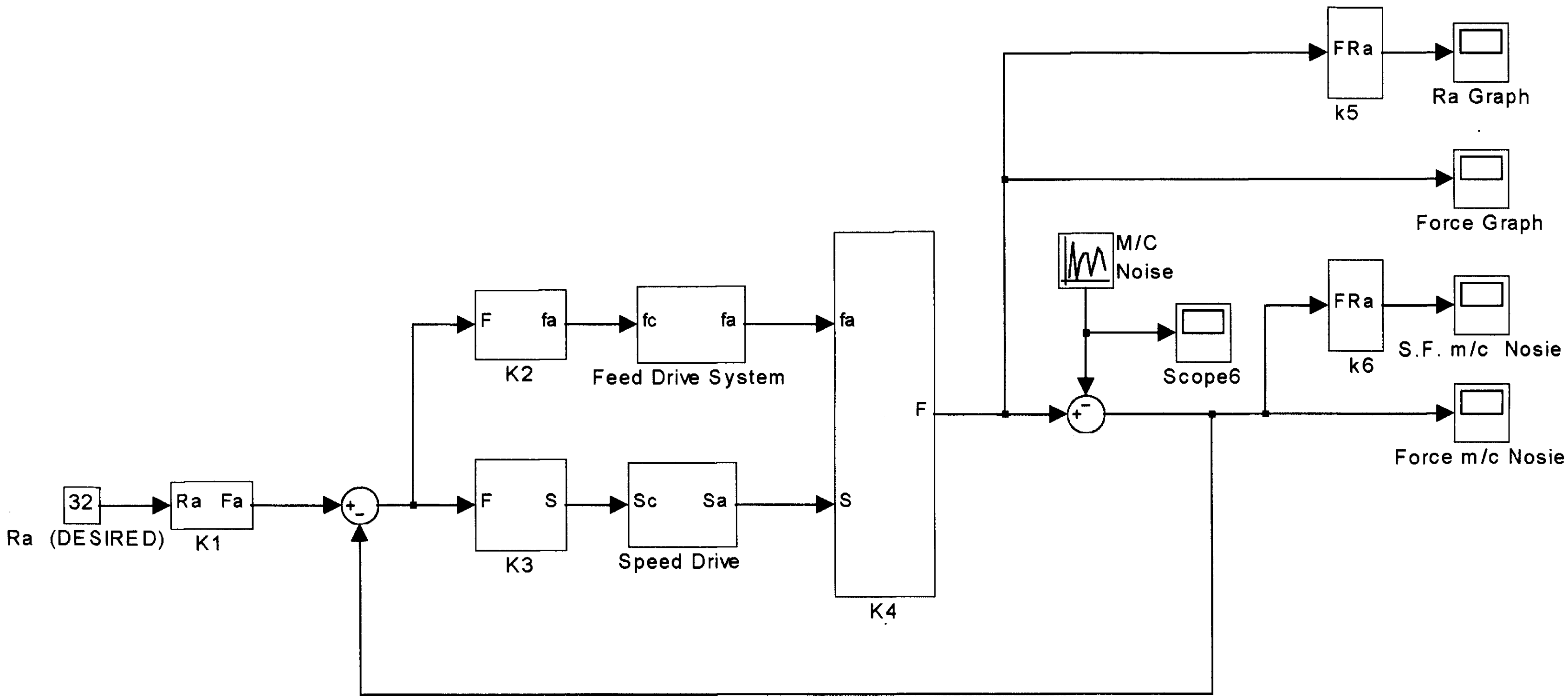


Figure 20. Control Model Block Diagram for Aluminum

The following describe the several control model transfer functions and signal of the processing methods.

K1: represent the transfer function of the relationship between the desired surface finish and the produced cutting force. The sub-block diagram of this transfer function is shown in Figure 21.

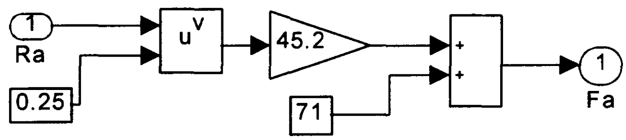


Figure 21. Surface Finish-Force Sub-Block Diagram

K2: Transfer function for force-feed derived from empirical modeling equation 6.6 to compute and generate the feed rate command signal f_c. Figure 22 represents the block diagram.

