Multilevel on-line surface roughness recognition system in end milling operation

by

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For the Graduate College

DEDICATION

This work is dedicated to
my loving wife Tiffany L. Howard-Savage for her devoted support and encouragement
and in memory of my mother Elizabeth Ann Savage.

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ABSTRACT

The use of computer numerically controlled (CNC) machines has become more widespread and as more machining centers are operating unattended, the need for a Smart CNC machine for on-line tool and process monitoring has become critical. An accurate and reliable method of providing real-time information is vital to the continued integration of adaptive control systems (ACS) with machine tools. ACSs are being developed to monitor parameters like tool wear through current sensing, tool breakage from cutting force signals, and tool chatter from vibration signals. These adaptive control systems' capabilities can be broadened to monitor and control various surface quality parameters. For this to happen, a method to provide accurate on-line information about the machined surface is needed.

A multi-level on-line fuzzy net controller and multiple regression model was designed to recognize surface roughness in vertical end-milling process. Both models integrate machining parameters of 1) feed speed, 2) depth of cut, 3) tool type, 4) tool material, 5) work material, 6) spindle speed, 7) vibration, and 8) tool diameter. The fuzzy net controller is composed of eight different fuzzy designs each having a fuzzifier, rule base, inference engine, and defuzzifier. Individual designs are referenced to perform surface recognition according to the parameter settings for tool diameter, work material, and tool type.

The recognition efficiency of the fuzzy net model and a multiple regression model of same configuration are compared with actual Ra readings taken by a profilometer. This multi-level on-line fuzzy net model displayed a recognition accuracy of 90% as compared to an accuracy of 82% for the multiple regression model.

CHAPTER I. INTRODUCTION

Manufacturing has played an ever-increasing role in our lives. Not only are we concerned with how products are produced and delivered to us, but we are also concerned with how well the products are built. Manufacturers around the world continuously seek new and improved methods of product manufacturing to meet the expectations of the consumer.

There are many aspects of manufacturing that can be considered when looking for new and improved methods of production. Efforts can be focused on manufacturing systems, manufacturing processes, or manufacturing materials. All of these efforts together transform raw materials into end products. Within the area of manufacturing processes, different processes can be evaluated for their impact on processing time, efficiency of production methods, and quality of finished products.

The quality of finished products is defined by how closely the finished product adheres to the specifications. Surface roughness (Ra) is the most commonly used index to determine surface quality. (Ra) is a measure of smoothness for a machined surface. Surface quality is defined and identified by the combination of surface finish, surface texture, and surface roughness. These surface characteristics will be covered next.

Surface finish and surface roughness express and represent the same characteristic. Surface roughness is defined as the fine irregularities produced on a workpiece by a cutting tool. Surface texture relates to deviations from a nominal surface that form the pattern of the surface. The terms surface texture, surface finish, and surface roughness are used interchangeably in industry as well as in this paper (Olivo, 1982).

Many lifelong attributes of a product are determined by how well the integrity of the surface finish is maintained. Painting or coating adherence, surface reflectivity, and frictional requirements are examples for which the surface roughness may be specified. Defects occur when the surface roughness requirement is not met. Applied surfaces may fail to adhere properly and parts may not assemble properly due to excessive frictional components exhibited through poorly machined surfaces.

Numerous factors affect surface roughness in the machining process. While some factors are difficult or impossible to control, some controllable process parameters include feed, cutting speed, tool geometry, and tool setup. Other factors that are harder to control include tool vibration, work-piece and machine vibration, tool wear and degradation, and work-piece and tool material variability (Coker & Shin, 1996). These factors interact to influence the quality of the surface finish produced. When the surface does not meet the specifications, parameters are adjusted and the original or a new workpiece is inserted into the machining center for machining.

To identify defects before they occur the process must be monitored and the machined surface measured on-line. By developing an on-line surface recognition system that provides real-time information about the machine process, better decisions can be made about the machining process before it is complete.

Traditionally and even today, the majority of surface measurements taken in industry are conducted off-line, after the machining process is complete. Off-line measurements require that the part(s) be removed from the machining center or that the machine be completely shut down for measurements to be taken. To add further to the cost of production, down time must be scheduled for this off-line inspection process. However, with the development and implementation of an accurate on-line surface roughness recognition system, inspection, rework, and setup cost can be eliminated.

The on-line surface roughness recognition (OSRR) system, like any other system, would perform well given only one set of machining conditions to monitor and measure. However, this is unrealistic in a true industrial environment. Machine setups involving different tools, different work materials, and many different feed rates and spindle speeds come together to produce the large variety of machined products that exist today. An OSRR system was developed successfully by Lou and Chen, (1997). However, this system was developed for one set of conditions (i.e., work material, tool design, and type). For this system to be utilized in a true industrial environment, it has to be able to respond in a more realistic industrial environment. Thus, there exists the need for a multi-level on-line surface roughness recognition system capable of providing real-time surface information for decision-making.

Purpose of the Study

The purpose of this research was to address the need of the end milling industry by developing a multi-level, on-line surface roughness recognition system. The development of this model incorporates multiple work materials, tools, and setup parameters to produce the most robust surface recognition model. This system was designed to provide the real-time surface roughness (Ra) values needed for on-line decision-making in a more realistic industrial environment. The purpose of proposing the fuzzy logic model is to develop an on-line system leading to a more finely tuned prediction model. This model is capable of formulating decisions more similar to human decision-making, an aspect the classical approach does not provide. This research focuses on the milling process of machining, more specifically end milling, in a vertical milling center.

Objectives of the Study

The objective of this research was to develop a multi-level on-line surface roughness recognition (M-OSRR) system. To achieve this main objective, multiple regression and fuzzy logic models were developed and compared to find the model that best predicts surface roughness. The most accurate model, or the one closest to the true (Ra), was then selected.

Significance of the Study

The M-OSRR system proposed in this research has potentially far-reaching impacts in the end milling community. Research by Lou and Chen (1997) involving the in-process surface recognition (ISR) system resulted in the development of a surface recognition system with only one tool type and one work material. The ISR system successfully predicted Ra with 93% accuracy. Lou and Chen's research provided very significant groundwork focused in end mill machining. The M-OSRR developed in the current research uses multiple tools and work materials. These additional parameters add an additional dimension to the surface recognition model. The M-OSRR system provides a more robust prediction model more suited for the various machine parameters and conditions that exist in industry today.

The current research also provides a method of assuring that quality is built into the product. The cost of this quality will no longer be inspected into the product by off-line inspection stations, but by a more accurate on-line prediction method. The capability of this M-OSRR system to deliver information in real-time enables the control system to make decisions critical to maintaining proper surface specifications. In addition to real-time responsiveness, this system can be designed with self-learning capabilities, meaning that the control system continuously would fine tune itself. A system with this capability would perform like a journeyman machinist when required to produce consistently high-quality machined products. This brings special benefits to the machining process, especially when working with infrequently processed or new materials. Each successive machining process would benefit from all previous machining processes. Therefore, research focused on developing this multiple on-line surface roughness recognition (M-OSRR) system is worthy of further study and development.

Research Question

The following questions were addressed in this study:

1. What are the relationships between the independent variables such as tool diameter, tool material type, work material type, feed rate, depth of cut, spindle speed, vibration, and the dependent variable surface roughness (Ra)?
2. Which model more accurately recognizes surface roughness (Ra): multiple regression or fuzzy logic?

Hypotheses of the Study

The following null hypotheses were tested

1. Tool diameter has no statistically significant effect on surface roughness (Ra).
2. Tool material type has no statistically significant effect on surface roughness (Ra).
3. Work material has no statistically significant effect on surface roughness (Ra).
4. Feed rate has no statistically significant effect on surface roughness (Ra).
5. Depth of cut has no statistically significant effect on surface roughness (Ra).

6. Spindle speed has no statistically significant effect on surface roughness (Ra).
7. Machine tool vibration has no statistically significant effect on surface roughness (Ra).
8. There is no statistical difference in accuracy between the multiple regression (M-OSRR) model and the fuzzy net (M-OSRR) model.

Delimitations of the Study

This study was conducted with the following delimitations:

1. This research was limited to the vertical machining center manufactured by Fadal. VMC-40 is the model number specific to the machining center.
2. Vibration inherent in the machine and the machining environment were uncontrolled variables.

Procedures of the Study

The procedures of the study consisted of the following:

1. Formulated the study problem.
2. Reviewed related literature concerning methods used to determine surface roughness (Ra) during and after the vertical end mill machining process.
3. Identified inferencing tool that could be applicable in this study to recognize surface roughness (Ra).
4. Identified tool size factor levels
5. Stage one: tool size data collection

6. Determined and developed a parameter design methodology for testing all independent variable effects.
7. Prepared a research proposal for the study.
8. Developed and completed C language program code for data collection.
9. Wrote CNC program for milling machine
10. Stage two: conducted Taguchi experimental design experiment.
11. Evaluated significant independent variables from stage 2.
12. Stage three: established training and testing parameters for regression and fuzzy logic models
13. Setup and conducted experimental run according to training parameters.
14. Developed multiple regression model for each design.
15. Developed and completed C program for fuzzy logic model
16. Stage four: fuzzy logic model development
17. Stage five: evaluated accuracy of multiple regression vs. fuzzy logic model
18. Interpreted findings.
19. Wrote the summaries, conclusions, and recommendations based on the findings.

CHAPTER II. LITERATURE REVIEW

In this research the M-OSRR system was used to predict surface roughness Ra during milling. The structure and function of the M-OSRR system is related to or influenced by the surface characteristics of the work-piece, milling operation, on- or off-line monitoring, direct or indirect measurement, sensors, surface recognition techniques, multiple regression statistics, and the fuzzy logic system. These factors are reviewed and discussed in this chapter.

Surface Characteristics

The quality of machined components is evaluated by how closely they adhere to product specifications of length, width, diameter, surface finish, and/or reflective properties. Bradley, Bohlmann, and Kurada (1998) stated that product quality currently is improved in industry through application of quality control techniques, after manufacture and implementation of concurrent design methods prior to manufacture. Lahidji (1997) states that in high speed turning operations dimensional accuracy, tool wear, and quality of surface finish are three factors that manufacturers must be able to control.

Coker and Shin (1996) noted that, among various process conditions, surface finish is a important factor in determining the quality of a work-piece. Surface roughness affects several functional attributes of parts, such as fatigue, contact surface friction, wear, contact stress distribution, and paintability (i.e., how well paint adheres to the surface).