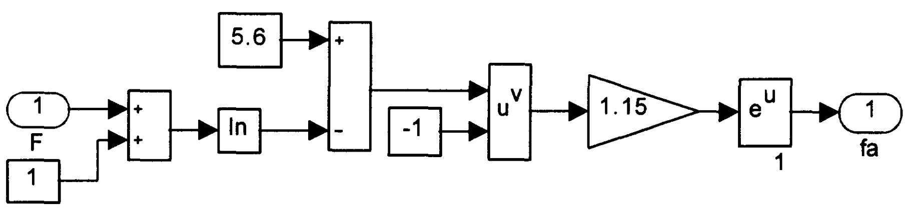


Figure 22 Force-Feed Rate Sub-Block Diagram

K3: Transfer function force-spindle speed shown Figure 23, derived from empirical equation 6.7 to compute and generate the spindle speed command signal S_c.

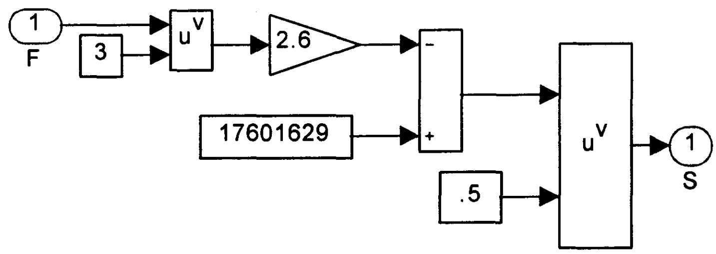


Figure 23 Force-Spindle Speed Sub-Block Diagram

K4: Multiple regression transfer function Figure 24 has been performed to produce the regulated, controlled cutting force based on the model algorithm equation derived from equation 6.8.

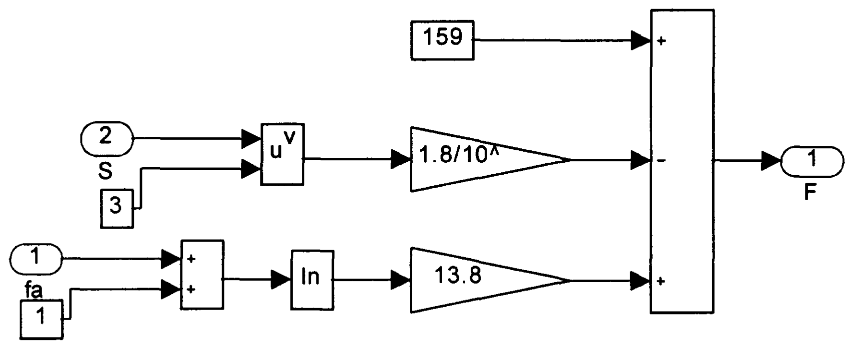


Figure 24 Cutting Force Control Algorithm Sub-Block Diagram

K5, K6: Force-Surface finish sub-block diagram is utilized to test and verify if the produced surface finish is the same as the desired surface finish. This is made known by Figure 25.

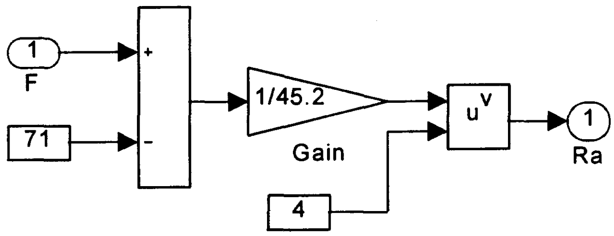


Figure 25 Force Surface Finish inspections Sub-Block Diagram

The above control model block diagram represent a solution of generic signal processing problem. It is convinient to consider this model as a building block that can be used to achieve the purpose of this research.

Machine Noise:The machine noise, Figure 26, is generated using a random of variation that related to the values that mentioned in section 3.3.1 Table 6 for the machine setup.

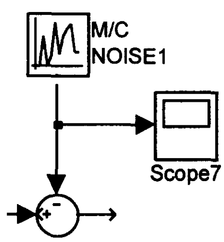


Figure 26 Machine Noise Diagram

This machine niose was done to represent the uncontrolable physical noise such as material hardening, tool wear etc...

Scope: The graph that appears in the scope of the matlab software represents the relatrionshiop between two variables as follows:

Scope of Ra results: this represents the graph of the required surface finish output (y axis) and the sampling time (x axis). The sampling rate is set as mentioned previously in section 3.3.1 table 9 for the machine setup.

Scope of Force Results: it represents the output of the cutting force (y axis) that was controlled by the empirical model based control and the sampling time. The graph was scaled and set between 0-950 to accommodate the output force value.

Scope of Ra with Noise: it represents the uncontrollable graph of the surface finish that was influenced by the machine noise and the value before the control model simulation.

Scope of Force with Noise: This graph was set at a high scale value (0-950) to represent the uncontrollable graph of the cutting force that was influenced by the machine noise and the value before the model control simulation.

Scope of Feed Rate: This shows the feed rate graph that is controlled during the machining operation to maintain a constant cutting force.

Scope of Spindle Speed: This shows the spindle speed graph that is controlled during the machining operation to maintain a constant cutting force.

6.3.2 Steel Work Piece Block Diagram

The block diagram of the proposed control model for the steel material work piece, based on the steel work piece model parameter as shown in Figure 26, this block diagram has a similar design as the one illustrated for the aluminum work piece. The parameter estimator algorithm for this block diagram was derived in 6.2.2. The main objective of this block diagram is the same as previously explained in the design of the alumunim work piece.

The following describes the transfer function and the signals processing system for the steel machining process. The transfer function for the control model block diagram is as follow:

K1: represent the transfer function of the relationship between the desired surface finish and the produced cutting force. The sub-block diagram of this transfer function is shown in Figure 27.

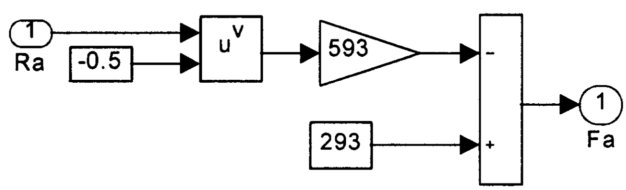


Figure 27. Surface Finish-Force Sub-Block Diagram

K2: Transfer function for force-feed derived from empirical modeling equation 6.11 to compute and generate the feed rate command signal f_c. Figure 28 represents its block diagram.

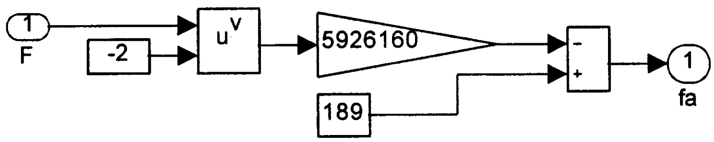


Figure 28 Force-Feed Rate Sub-Block Diagram

K3: Transfer function force-spindle speed derived from empirical equation 6.12 to compute and generate the spindle speed command signal S_c shown in Figure 29.

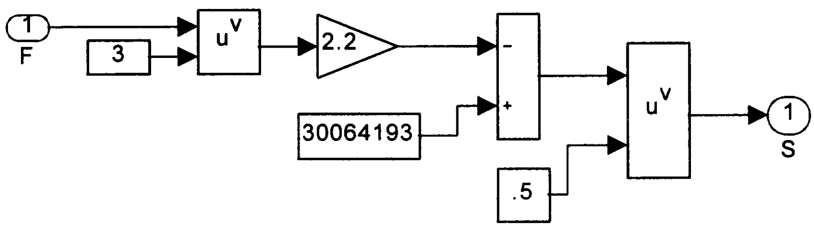


Figure 29 Force-Spindle Speed Sub-Block Diagram

K4: Multiple regression transfer function Figure 30 has been performed to produce the regulated, controlled cutting force based on the model algorithm equation derived from equation 6.13.

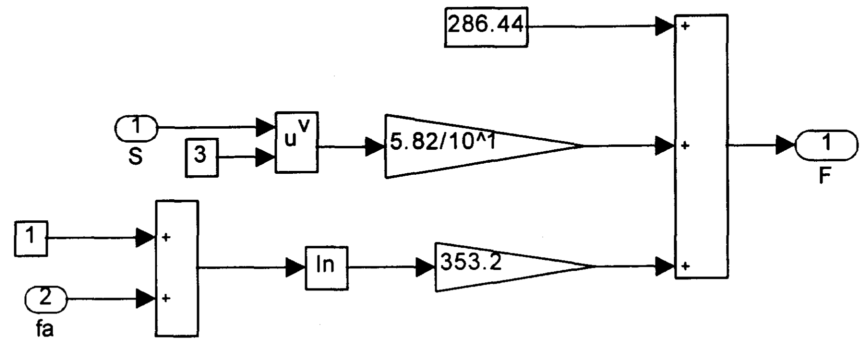


Figure 30 Cutting Force Control Algorithm Sub-Block Diagram

K5, K6: Force-Surface finish sub-block diagram is utilized to test and verify if the produced surface finish is the same as the desired surface finish. This is made known by Figure 31.

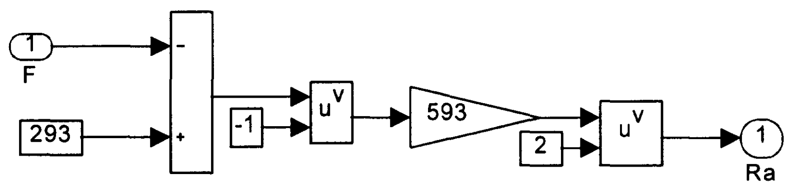


Figure 31 Force Surface Finish inspections Sub-Block Diagram

The above control model block diagram represent a solution of generic signal processing problem. It is convinient to consider this model as a building block that can be used toachieve the purpose of this research.