Research involving the monitoring and prediction of surface roughness or texture has been done with emphasis on the accuracy of the machined surface and the efficiency of the machining process (Beak, Ko, & Kim, 1997). The current research was conducted through the evaluation of machined surfaces during their production by the end milling process. A basic understanding of the milling process used in this research is covered in the following section.

Milling Process

One of the most common metal removal operations used in industry is the end milling process (Sutherland & Devor, 1986). End milling is used to make slots, pockets, precision molds, and dies. It has been used widely in the aerospace industry to machine high-strength and temperature resistant alloys (Wilson & Cox, 1965). Drilling, sawing, turning, and milling are other processes used to remove material.

Milling generally uses a multipoint tool, which is rotated to create the cutting motion. The feed motion is produced by feeding the workpiece in a straight line into the cutter.

Direct versus Indirect Monitoring

Direct methods refer to systems that can measure a property of the tool, such as the area of tool flank wear or the depth of crater wear. Optical sensors (Giusti & Santochi,1979; Jeon & Kim, 1988), vision systems (Pedersen, 1990), and microprobes (Ham, Schmidt, & Babcock, 1968) are examples of sensors used in direct methods. These methods have the advantage of high measurement accuracy, but cannot be adopted easily for on-line applications, principally because of the interruption caused by coolant and chips (Lister & Barrow, 1986; Tlutsy & Andrews, 1983). The indirect methods measure three general aspects: one or more of the indicators or parameters associated with vibration (Shaw & Shangbani, as cited in Nayfey & Abu-Zahra, 1996); acoustic emission (Dalpiaz & Remondi, 1988; Emel & Kannatey-Asibu, 1988; Iwata & Moriwaki, 1977; Kannatey-Asibu, 1981, 1984); and cutting temperature and surface roughness. These surface roughness measurement devices are further grouped into two classes, contact and non-contact.

An amplified stylus profilometer is the most popular and prevalent contact instrument used to measure surface roughness in industry and research laboratories because it is fast, repeatable, easy to interpret, and relatively inexpensive (Mitsui, 1986; Shin, Oh, & Coker, 1995). In addition, stylus profilometers are used as the standard for comparing most of the newly invented surface roughness measuring instruments or techniques. This instrument uses a tracer or pickup incorporating a diamond stylus and a transducer able to generate electrical signals as it moves across the surface to be measured. The electrical signals are then amplified, converted from analog to digital, processed according to an algorithm, and displayed.

In the current study, the surface is explored by a stylus traversed at constant tracing speed, and the vertical motion is measured by an inductive displacement transducer. The measurement has a fairly good resolution and a large range that satisfies the measurements of most manufactured surfaces. However, this stylus profilometer has some limitations, which include excessive time required to scan large areas, being restricted to off-line use, and difficulty in using on non-flat surfaces (Shin, Oh, & Coker, 1995).

Surface finish can be specified in terms of many different parameters. For the current study, a large number of developed surface roughness parameters were conceived, and the instruments to evaluate them were developed, due to the need for different parameters in a wide variety of operations. One of the parameters of surface finish used in this study is the Roughness Average, (Ra). This parameter is also known as the arithmetic mean roughness value, arithmetic average (AA), or centerline average (CLA) (see equation 1). Ra is universally recognized as the most common international parameter of roughness, defined by the following equation:

$$R_a = \frac{1}{L}\int_0^L |Y(x)| dx \qquad 2.1$$

where Ra is the arithmetic average deviation from the mean line, L is the sampling length, and Y is the ordinate of the curve of the profile, the arithmetic mean of the departure of the roughness profile from the mean line (Lou & Chen, 1997).

Measurement On-line vs. Off-line

The method used to monitor the machining process is critical to its integration into the overall machining system. Monitoring can be performed on- or off-line by either direct or indirect means (Cook, 1980). The need for on-line tool and process monitoring has become critical since the use of computer numerically controlled (CNC) machines and the move toward unattended machining centers has become more widespread (Frost-Smith, 1970; Koren, 1989). The on-line designation for a sensing method means that it is performed while metal is being removed (or during normal disengagement), without interrupting the process. Off-line methods can be performed on the machine or away from the machine. In either case, these methods require either scheduling idle time for the measurements or interrupting the process. Both means are effective in gathering important information about surface characteristics, but on-line monitoring is preferred. On-line monitoring provides real-time information about the process. This real-time feedback enables the machinist or operator to adjust the appropriate machining parameters in order to produce the desired surface roughness, reduce tool wear, and reduce the probability of tool breakage. However, monitoring or measurement conducted on- or off-line would not be possible without the use of sensors or sensory devices.

Sensors

Sensor technology is playing an ever-increasing role in the manufacturing environment for a wide variety of tasks, such as tool wear assessment, machine tool condition monitoring, and quantification of the surface finish. The demand for incorporating sensor technology into the production environment is being driven by the increasing need to minimize manufacturing costs while simultaneously producing parts of higher quality. Grouped into the two monitoring methods, direct and indirect, Table 2.1 shows an example of sensor use. The sensors are categorized according to the type of measurement taken.

Table 2.1. Principal classification of tool breakage sensing methods

Procedure		**Measurement**	**Transducer**
Direct	Optical	Shape or position of cutting edge	CCD camera, optical transducer
	Tool-workpiece Distance	Distance of workpiece and tool or toolholder	Gap or displacement sensor, micrometer
Indirect	Cutting Force	Change of cutting force	Piezo or strain gauge dynamometer
	Acoustic emission	Stress wave energy	AE transducer
	Ultrasonic energy	Ultrasonic Vibration	High frequency
	Accelerometer		
	Sound	Acoustic waves	Microphone
	Vibration	Vibration of tool or tool post	Accelerometer
	Power Output combine	Current of spindle or feed motor	Hall-effect sensor

(Kim & Choi, 1996)

Surface Recognition Techniques

In previous research involving the monitoring or prediction of the surface roughness, the combination of multiple materials and tool types has not been investigated involving end milling. Research done by Coker, Oh, and Shin (1998) used various workpiece materials; however, various material removal processes were used in order to evaluate the capability of an ultrasonic system for the in-process surface roughness measurement of machined parts.

Some other work has been done to attempt to predict the roughness, but each approach seems to have its own limitations. The analytical approach depends on geometrical work to derive an ideal profile from which the roughness can be predicted. A turning example of such an approach was shown by Vajpayee (1981). This approach can become limited by any number of unpredictable events and can become quite complex if an attempt is made to model all contributing factors. Ismail, Elbestawi, and Urbasik (1993) present a more complex scheme for peripheral milling that includes tool wear, cutter vibrations, and run out. The approach starts with analytical formulas that are supplemented by the machine tool characteristics and experimental data.

Factorial regression is another way to predict the surface roughness (Dontamsetti & Fischer, 1988; Sundaram & Lambert, 1979). For this approach, experiments must be conducted with all factors of significance considered. This can lead to a myriad of experiments and tedious work that may not be transferable to other machine tools and processes. For both analytical and experimental predictions, most of the work has been done on turned surfaces, as the surface is basically described by a two-dimensional (2D) model. With other 3D surfaces, such as ground and milled pieces, the prediction can become much more complex. It is, therefore, advantageous to measure the roughness in-process or on-line (Coker & Shin, 1996).

Optical

With the range for common finish machining being 0.5 μm to 5 μm in Ra, the present optical systems are mostly area-averaging in nature. One optical method uses a fibre-optic bundle to measure the intensity of a beam of light reflected from the machined surface in the specular direction (Dornfield & Fei, 1986; Inasaki, 1982, 1985; Spurgeon & Slater, 1974). The distance from the surface to the sensor affects the intensity and therefore must be kept constant. Another technique using fiber-optics measures the diffuseness of the reflected light from the surface (Takeyama, Sekiguchi, Murata, & Matsuzaki, 1976). The reflectivity of the surface must also be taken into consideration with a correlation chart generated for each material.

In research conducted by Scott and Donovan (1998), a fiber-optic proximity detector transducer was used to characterize surface profiles of both a machined steel surface and a vitrified aluminum oxide grinding wheel. The results of the surface profiles were compared with the signals obtained from a conventional contact profilometer. It was found that the major difficulty with the optical system was its reliance on constant reflectivity, because an area with lower reflectivity will give an output indicating greater separation from the transducer. This is likely to limit the effectiveness of the method where cutting fluid, chips, or any extraneous materials are present on the surface of the machined material. Bradley, Bohlmann, and Kurada (1998) conducted research to compare a fiber optical system with the stylus surface profile measurements performed on a standard set of machined surface samples. However, the main limitation of this system was found to be the large laser spot size (as compared to the probe tip of a profilometer).

Another approach to roughness measurement with an optical technique utilizes machine vision systems to view the surface. A light source is used to illuminate the surface, and a digital system views the surface. Data from the digital system are sent to a computer for analysis (Devoe & Zhang, 1993; Luk, Huynh, & North, 1987; Sundar & Raman, 1993). The digitized data are then used with a correlation chart to obtain actual roughness values.

In all of the optical techniques, some limitations have been discovered in their in-process use. In the harsh machining environment, cutting fluid or any extraneous materials seem to affect the measurements. In addition, any of the parametric methods must be carefully correlated for each material with differing reflectances (Coker & Shin, 1996).

Non-optical

Non-optical methods that are being researched include an inductance pickup and a capacitance probe (Garbini, Koh, Jorgensen, & Ramulu, 1992; Sathyanarayanan & Radhakrishnan, 1988). The first of these, the inductance pickup, depends on the placement of a sensor in close proximity of the surface to measure the inductance. This measurement gives a parametric value that may be used to give a comparative roughness. The inductive system is limited to measuring magnetic materials. The capacitive systems also depend on the placement of a sensor in close proximity to the surface. The sensor measures the capacitance between the sensor and the surface, and gives a comparative roughness parameter. Both of these methods would be adversely affected by cutting fluid and chips.

Ultrasonic

A spherically focused ultrasonic sensor is positioned with a non-normal incidence angle above the surface. The sensor sends out an ultrasonic pulse to the surface and measures the amplitude of the returned signal (Coker & Shin, 1996).

Laser speckle

Speckle techniques include laser-speckle correlation and monochromatic and polychromatic speckle-contrast methods. Each method has its own range, from 0.01 μm to 20 μm. These methods are simple to use; however, they yield only Ra or Rq (Lou & Chen, 1997).