In practical milling process, there is a noise present in the system, such as change in the property of the raw material, tool wear, breakage of the tool, change of nose radius, etc... It adds a noise in the model in order to test the referance of the output with the effect of the noise, the cutting force and the surface finish results indicates a large over sheet transit. When the noise is removed from the model a perfect result waas obtained.

6.4 Simulation and Experimental Results

This section represents the control design and the simulation that is carried out for the proposed control model to determine the exactness of the model performance in the end milling operation. As it was made clear previously, the main objective of the control model is to produce a desired surface finish by controlling and manipulating the operating parameters of the milling process and regulated and maintain the cutting force as a constant value. The performance of the control model block diagram was tested with computer simulation using the Matlab 5.3 software. To carry out this simulation, a desired reference value of the surface finish has been selected to initiate the operation of the simulation process. The procedure started by computing the initiated cutting force on the K_1 transfer function. This cutting force value instantaneously figured the values of the feed rate (f_c) and the spindle speed (s_c) command; these values were base on the transfer function K_2 for the feed rate and K_3 for the spindle speed. The transfer function of the feed drive system as well as the speed drive system, simultaneously controlled the command signals (f_c) and (s_c), and generated the actual feed rate (f_a) and the actual spindle speed (s_a) required to generate and control the constant cutting force based on the algorithm K4. The results of the simulated surface finish is tested and confirmed by the transfer function model, K5.

6.4.1 Simulation

An experiment for aluminum workpiece was run in order to verify the ability of the enhanced empirical model based control simulation. The desired surface finish was chosen to be 32 μin. The experiment was carried out with a low depth of cut of 0.01 in; the block diagram in Figure 32 shows the simulation output of this experiment. Observing the data of the block diagram, one can notice that the feed rate started at 17.46 in/min, and then regulated by the feed drive system to achieve a controlled value of 12.78 in/min. The same technique occurred to the spindle speed to achieve a controlled value of 2134 RPM. The controlling and change of the spindle speed and the feed rate were necessary to produce a constant value of 177.78 Newton for the cutting force. The surface finish roughness was tested with the transfer function K5 and the result obtained was 31.05 μin, compared with the desired surface finish of 32 μin.