Acoustic emission

Acoustic emission (AE) may be used to detect tool breakage. AE signals have a frequency range of 100 kHz to 1 MHz, and are insensitive to low frequency vibrations ranging under 100 Hz. However, their plastic deformation or strain sensitivity makes the differentiation between the changes in the cutting conditions and tool chipping difficult. Therefore, AE sensors have been more applicable to repetitive manufacturing, which allows calibration of thresholds from the machining of the first part (Atlintas & Munasinghe, 1996).

Sound

With the presence of chatter and forced vibration, Tlusty and Smith (1992) proposed the use of sound pressure measured with a microphone in monitoring the chatter vibrations. The microphone was placed above the spindle, but aimed toward the cutting zone. Chatter vibrations produce high pitch strong and irritating noise at a frequency close to one of the natural structural modes, causing the chip regeneration. The magnitude of the sound spectrum then becomes considerably larger during chatter vibrations than the stable and chatter free machining. However, care must be taken to cancel the sound interference caused by rotating parts and other machine tools in the shop. In research conducted by Altintas and Munasinghe (1996), a microphone measuring the sound pressure was used by a chatter detection module. Chatter was detected when the magnitude of the monitored sound spectrum exceeded a threshold. The thresholds were calibrated when the microphone was first installed and sound was measured from a sample chatter free machining test.

Current measurements

In a study conducted by Altintas (1992), the feed drive system of a vertical milling machine with an in-house retrofitted CNC system was analyzed for predicting milling forces and detecting tool failures from current measurements. It was shown that the cutting force could be predicted satisfactorily, if the friction in the drives is considered and if tooth-passing frequency is within the bandwidth of the servo.

Dynamometer

Liao and Young (1994) used a dynamometer to collect dynamic cutting force signals when proposing an on-line control method to suppress regenerative chatter vibration during the end milling process. Chatter vibration can degrade the surface finish during machining (Lin & Chang, 1998). Therefore, by proposing methods to control or eliminate chatter in machining, we also consider improving surface finish. However, this method of chatter control has some drawbacks. While speed regulation can suppress chatter caused by the identified chatter frequency, it may excite another frequency where chatter will be experienced.

Accelerometer

The presence of chatter and forced vibrations can be detected by an accelerometer (Altintas & Munasinghe, 1996). Accelerometers are commonly attached to the spindle head, just above the chuck. However, when the workpiece is significantly more flexible that the spindle structure, the localized vibrations in the cutting zone may not be transmitted to the accelerometer attached to the head.

Lin, DeVor, and Kappoor (1990) used an accelerometer to measure acceleration signals experienced in a workpiece when investigating the use of variable speed cutting for vibration control in the face milling process. Ismall, Elbestawi, Du, and Urbasik (1993), You and Ehmann (1991), and Montgomery and Altintas (1991) used an accelerometer to collect vibration data to develop a surface topography model. This model was used to simulate the surface profile generated after end milling operations and to study the effects of vibration on the surface finish profile. The surface topography simulation model incorporated the effects of tool geometry, cutting parameters, and relative motion between the cutting tool and the workpiece on the surface finish profile. It was found that runout and tool dynamics significantly affect the characteristics of the machined surface finish (Lin & Chang, 1998).

Accelerometers produce electrical signals that are representative of energy that exists in the machining process. The force acting on the measuring element (accelerometer) is proportional to the acceleration in accordance with Newton's first law: $F = MA$. An electrical signal is produced proportional to the force (and hence the acceleration).

Principle of an Accelerometer

Vibration is defined as a small oscillation about some equilibrium point. One way to describe the amplitude of vibration is through the use of acceleration levels. Using a rod and piston as an example, the maximum acceleration occurs at the top and at the bottom of the stroke, + and – , respectively. At each of these two extremes, the piston must decelerate to a stop and then accelerate in either a downward or an upward direction. This acceleration exerts a force on the rod; force is greatest when the piston is changing direction. F = MA, where F represents force, M represents mass, and A represents acceleration (Figure 2.1). Acceleration is a maximum negative value at the top and a maximum positive value at the bottom. Acceleration is experienced throughout the system, except where the centerline of the piston crosses the 0 center point of travel (Goldman, 1991).

To explain further how this vibration is measured by an accelerometer, the principle of the accelerometer is discussed. Consider a body of mass *m* attached to a vibrating surface through a spring and damper, as shown in Figure 2.2.

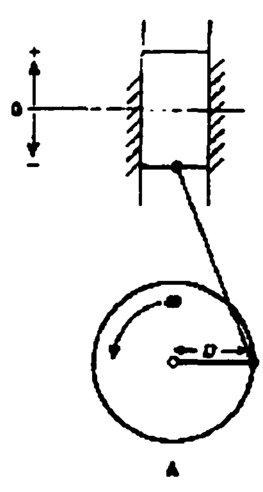
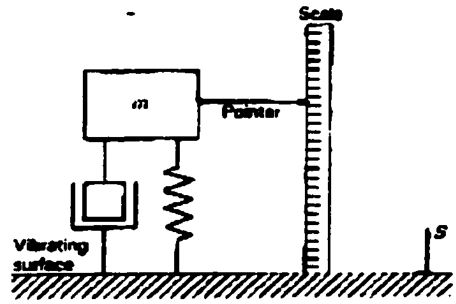


Figure 2.1. Piston and rod (Goldman, 1991)



Principle of an accelerometer.

Figure 2.2. Principle of an accelerometer
(Anderson & Bratos-Anderson, 1987)

Assume that the vibrating surface, or base, has a displacement of amplitude S and an acceleration amplitude $S\omega^2$, which is being measured. A scale is attached to the base and moves with it. A pointer is rigidly attached to the mass and moves over the scale. Thus, the pointer, as it moves over the scale, will indicate the relative displacement z (with amplitude Z) of the body relative to the base. This can be expressed in the following equation:

$$Z/(S\omega^2) = (1/\omega_n^2)/[\{1-(\omega/\omega_n)^2\}^2 + (2\xi\omega/\omega_n)^2]^{0.5} \qquad 2.2$$

where Z = amplitude corresponding to relative displacement z;

$S\omega^2$ = acceleration amplitude;

ω_n = undamped circular natural frequency or angular frequency;

ω/ω_n = ratio of angular velocity and undamped circular natural frequency; and

ξ= damping ratio.

When the ratio ω/ω^2 is small, the ratio of $Z/(S\omega^2)$ is almost constant and independent of frequency and damping ratio. Under this condition, the amplitude of the relative displacement Z is proportional to the acceleration amplitude of the base. In general, it may be said that the instantaneous displacement z is proportional to the acceleration of the base. When Z is measured, a quantity proportional to the amplitude of the base acceleration is obtained. Once the right-hand side of the equation is known, the amplitude of the base acceleration is known; therefore, provided that the frequencies of base vibration are much less than the resonant frequency, a single constant may be used to relate z to the acceleration of the base. This constant can relate to voltage as is explained further.

As the body of mass *m* vibrates relative to the base of accelerometer, the piezo-electric discs come under pressure. It is a property of piezo-electric materials that when they are under changing pressure in this way, an output voltage is self-generated by the material. This output voltage is proportional to *z* and is equivalent to the pointer displacement on the scale as shown in Figure 2.2 (Anderson & Bratos-Anderson, 1987).

Multiple Regression Statistics

Multiple regression (MR) is a statistical technique used to examine the relationship between two or more predictor variables (PVs) and a criterion variable (CV). Simple linear regression is limited to a single predictor variable. Predictor variables (a.k.a. independent variables) are variables that the researcher can manipulate or have some control over. Some general examples of PVs are gender, trial duration, or drug exposure. Criterion variables (a.k.a. dependent variables) are variables measured during an experiment. Some general examples of CVs are reaction time, math scores, or heart rate.

When the criterion variable is studied as a function of the predictor variables, MR can be employed. Multiple regression is used to determine a linear relationship between variables that can be used in prediction and explanation. For example, if one is interested in examining the relationship that gender and age (PVs) have with an individual's income (CV), MR would be an appropriate technique for analysis. The model used for multiple regression is:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots + \beta_{h-1} X_{i,h-1} + \varepsilon_i \quad (i,\ldots,N), \qquad 2.3$$

where

Y_i	is the value of the dependent variable for experimental unit i;
$\beta_0,\ldots,\beta_{h-1}$	are the partial regression coefficients;
$X_{i1},\ldots,X_{i,h-1}$	are the independent variables; and
ε_i	the random error term, with mean equal to zero and variance equal to σ_ε^2.

More about the model:

- The observed value of Y_i is the sum of two components: the constant predictor term, $\beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots + \beta_{h-1} X_{i,h-1}$, plus the random error term, ε_i. The error term represents the amount of contribution not accounted for by the independent variables.
- If the independent variables are quantitative, the unknown parameter can be interpreted as follows: the parameter β_0 is the Y intercept of the regression line. $\beta_0,\ldots,\beta_{h-1}$ are partial regression coefficients applied to the X_{ij}'s to predict Y_i.

The effects of an important variable cannot be controlled, for if it is omitted from the model that model is incorrectly specified. Interpretation of the results is misleading. Some predictors might get credit for having a strong relationship with the dependent variable, when, in fact, the omitted variable is the true causal factor.

At the same time, the model cannot be overloaded with too many variables. The number of variables in the model affects the likelihood of rejecting the null hypothesis: more variables in the model means that a larger *F*-score (and, therefore, a larger proportion of explained variance) is needed to achieve statistical significance. Too many unrelated variables in the model might lead to a type-II error (failing to reject a significant hypothesis) (Freund, 1984; Lane, 1999).

Fuzzy Logic

The theorem of fuzzy sets and fuzzy logic was first introduced in the 1960s by Lotfi Zadeh, professor of electrical engineering and computer science at Berkeley. Fuzzy sets and fuzzy logic are powerful mathematical tools for modeling uncertain systems in industry, nature, and humanity, and facilitators for common-sense reasoning in decision-making in the absence of complete and precise information.

Fuzzy logic is a departure from classical two-valued sets and logic, in that it uses "soft" linguistic (e.g., large, hot, tall) system variables and a continuous range of truth values in the interval [0,1], rather than strict binary (True or False) decisions and assignments (Bonde, 1996). The fuzzy system provides systematic mathematical expressions to interpret this information linguistically, and it performs numerical computation by using linguistic labels stipulated by membership functions. A selection of fuzzy IF-THEN rules forms the key component of a fuzzy inference system that can model human expertise effectively in a specific application (Jang, Sun, & Mizutani, 1997). Fuzzy rule-based systems apply IF-THEN rules to solve many types of "real-world" problems, especially where a system is difficult to model or is controlled by a human operator or expert, or where ambiguity or vagueness is common

A typical fuzzy logic system consists of a fuzzifier, fuzzy rule base, fuzzy inference engine, and a defuzzifier, depicted in Figure 2.3. This fuzzy logic system is often called the fuzzy logic controller, since it has been used mainly as a controller for decision-making systems. It was first proposed by Mamdani (1974) and has been applied successfully to a variety of industrial processes and consumer products. The fuzzy logic system has many attractive features:

- It is suitable for engineering systems because its inputs and outputs are real-valued variables;
- It provides a natural framework to incorporate fuzzy IF-THEN rules from human experts; and
- There is much freedom in the choices of fuzzifier, fuzzy inference engine, and defuzzifier (Wang, 1994).

Fuzzy Nets

Neural networks are useful for estimating nonlinear mapping and fuzzy logic is useful for controlling complex systems. In a dynamic platform, it is difficult to obtain a fuzzy rule bank from experts for an intelligent machining control system. Fuzzy-nets is a method proposed to overcome this limitation of neural networks and fuzzy logic. Fuzzy-nets systems combine the learning capability of neural networks with the reasoning capability of fuzzy logic (Chen & Lin, 1997).

Summary

This literature review provided an overview of the surface characteristics, milling operation, on-line or off-line monitoring, direct or indirect measurement, sensors, surface recognition techniques, multiple regression models, and the fuzzy logic system. This review sought to bring forward the importance of surface quality. The quality of a finished surface plays an significant role in milling, since a high-quality milled surface improves fatigue life, wear, contact stress distribution, paintability, and reduces contact surface friction.

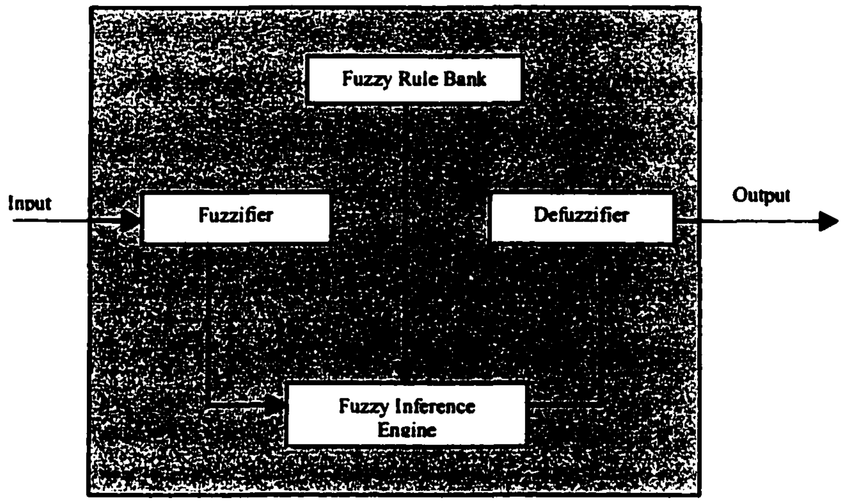


Figure 2.3. Structure of fuzzy logic controller

Since many factors, such as feed rate, spindle speed, tool type, work material, and vibration, influence surface quality, each factor is studied in this research.

According to previous reviews, research involving the combination of the end milling process while using multiple tools and work materials to develop an on-line surface recognition system was not identified. Through the review of sensors, the accelerometer appeared to provide the most feasible method for collecting vibration data experience in the milling process, and was thus used in this research. Fuzzy net was chosen as the decision making technique which will model the machine process. Fuzzy nets is capable of modeling linear and nonlinear systems by combining experimental and human expert input to develop the decision-making rule base.

CHAPTER III. METHODOLOGY

The methodologies used to conduct this research include: a hardware setup to collect data on-line and with an in-process system, sensors used for monitoring the machining process, an A/D converter connection, and C programming used for communication and interpretation of the machining data. The experimental setup using the Taguchi experimental design is also explained, along with the validation of a fuzzy net and statistical model used to develop a robust online surface prediction system in end milling. This chapter addresses the relationship between each of these research components needed in order to conduct this study; thus, the details of these methods are presented in this chapter.

Hardware Setup

In any study, equipment and hardware play critical roles in conducting a viable experiment and collecting results consistent with the purpose of the study. A fundamental understanding of computer/machining equipment and data acquisition devices, which include proximity sensors, accelerometers, and signal converters (i.e., analog to digital or digital to analog), is important in understanding the activities conducted in this research. Accordingly, this section describes the hardware and its use in this research.

All machining was done in a Fadal VMC-40 vertical machining center with multiple tool-change capability. This machine is capable of three-axis movement (along the x, y, and z planes). Programs can be developed in the VMC cpu or downloaded from a 3 ½" diskette or data link. Information was collected using of a 353B33 accelerometer and a Micro Switch 922 Series 3-wire DC proximity sensor. The accelerometer was used to collect vibration data generated by the cutting action of the work tool. The proximity sensor was used to count the rotations of the spindle as the tool is cutting. The proximity information then was graphed along with the accelerometer data, which enabled the identification of vibrations produced during different phases of the cutting sequence. Data from both sensors were converted from analog to digital signals through an Omega CIO-DAS-1602/12 A/D converter. The A/D converter-output was connected to a Pentium I personal computer via an I/O interface (Figure 3.1).

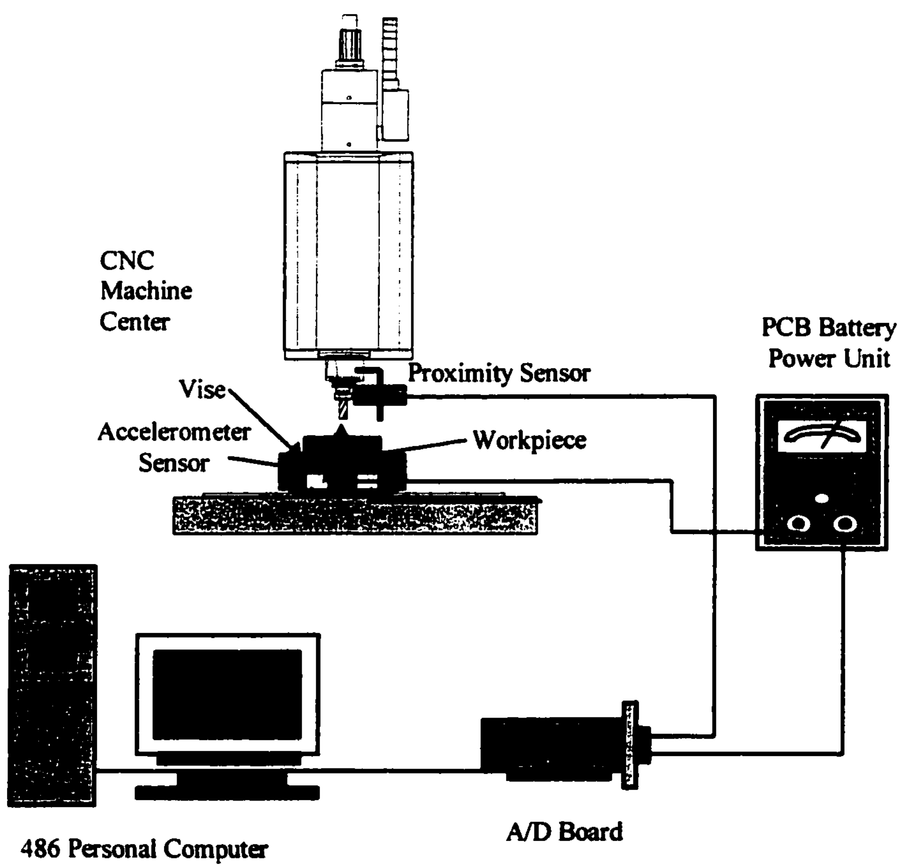


Figure 3.1. Hardware setup

Two power supplies were used. One power supply was used to amplify the signal from the accelerometer. This amplified signal was then sent to the A/D board. The second power supply was used to power the proximity sensor and circuitry. A signal was produced during the switched phase of the proximity sensor. This signal was sent to the A/D board on a separate channel from the one used for the accelerometer signal.

The workpiece material used in this research was 6061 aluminum and 1018 steel blocks. The blocks were be cut 1.00" x 1.00" x 1.00". Various feed and spindle speeds, depths of cut, work materials, tool materials and types, and tool diameters were tested.

A stylus profilometer was used off-line to measure the surface roughness value of the machined samples. This instrument uses a tracer or pickup incorporating a diamond stylus and a transducer able to generate electrical signals as it moves across the surface to be measured (Lou & Chen, 1997). The surface finish measurements were made off-line with the roughness average Ra values rated in microinches (μi).

Software Setup

The software setup consisted of a CNC machining program, an A/D converting program, a rotational average calculation program, an experimental rule base generation program, and an Ra recognition program. The CNC machining program was written for cutting the work pieces at different spindle speeds, feed rates, and depths of cut. The A/D converting program was developed in C programming language. The rotational average calculation program calculated the vibration average per revolution. The rule base for each design was developed by the rule base program and from expert input.