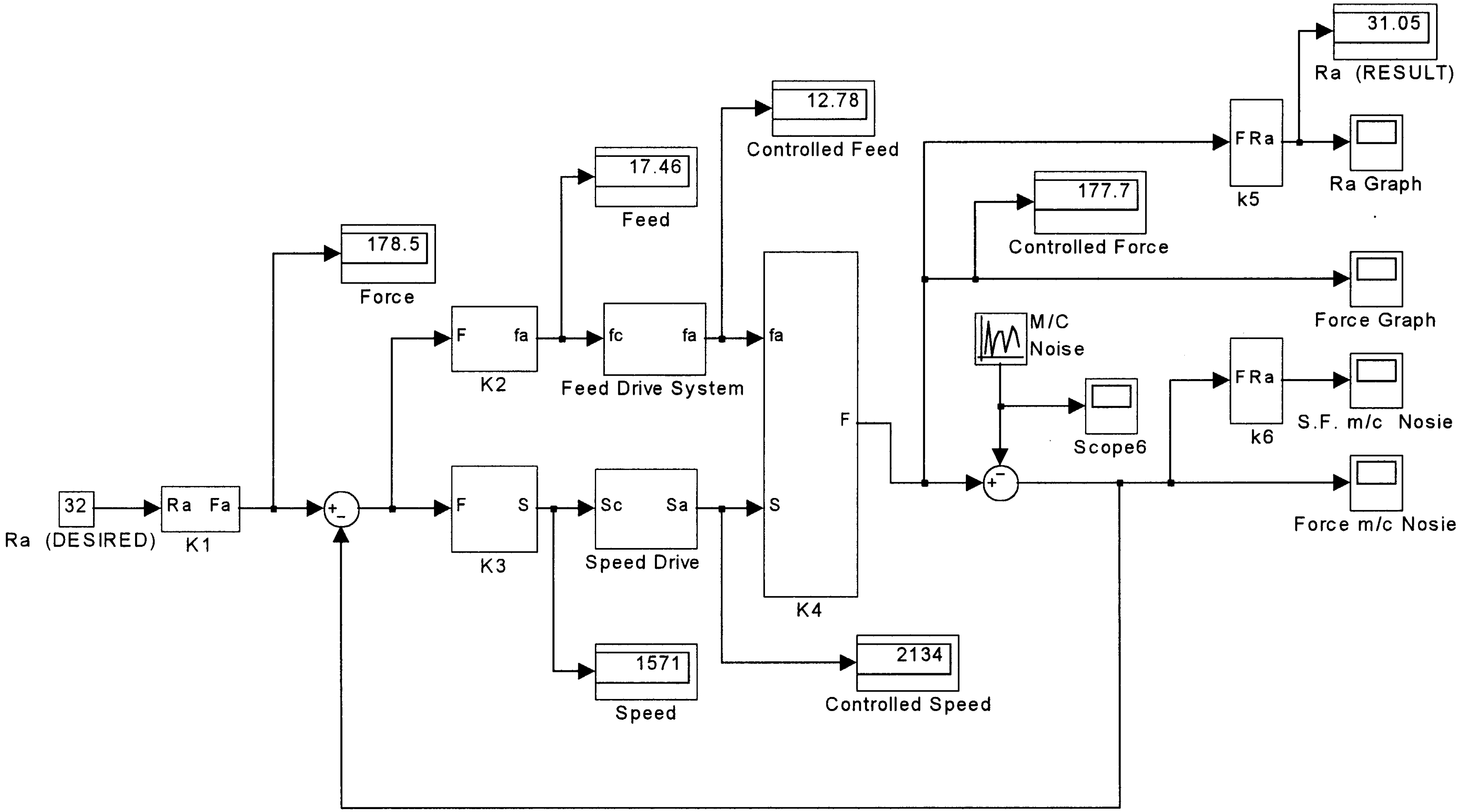


Figure 32 Simulation Block Diagram for the Experiment Results

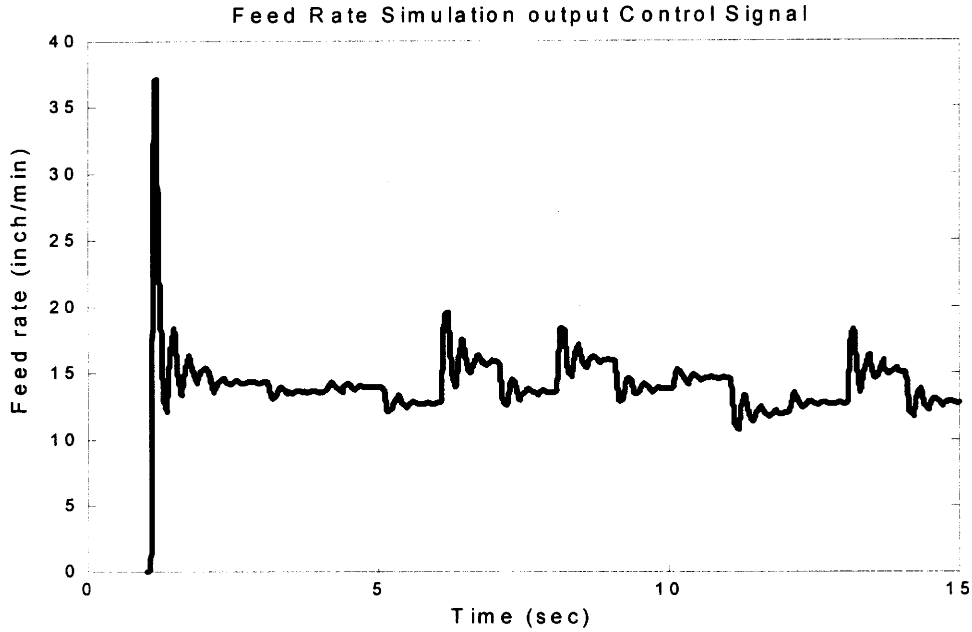


Figure 33 Feed Rate Simulation Output

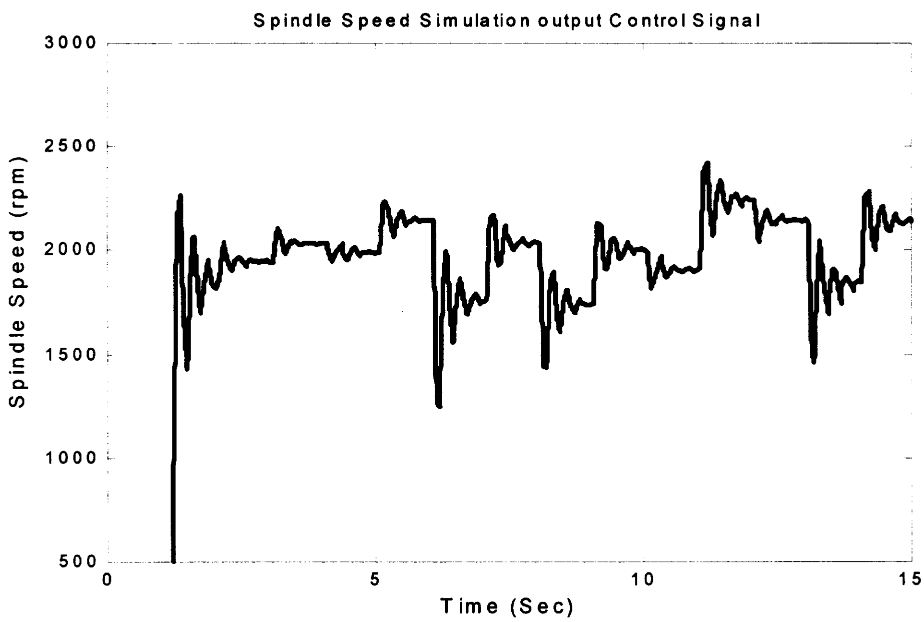


Figure 34 Spindle Speed Simulation Output

The Feed Rate and the Spindle Speed output are illustrated in Figure 33 and Figure 34 respectively. It can be observed that the model control regulates and changes the value of the Feed Rate and the Spindle Speed during the machining process to regulate the Cutting Force and maintain it constant so that the required surface finish can be achieved.

6.4.2 Simulation Experimental

The simulation experiment results shown in Table 21 has confirmed and indicated that the control model was efficient to produce the required value of surface finish. As indicated in the above table, the control model appears to be more effective for machining material to produce a smooth surface finish. At rough surface finish exceeds 40 μin, the control model start to give a slow response and low sensitivity to get the required surface finish value

6.5 Analysis of the Results

The process of similar simulation experiments has been carried out to analysis he results of different values of required surface finish to validate the performance of the model simulation with different operating machining parameters. The experimental conditions of Table 21 are used as the input to a computer Matlab 5.3 simulation for the proposed mathematical model. In order to be able to compare the experimental and the simulated output for the machining parameter, the surface finish, the cutting force, and it was necessary to choose a required surface finish value. Table 21 lists the input and output of the simulation results for spindle speed, feed rate, cutting force, and the required surface finish compared with the results obtained.

Table 21 Simulation Experimental Results

Simulation no	Desired Surface Finish	Machining Parameters Before Simulation			Servo Drive System			Produced Surface Finish
		Force	Feed	Speed	Force	Feed	Speed	
1	15	161.40	14.06	1974	166.50	10.43	2443	19.81
2	20	166.67	14.96	1895	169.90	11.11	2356	22.92
3	25	172.10	16.32	1704	173.00	11.73	2272	25.94
4	30	176.80	17.53	1563	175.90	12.36	2189	28.99
5	32	178.50	17.46	1571	177.70	12.78	2134	31.05
6	35	180.90	18.59	1437	178.60	12.99	2108	32.07
7	40	184.70	19.10	1377	181.60	13.80	2007	35.89
8	45	188.10	19.99	1270	183.90	14.00	1925	38.98
9	50	191.20	21.23	1116	185.70	15.00	1880	41.43
10	60	196.80	23.33	825	195.20	16.22	1716	46.43

The graph in figure 35 indicates the output of the cutting force without the control model effect. As shown, the cutting force has no specific value and has a random trend. It is obvious from Figure 37 that if the feedback control was not applied, the surface finish results will also behave randomly.