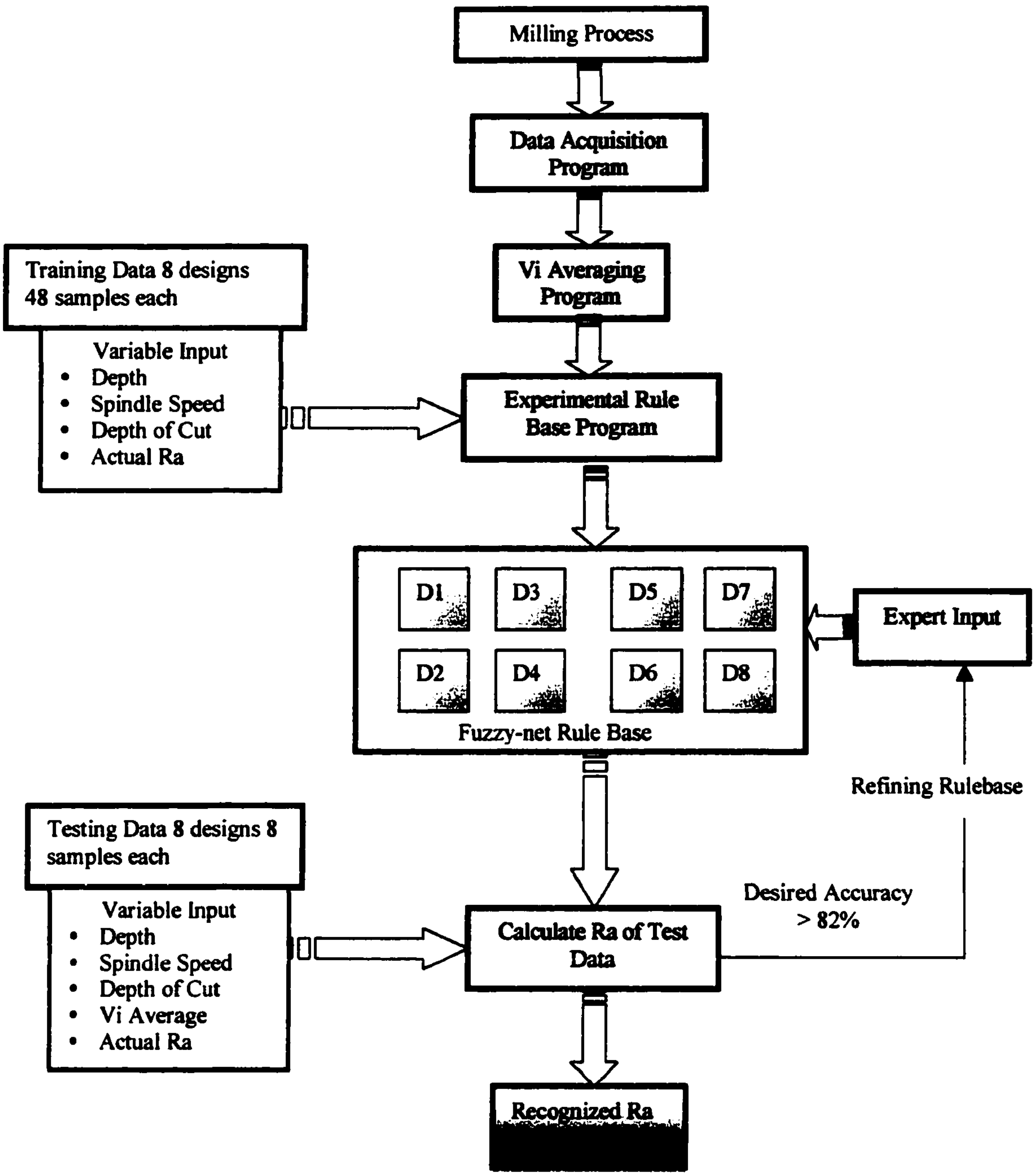


Figure 3.2. Software setup

The Ra recognition program integrates the combined rule base and testing data to calculate a new Ra value (Figure 3.2). The combined rule base was refined until the accuracy of the fuzzy net model exceeded that of the multiple regression model.

Stage One: Evaluate the Effects of Tool Size

The purpose of stage one was to evaluate tool diameter as a contributing factor to surface roughness. For stage one, spindle speed, depth of cut, and type of work material remains constant. Three tool diameters were evaluated independently of tool design. Each of the three tools used in stage one was a four-flute high-speed steel (HSS) design. The tools were three different sizes: 0.5", 0.75", and 1.00". At a spindle speed of 2000 RPM, 0.01" was used for depth of cut on 6061 aluminum blocks, which comprised the workpiece material for all trials. The diameters of tools under study were determined by what is most commonly used in industry (see Appendix F). Feed rate was also evaluated at three experimental levels that were determined by the researcher as a good range of speeds to be evaluated. Feed-rates of 10, 20, and 30 ipm are used as experimental levels for feed-rate.

Two factors being tested at multiple levels are feed rate and tool diameter. Vibration and Ra data are collected and recorded separately in a table.

The experimental model used in this study was a 3×3 design. The experimental trials were grouped by tool diameter with the experimental runs completed according to this grouping.

Figure 3.3 shows an example of the proximity and accelerometer data collected from a pilot trial with 1.00" cutting tool at a feed rate of 20 ipm. The square line represents the revolution proximity data and the erratic line represents the vibration data. The arrow line indicates the range of one revolution. The average of all the absolute values from vibration data were collected for statistical analysis. Five average values were collected for repetitions in this experiment. The following equation indicates the method of calculating the three average vibration data:

$$V_i = \sum_{j=(i-1)*k}^{i*k} |Vibration(j)| / k, \quad i=1,2,and\,3., \tag{3.1}$$

where k represents the total number of data in each revolution (as indicated in Figure 3.1). For example, if i = 1, then the V_i was calculated through the vibration data points from point number 0 to point number k (to have a total of k data in one revolution). Vibration (V_i) was measured in units of voltage (Figure 3.3).

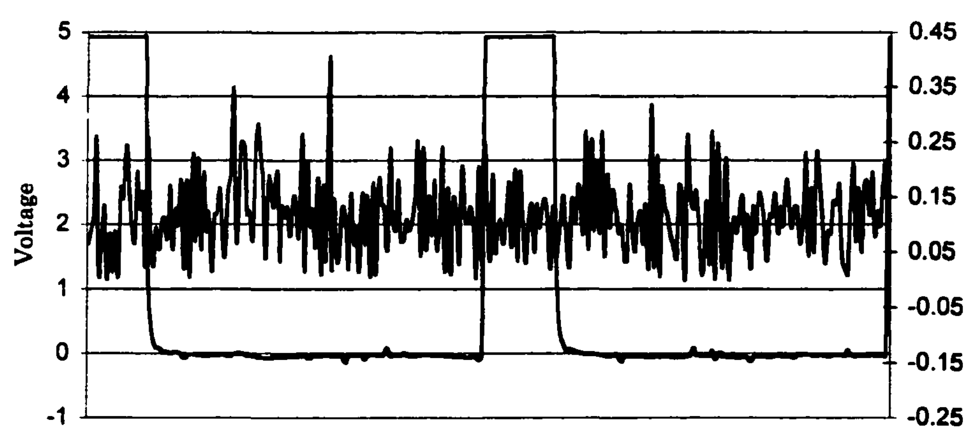


Figure 3.3. Sample vibration and proximity signal

Stage Two: Taguchi Approach to Determine Significant Factors

The Taguchi experimental design approach was used in stage two of the study. The Taguchi approach simplifies the number of runs necessary when determining the significant effect of independent variables. The dependent variables in stage two were the same as in stage one, R_a and V_i; however, the constant independent variables used in stage one were tested at different treatment levels. Work material type, spindle speed, depth of cut, feed rate, and tool material type were tested at two levels. The two work materials used were aluminum 6061 and 1018 steel. At spindle speeds of 1500 and 2000 revolutions per minute, 0.01" and 0.03" were used for depths of cut. Using cutter feed speeds of 8" and 16" per minute, high-speed steel (HSS) and carbide were used as the two tool material types. Tool diameter was the only factor to remain fixed at 0.75". An L16 orthogonal array was used to set up testing parameters for each sample run. This design accommodates five main effects and 10 two-way interactions for a total of 15 DOF, the maximum that can be assigned to an L16 without confounding. When the factors are assigned to columns A, B, C, D, and E, the resulting design is equivalent to a 2^{5-1} fractional factorial (Fowlkes & Creveling, 1995) (Table 3.1). The factor column assignment is shown in Table 3.2.

Stage Three: Multiple Regression-Based M-OSRR Model

The Statistical Package for the Social Sciences (SPSS) version. 8.0 software was used for computation and in the development of the multiple regression model. In developing the multiple regression model, the significant factors determined from stages one and two were entered into the model.

Table 3.1. L16 experimental design matrix

RUN	1 A	2 B	3	4 C	5	6	7	8 D	9	10	11	12	13	14	15 E
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
3	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2
4	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
5	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2
6	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1
7	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1
8	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2
9	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
10	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1
11	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1
12	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2
13	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1
14	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2
15	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2
16	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1
			1X2		1X4	2X4	8X15		1X8	2X8	4X15	4X8	2X15	1X15	

Table 3.2. Experimental design layout

Run	**Tool** **A**	**Matl** **B**	**3**	**Spin** **C**	**5**	**6**	**7**	**Feed** **D**	**9**	**10**	**11**	**12**	**13**	**14**	**Dep** **E**
1	HSS	Al	1	1500	1	1	1	8	1	1	1	1	1	1	0.01
2	HSS	Al	1	1500	1	1	1	16	2	2	2	2	2	2	0.03
3	HSS	Al	1	2000	2	2	2	8	1	1	1	2	2	2	0.03
4	HSS	Al	1	2000	2	2	2	16	2	2	2	1	1	1	0.01
5	HSS	S	2	1500	1	2	2	8	1	2	2	1	1	2	0.03
6	HSS	S	2	1500	1	2	2	16	2	1	1	2	2	1	0.01
7	HSS	S	2	2000	2	1	1	8	1	2	2	2	2	1	0.01
8	HSS	S	2	2000	2	1	1	16	2	1	1	1	1	2	0.03
9	Carb	Al	2	1500	2	1	2	8	2	1	2	1	2	1	0.03
10	Carb	Al	2	1500	2	1	2	16	1	2	1	2	1	2	0.01
11	Carb	Al	2	2000	1	2	1	8	2	1	2	2	1	2	0.01
12	Carb	Al	2	2000	1	2	1	16	1	2	1	1	2	1	0.03
13	Carb	S	1	1500	2	2	1	8	2	2	1	1	2	2	0.01
14	Carb	S	1	1500	2	2	1	16	1	1	2	2	1	1	0.03
15	Carb	S	1	2000	1	1	2	8	2	2	1	2	1	1	0.03
16	Carb	S	1	2000	1	1	2	16	1	1	2	1	2	2	0.01
			1x2		1x4	2x4	8x15		1x8	2x8	4x15	4x8	2x15	1x15	

Research by Lou and Chen (1997) proposed four steps to conduct a multiple regression analysis.

1. Determine the regression model. The multiple regression equation is (Kirk, 1995):

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots + \beta_{h-1} X_{i,h-1} + \varepsilon_i \quad (i, \ldots, N) \tag{3.2}$$

where Y_i= the predicted R_a value, $\beta_0,\ldots,\beta_{h-1}$ are the partial regression coefficients, $X_{i1},\ldots,X_{i,hi}$ are the independent variables, and ε_i is the random error term with mean equal to zero and variance equal to σ_ε^2. Estimation of the parameters will be done by the least squares method.

2. Determine *R*, R^2, Adjusted R^2 The multiple correlation coefficient *R* is a Pearson product-moment correlation coefficient between the criterion variable Y and the predicted score on the criterion variable, $\hat{Y}$. *R* can be expressed as:

$$R_{Y \cdot 1,2 \ldots K} = \sqrt{\beta_1 r_{Y1} + \beta_2 r_{Y2} + \ldots + \beta_K r_{YK}} = R_{y\hat{y}} . \tag{3.3}$$

This expression means that the square root of the sum of the products of beta coefficients multiplied by the correlations between the criterion variable and the respective predictors variable is equal to *R*. The proportion of the variation in the criterion variable that can be attributed to the variation of the combined predictor variables is represented by the square of the multiple correlation coefficient, or R^2. The sample *R*-squared value tends to estimate optimistically how well the models fits the population. The model usually does not fit the population as well as it fits the sample from which it is derived. Adjusted *R*-squared attempts to correct *R*-squared to reflect more closely the goodness of fit of the model in the population.

3. Determine whether the value of multiple R is statistically significant. For multiple correlation, one can test the null hypothesis H_o: $R = 0$. An F statistic can be used to test this hypothesis by

$$F = \frac{R^2/k^2}{(1-R^2)/(n-k-1)}, \tag{3.4}$$

where R = the multiple correlation coefficient and k = the number of predictor variables. If the computed value of F exceeds the critical value of F for a given level of significance, then H_o: $R = 0$ is rejected. This result would support the conclusion that there is a nonzero relationship between the dependent and independent variables.

4. Determine the significance of the predictor variables. The regression coefficient β_i can be tested for statistical significance by the t value

$$t = \frac{\beta_i}{S_{\beta i}}, \tag{3.5}$$

where β_i = the regression coefficient and $S_{\beta i}$ = the standard error of the respective coefficient. If the computed value of t exceeds the critical value of t for a given level of significance, the null hypothesis is rejected and it can be concluded that the population partial regression coefficient for the predictor variable is not zero.

The proposed multiple regression model for this study was derived after significant factors were determined from stages one and two. In this model, the dependent variable was the surface roughness average value, R_a (Yi). The structure of the multiple regression, multiple on-line surface roughness recognition (MR-MOSRR) model is depicted in Figure 3.4.

The seven independent variables were (F) feed rate (X_{1i}), (D) depth of cut (X_{2i}), (S) spindle speed (X_{3i}), and (V) vibration average per revolution (X_{4i}) of the accelerometer sensor (see formula 3.0), (TD) tool diameter (CX_{1i}), (TM) tool material (CX_{2i}), and (WM) work material (CX_{3i}). The regression equation for each design does not include TD, TM, or WM. These are categorical variables and can not be used as predictors. The proposed multiple regression model is a two-way interaction equation:

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \beta_4 X_{4i} + \beta_5 X_{1i} X_{2i} + \beta_6 X_{1i} X_{3i} + \beta_7 X_{1i} X_4 + \beta_8 X_{2i} X_{3i} + \beta_9 X_{2i} X_{4i} + \beta_{10} X_{3i} X_{4i} + \varepsilon_i .$$

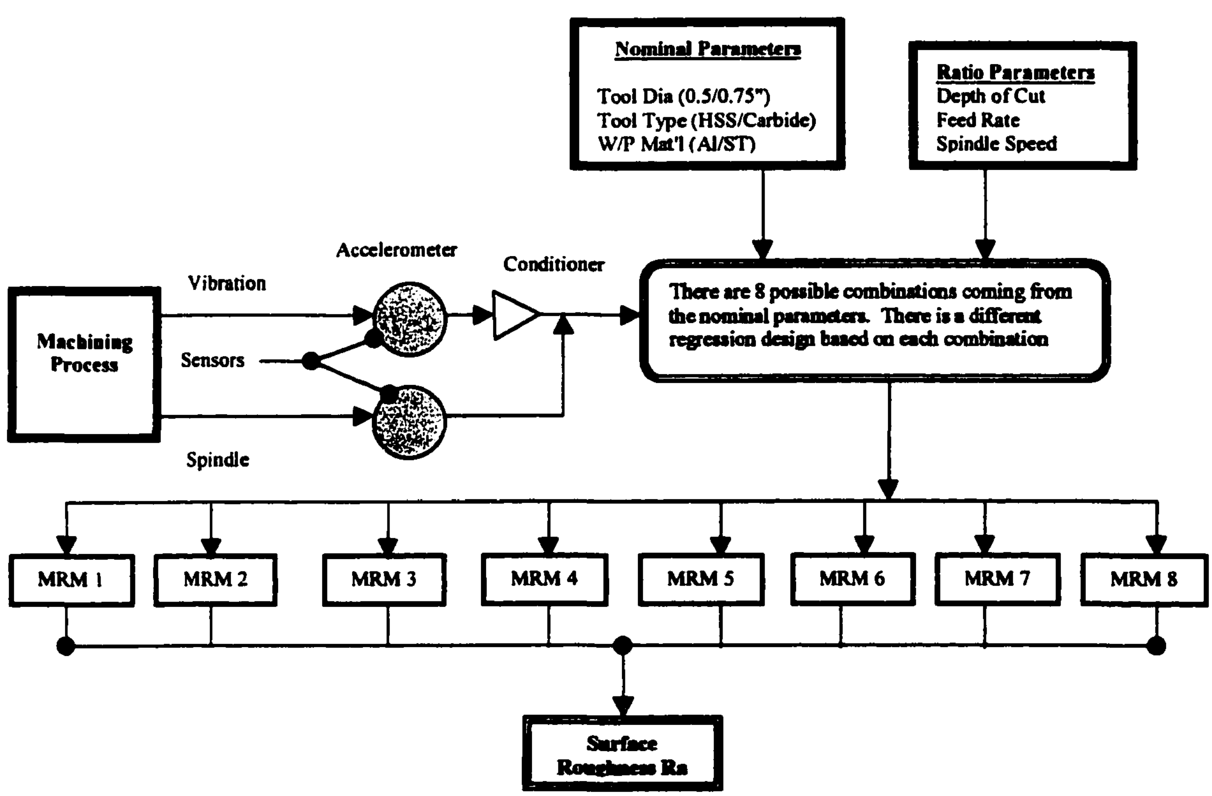


Figure 3.4. Structure of the MR-MOSRR model

Stage Four: FuzzyNet-Based M-OSRR Model

The steps for developing a fuzzy model are as follows

1. *Divide the Input Space into Fuzzy Regions (membership function MF).* Input factors were the same significant independent factors from stages 1 and 2 which were entered into the regression model. In this study, the input variables were feed rate (F), spindle speed (S), depth of cut (D), and vibration average per revolution (V). The output variable was the surface roughness, Ra.

The input-output space is $X_F\, X_S\, X_D\, X_V\, Y_{Ra}$. The factors and their ranges are as follows:

INPUTS

Tool diameter: two values CX_{11} & CX_{12} (Crisp model)

Tool material: has two values Carbide CX_{21} & High Speed Steel CX_{22} (Crisp model)

Work material: two values Aluminum CX_{31}& Steel CX_{32} (Crisp model)

Feed Speed: $X_1 \in [5,19]$ inches/min

3 MFs regions for X_1 are denoted by

Slow (S1), Medium (MD), Fast (L1)

Depth of Cut: $X_2 \in$ [0.005",0.039"] in inches

3 MFs regions for X_2 are denoted by

Shallow (S1), Medium (MD), Deep (L1)

Spindle Speed: $X_3 \in [1400,2100]$ rev/min

3MFs regions for X_3 are denoted by.

Slow (S1), Medium (MD), Fast (L1)

Average Vibration: $X_4 \in [X_{4,min}, X_{4,max}]$ micro-volts where $X_{4,min}$ and $X_{4,max}$ were obtained from experimental results

5 MFs regions of X_4 are denoted by:

Low (S2), Medium Low (S1),

Medium (MD), Medium High (L1), High (L2)

OUTPUT

R_a: $Y_i \in [Y_{i,min}, Y_{i,max}]$ in micro-inches where $Y_{i,min}$ and $Y_{i,max}$ were obtained from experimental results

7 MFs of Y_i are denoted by:

High-quality polished finish (S3), Fine (S2), Medium fine (S1)

Medium (MD) Medium course (L1), Course (L2), Low quality finish grit (L3)

A triangular membership function specified by three parameters {a,b,c} was employed as follows:

$$\text{Triangle}(x; a,b,c) = \begin{cases} 0 & x \le a \\ \dfrac{x-a}{b-a} & a \le x \le b \\ \dfrac{c-x}{c-b} & b \le x \le c \\ 0 & c \le x \end{cases} \tag{3.6}$$

The spread of the input feature $$s = \frac{x_i^+ - x_i^-}{2N} \quad (i = 1,2,\dots, k) \tag{3.7}$$

Where x_i^+ and x_i^- are the domain intervals of variable x_i, $x_i \in X_i$. There are 2N+1 fuzzy regions quantizing the universe of discourse X_i. Figure 3.5 depicts the domain interval of the input-output variable.

The center points of each linguistic variable are

$$(x_i^-, x_i^- + s, \ldots, x_i^- + (2N-1)s, x_i^+) \qquad (3.8)$$

2. *Generate fuzzy rules from given data pairs through experimentation:*

   1. Determine the degree of input-output data obtained from the successful experiment.
   2. Design input-output pairs to regions with a maximum degree.
   3. Obtain one rule from one pair of designed input-output data.

   In this study, the input-output pairs for the fuzzy model are

$$[F^i, S^i, D^i, V^i, Ra^i], \qquad (3.9)$$

   where *i* denotes the number of input-output pairs.