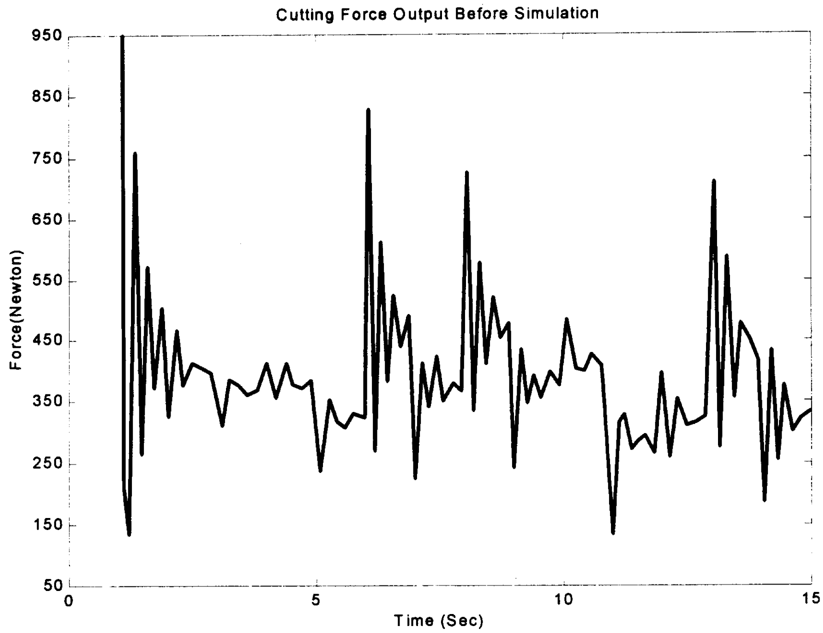


Figure 35 Cutting force output before using model Simulation

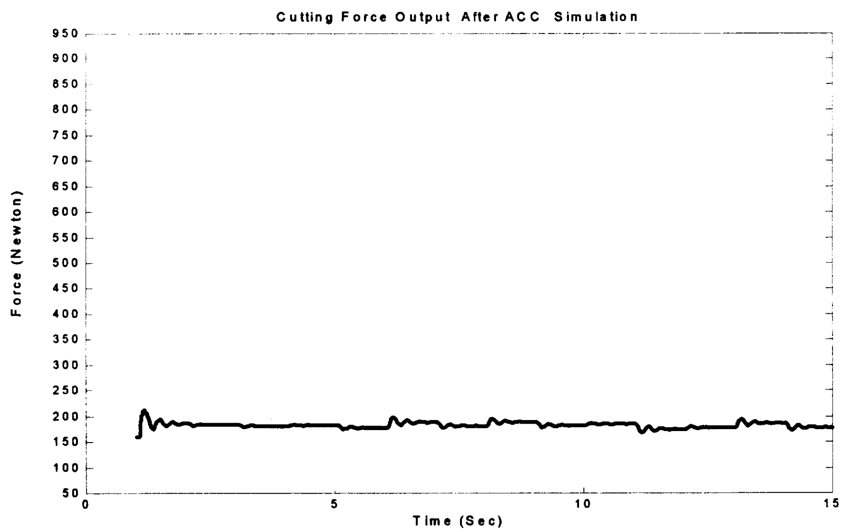


Figure 36 Cutting Force Output After using model Simulation

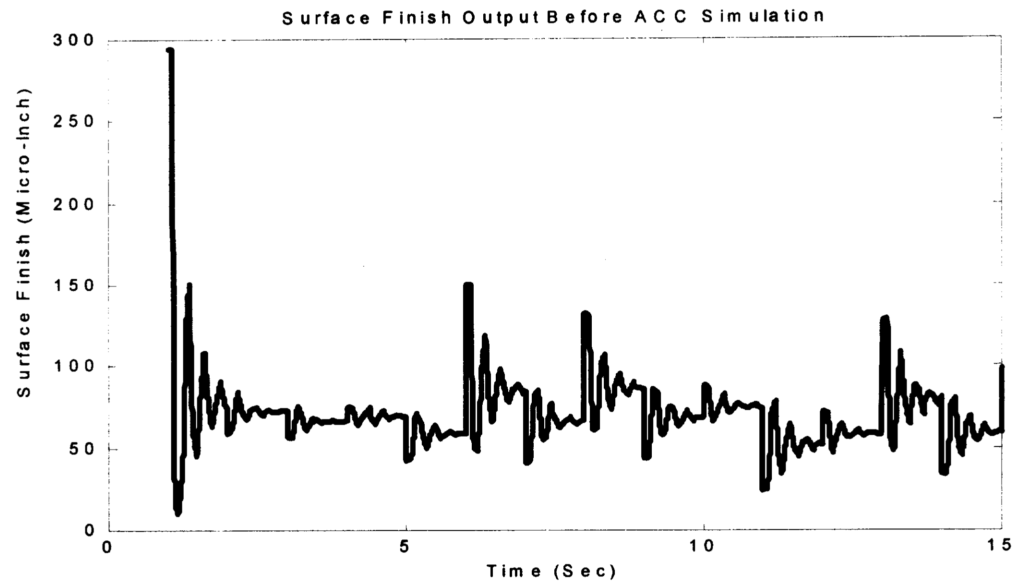


Figure 37 Surface finish output before using model Simulation

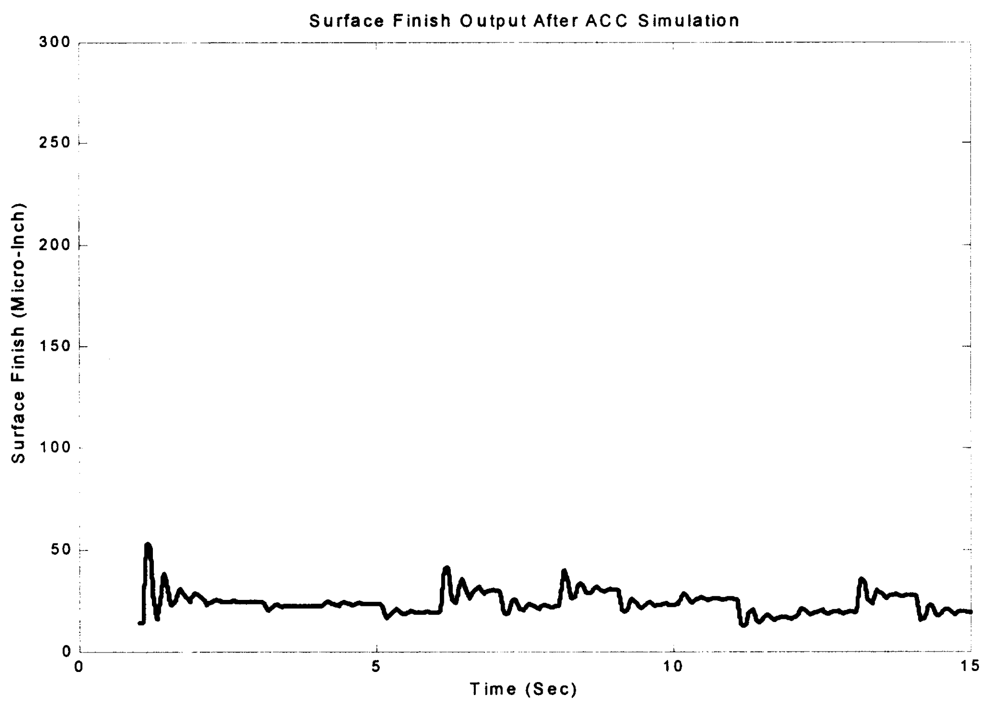


Figure 38 Surface Finish Output After using model Simulation

It can be observed form Table 21 that the trend of the cutting force and the surface finish are the same as explained previously in Chapter 5.3.2, these results show that the cutting force increases when the feed rate increases, and the cutting force also increase when the spindle speed decrease. All above confirms the adequacy of the model that is explained in Chapter 5.

The above simulation analysis and the results of the proposed control model simulation was efficient to maintain the cutting force constant during the machining process and produce the required surface finish.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Experiments have been conducted, and results have been obtained, for two different work pieces of aluminum and steel undergoing an end milling machining process. On-line cutting forces as well as surface finish have been measured under different operating parameters.

A mathematical model and empirical equations were developed, single and multiple regression analyses have been used to correlate the surface finish to the cutting force; these analyses have also been used to relate the cutting force to the milling operating parameters namely, spindle speed, feed rate, and depth of cut.

A different analysis has been conducted to confirm the adequacy of the model. The analysis indicated that, if the cutting force were maintained constant, then the surface roughness would also be constant during the machining operation.