   1. The degrees of each pair were determined by the function:

      where x_c is the center of the linguistic level x and x_s is the width of the linguistic level x and equal to s.

$$\mu(x_i) = \begin{cases} 1 - \dfrac{|x_i - x_c|}{x_s}, x_i \in [x_c, x_c + x_s] \\ 1 - \dfrac{|x_c - x_i|}{x_s}, x_i \in [x_c - x_s, x_c] \\ 0, \quad \textit{otherwise} \end{cases} \qquad (3.10)$$

   2. After all input and output elements are determined, each element is assigned to the region with the maximum degree.

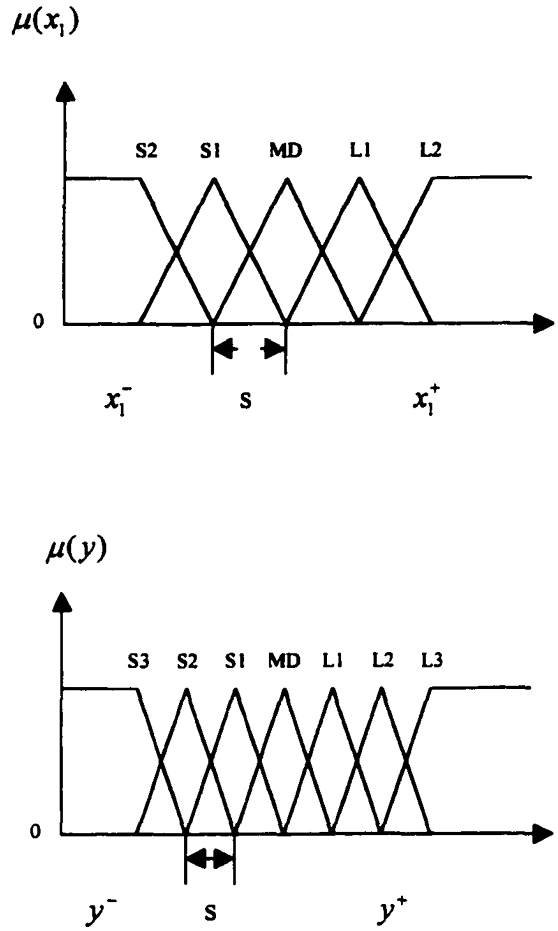


Figure 3.5. The domain interval of the input-output variable and triangular membership function (Wang, 1994)

3. One rule from one pair of the desired input-output pairs is also assigned. For example, the degree of one input-output pair: [F1, S1, D1, V1, R_a1] was determined by (3.10) as:

$$\mu(F^1) = \{0.9 \in L1, 0.1 \in L2\}$$
$$\mu(S^1) = \{0.6 \in S1, 0.4 \in S2\}$$
$$\mu(D^1) = \{0.8 \in MD, 0.2 \in S1\}$$
$$\mu(V^1) = \{0.3 \in L1, 0.7 \in MD\}$$
$$\mu(Ra^1) = \{0.7 \in S3, 0.3 \in S2\}$$

The region of each variable with the maximum degree is:

$$F^1 \in L1, S^1 \in S1, D^1 \in MD, V^1 \in MD, Ra^1 \in S3$$

It would then follow that rule one is:

IF F^1 is L1 and S^1 is S1 and D^1 is MD and V^1 is MD THEN Ra^1 is S3

3. *Assign a degree to each rule and resolve conflicting rules.*

Two rules are considered to be conflicting when they have the same IF condition but different THEN actions. An example

IF feed speed is S1 and spindle speed is MD and depth of cut is L2 THEN Ra is L2

IF feed speed is S1 and spindle speed is MD and depth of cut is L2 THEN Ra is L3

This can also be expressed as:

Rule i = IF {X_1 = S1, X_2 = MD, X_3 = L2} THEN {Y= L2}

Rule j = IF {X_1 = S1, X_2 = MD, X_3 = L2} THEN {Y = L3}

To resolve this conflict, consider the number of 'n' occurrences of Rule "i" and 'm' occurrences of Rule "j." When all rules have been determined from the training data, the following condition of $n > m$ will be checked. If this statement is true, then rule "i" will be the resulting rule for the condition [{X_1 = S1, X_2 = MD, X_3 = L2} then {Y = L2}] and will be added to the rule bank. The condition of Rule "j" will be discarded. If $n < m$ is true, then rule "j" will be the resulting rule. When $n = m$, the output membership function $\mu(y_i)$ will be increased until the conflict can be resolved by the aforementioned procedure.

4. *Create a combined rule base*

A combined rule base consists of two kinds of rules: rules generated from numerical data by means of step 1-3, and linguistic rules determined by a human expert.

5. *Defuzzification*

Defuzzification is a method used to obtain a crisp value extracted from a fuzzy set as a representative value. Methods used in defuzzification are centroid of area, maximum selector, and minimum selector (Chen & Lin, 1997). In this study, the centroid of area method will be applied:

$$y = \frac{\sum \mu_o^i y^i}{\sum \mu_o^i} \tag{3.11}$$

where $\mu_o^i = \min\{\mu(X_1^i), \mu(X_2^i), \ldots, \mu(X_n^i)\}$, $y^i =$ the center value of regions, and y = the output for a given input datum. This is the most widely-adopted defuzzification strategy, and is reminiscent of the calculation of expression values of probability distributions. The fuzzy model is depicted in Figure 3.6.

Stage Five: Accuracy of the Regression Model vs. the Fuzzy Model

Accuracy of the regression model was compared with the accuracy of the fuzzy model. The model resulting in an Ra value that deviates the least from the actual Ra value is regarded as the most robust surface roughness prediction model.

Percentage deviation was the criterion used in this study to judge the prediction efficiency of the multiple regression model ($\bar{\bar{\phi}}_{MR}$) and the fuzzy-net model ($\bar{\bar{\phi}}_{FL}$). To obtain these values, there are three steps:

Step 1. There were 8 test data within each design *j*. Each testing sample data has one Ra'_{iMR} which is Ra recognized by multiple regression model, and one Ra'_{iFL} Ra value recognized by fuzzy net model.

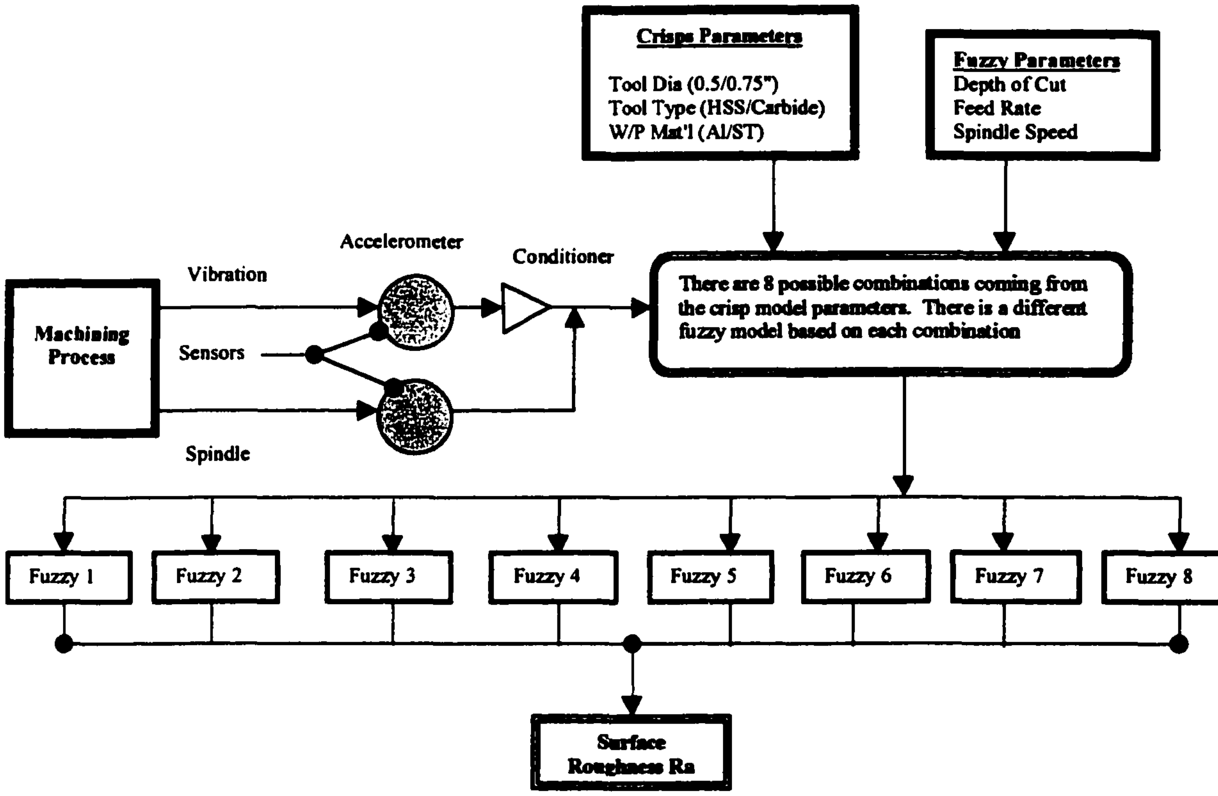


Figure 3.6. Illustration of Crisp-Fuzzy M-OSRR system model

The surface of each test work piece was measured using a profilometer to obtain an actual Ra (Ra_i). Therefore, the deviation of each testing sample (ϕ_k) was defined as:

$$\phi_{kMR} = \frac{|Ra_i - Ra'_{iMR}|}{Ra_i} * 100\%, \text{ for regression model} \quad (3.12)$$

and where

$$\phi_{kFL} = \frac{|Ra_i - Ra'_{iFL}|}{Ra_i} * 100\%, \text{ for fuzzy net model} \quad (3.13)$$

Ra'_{iMR}: recognized Ra by multiple regression model;

Ra_i : actual R_a measured by a profilometer;

ϕ_{iMR} : percentage deviation for multiple regression model;

Ra'_{iFL} : recognized Ra by multiple regression model; and

ϕ_{iFL} : percentage deviation for multiple regression model.

Step 2: Identify the average of deviation of each design. Each design j, ϕ_{iFL} and ϕ_{iMR} was be summed and averaged to give average $\bar{\phi}_{jFL}$ for fuzzy net and $\bar{\phi}_{jMR}$ for multiple regression. The procedure is represented by formula 3.15

$$\bar{\phi}_{jMR} = \frac{\sum_{k=1}^{m} \phi_{kMR}}{m}, \text{ for regression model} \tag{3.14}$$

and

$$\bar{\phi}_{jFL} = \frac{\sum_{k=1}^{m} \phi_{kFL}}{m}, \text{ for fuzzy net model} \tag{3.15}$$

where

m: number of samples within each design (in this case, m equals 8).