The previously derived model makes it possible to develop a new method of an empirical model based control simulation. It is capable of producing and controlling a prescribed surface finish. This is achieved by controlling both spindle speed and feed rate of the machining process in order to maintain a constant cutting force.Simulation experiments have been conducted with different values of required surface finish to validate the performance of the control model; the results indicate the following:

- The control model was effective and capable of regulating and maintaining a constant cutting force during the milling process, the system was stable over a wide range of cutting conditions.
- The output signals of the cutting force components are correlated to the output signals of the surface finish.
- A desired surface finish has been achieved by simultaneously changing the spindle speed and feed rate.
- The control model was found more effective for the finish-machining operation where the surface roughness is below 45 μin. For a rough-machining operation, the model starts to give a slow response and low sensitivity to get the desired surface roughness. (The proposed control model was developed for fine machining process.)

The developed model is useful for the end milling operation and helpful to eliminate many problems associated with the surface finish machining process.

Recommendations and Topics for further Research

This Research work has provided different developments that are useful for further research studies. The area of control model system needs further work. The following are different interesting areas for future research:

- Further development in control model based on contour and complex surface finish.
- Measuring on-line surface finish still unknown and further work is required in the field of machining process.
- New models are needed to correlate the tolerance with the surface finish.
- Further development is needed for a universal and unique control algorithm that can be used for all types of materials.

APPENDIX

Experimental Results and Data Analysis

All the experimental results and the empirical relationships generated from the statistical analysis are included in the attached Compact Disc (CD).

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