Step 3: Identify the overall average for the average deviation for each model was considered the final accuracy of each model. This is given by:

$$\bar{\bar{\phi}}_{MR} = \frac{\sum_{j=1}^{n} \bar{\phi}_{jMR}}{n}, \text{ overall deviation of MR model} \tag{3.16}$$

$$\bar{\bar{\phi}}_{FL} = \frac{\sum_{j=1}^{n} \bar{\phi}_{jFL}}{n}, \text{ overall deviation of using fuzzy net model} \tag{3.17}$$

Table 3.3. Model accuracy

Design (j)	Design Configuration	Average Deviation for MR Model	Average Deviation for Fuzzy net Model	Samples (m)
1	$TD_1TM_1WM_1$	$\bar{\phi}_{1MR}$	$\bar{\phi}_{1FL}$	8
2	$TD_1TM_1WM_2$	$\bar{\phi}_{2MR}$	$\bar{\phi}_{2FL}$	8
3	$TD_1TM_2WM_1$	$\bar{\phi}_{3MR}$	$\bar{\phi}_{3FL}$	8
4	$TD_1TM_2WM_2$	$\bar{\phi}_{4MR}$	$\bar{\phi}_{4FL}$	8
5	$TD_2TM_1WM_1$	$\bar{\phi}_{5MR}$	$\bar{\phi}_{5FL}$	8
6	$TD_2TM_1WM_2$	$\bar{\phi}_{6MR}$	$\bar{\phi}_{6FL}$	8
7	$TD_2TM_2WM_1$	$\bar{\phi}_{7MR}$	$\bar{\phi}_{7FL}$	8
8	$TD_2TM_2WM_2$	$\bar{\phi}_{8MR}$	$\bar{\phi}_{8FL}$	8
Total *n=8*		$\bar{\bar{\phi}}_{MR} = \frac{\sum_{i=1}^{n} \bar{\phi}_{iMR}}{n}$	$\bar{\bar{\phi}}_{FL} = \frac{\sum_{i=1}^{n} \bar{\phi}_{iFL}}{n}$	64
Accuracy		$1 - \bar{\bar{\phi}}_{MR}$	$1 - \bar{\bar{\phi}}_{FL}$	

where n is the number of designs (in this case, n equal 8). The complete process is represented in Table 3.3.

Data Sample Size

Table 3.4 shows the parameters and settings of samples collected as training data for the fuzzy net model rule base. The sample size of this setup was determined by the multiplication of choices rule (Freund, 1984), which is:

$$n_1 * n_2 * \text{K } n_k = \# choices \quad (k = 3) \quad (3.18)$$

where k is the number of parameters and n is the number of settings of each k.

Table 3.4. Parameters and settings for the training data

Feed (ipm)	Depth (inches)	Rpm
8	0.01	1500
11	0.02	1667
14	0.03	1833
16		2000

The number of choices for feed was 4, for depth was 3, and for rpm was 4; hence there were 4 * 3 * 4 = 48 samples for each model.

The fuzzy net and multiple regression models each have 8 designs. The number of models was determined by equation 3.16. {3 crisp parameters; tool diameter (2 levels), tool material type (2 levels), and work material (2 levels) = 8 designs}. The total number of samples of training data collected for this study was 384. Testing data were collected in the same manner (Table 3.5). The number of choices for feed was 2, depth of cut was 2, and rpm was 2 which totaled 8 sample data. With 8 designs, the total number of sample data values needed for the testing model was 64.

Table 3.5. Parameters and settings for the testing data

Feed (ipm)	Depth (inches)	Rpm
10	0.015	1583
14	0.025	1917

Summary

This chapter details the procedures and methodology of completing this research. The purpose of this research was to develop a multi-level on-line surface roughness recognition system capable of providing real-time information about the machining process.

For surface roughness to be recognized in real time, a real-time source of information is required. This source is critical to the development of an on-line decision-making system. In this research, the accelerometer provides the vibration excitation response from the end milling process. The analysis and results are presented in chapter 4.

CHAPTER IV. ANALYSIS AND RESULTS

Stage One

The purpose of this stage was to evaluate tool diameter as a contributing factor to surface roughness. Spindle speed, depth of cut, and type of work material remained constant. Three tool diameters were evaluated independently of tool design. Each of the three tools used was a four-flute high-speed steel (HSS) design. The tools were three different sizes: 0.5", 0.75", and 1.00". At a spindle speed of 2000 RPM, 0.01" was used for depth of cut on 6061 aluminum blocks, which comprised the workpiece material for all trials. Feed rate also was evaluated at three experimental levels. Feed rates of 10, 20, and 30 ipm were used as experimental levels for feed rate.

Two factors that were tested at multiple levels were feed rate and tool diameter. Vibration and *Ra* data were collected and recorded separately. The experimental model used in this study is a 3×3 design. The trials were conducted in a non-random order, grouping trials according to tool diameter. Table 4.1 displays vibration data at each level of testing. This data is designated by *Vi*. Table 4.2 displays the *Ra* values measured by the surface profilometer.

Several analyses were run on the vibration and *Ra* data. In determining the effects of tool diameter and feed rate on vibration and surface roughness, a correlation table first was generated to identify the level of effect on the dependent variables, *Vi* and *Ra*. The results of the correlation table are shown in Table 4.3. According to the data, feed rate correlates most clearly with *Vi* (-0.435) and *Ra* (0.614). The tool diameter presents some correlation with both *Vi* (-0.192) and *Ra* (0.257), with diameter being inversely correlated with *Vi*.

Table 4.1. Average vibration data Vi

	FEED RATE, IPM			
TOOL SIZE	10	20	30	Tool Size Averages
0.5"	0.1918 0.1904 0.1868	0.1262 0.1225 0.1183	0.0396 0.0409 0.0426	.1177
0.75"	0.0614 0.0550 0.0566	0.1146 0.1018 0.1006	0.1444 0.1354 0.1247	.0994
1.00"	0.1250 0.1273 0.1224	0.1167 0.1107 0.1071	0.0543 0.0537 0.0530	.0967
Feed Rate Averages	.1241	.1132	.0765	

Table 4.2. Average surface roughness value Ra

	FEED RATE, IPM			
TOOL SIZE	10	20	30	Tool Size Averages
0.5"	42 42 45	29 31 31	53 54 54	42.33
0.75"	32 33 33	57 97 97	132 134 142	84.11
1.00"	50 51 52	55 56 56	79 80 83	62.44
Feed Rate Averages	42.22	56.55	90.11	

The result of R = -0.192 for tool diameter and vibration indicates that vibration experienced in the workpiece decreased as the tool diameter increased. The effect of tool diameter was more evident when the effect of feed rate is controlled as shown in table 4.4. Note that *Vi* (-0.2135) and *Ra* (0.3268) have slightly better correlation values with tool diameter.

Table 4.3. Partial correlation coefficients for diameter (2-tailed significance; $\alpha = .05$)

		Feed rate	Ra	Vi	Dia.
Feed rate	R		.614	-.435	
	P		.001	.023	
Ra	R	.614		.047	.258
	P	.001		.815	.194
Vi	R	-.435	.047		-.195
	P	.023	.815		.337
Dia.	R		.258	-.192	
	P		.194	.337	

Table 4.4. Partial correlation coefficients feed rate controlled for diameter (2-tailed significance; $\alpha = .05$)

	Vi	Ra
R	-.2725	.3268
P	.1780	.1030

The levels of significance for tool diameter and feed rate are listed in Tables 4.5 and 4.6. The null hypotheses H_{o1}, H_{o2}, H_{o3}, and H_{o4} are:

1. H_{o1}: $R_{a1} = R_{a2} = R_{a3}$;

   H_{a1}: $R_{a1} \neq R_{a2} \neq R_{a3}$,

   Where R_a denotes the average surface in microinches

2. H_{o2}: $V_{i1} = V_{i2} = V_{i3}$;

   H_{a2}: $V_{i1} \neq V_{i2} \neq V_{i3}$,

   Where *Vi* denotes the average vibration voltage measured in volts.

3. H_{o3}: $R_{a'1} = R_{a'2} = R_{a'3}$;

   H_{a3}: $R_{a'1} \neq R_{a'2} \neq R_{a'3}$, Where Ra', denotes the average surface value for the interaction tool diameter and feed rate.

4. H_{o4}: $V_{i'1} = V_{i'2} = V_{i'3}$;

H_{a4}: $V_{i'1} \neq V_{i'2} \neq V_{i'3}$,

Where *Vi'*, denotes the average vibration voltage for the interaction of tool diameter and feed rate.

From Table 4.5, surface roughness (*Ra*) was affected significantly by feed rate, tool diameter, and interaction of feed rate and tool diameter. The ANOVA with *Ra* as the dependent variable including feed rate and tool diameter as the independent variables had values for R^2 of .958 and .940 for the adjusted R^2. These results reject H_{o1} and H_{o3}.

Table 4.5. ANOVA for surface roughness (Ra)

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	26220.963	8	3277.620	51.571	.000
Intercept	107037.037	1	107037.037	1684.10	.000
FDSPEED	10874.296	2	5437.148	85.550	.000
DIA	7857.852	2	3928.926	61.819	.000
FDSPEED * DIA	7488.815	4	1872.204	29.458	.000
Error	1144	18	63.556		
Total	134402	27			
Corrected Total	27364.963	26			

From Table 4.6, feed rate, tool diameter, and the interaction of feed rate and tool diameter all were significant with respect to vibration. The ANOVA with *Vi* as the dependent variable including feed rate and tool diameter as the independent variables had values for R^2 of .991 and .987 for the adjusted R^2. These results reject H_{o2} and H_{o4}.

Table 4.6. ANOVA for vibration (Vi)

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	4.641E-02	8	5.802E-03	239.147	.000
Intercept	.339	1	.339	13976.84	.000
FDSPEED	2.171E-02	2	1.085E-02	447.401	.000
DIA	3.267E-03	2	1.633E-03	67.327	.000
FDSPEED * DIA	2.144E-02	4	5.360E-03	220.931	.000
Error	4.367E-04	18	2.426E-05		
Total	.386	27			
Corrected Total	4.685E-02	26			

Next, a linear regression equation was completed on the data. The regression analysis was done in two sets, one using *Vi* as the predicted value and the other using *Ra* as the predicted value. Results of the regression analysis procedure with *Ra* as the predicted value are shown in Tables 4.7 and 4.8. Table 4.7 displays the model summary for the independent variable entered into the regression model with *Ra* as the dependent variable. This model represents the variance associated with *Ra* contributed by tool diameter and feed rate. The dependent variable is *Ra* with the independent variables being the regression equation constant, tool diameter, and feed rate. The regression model with tool diameter and feed rate has a value for R of .666, R^2 of .444, and adjusted R^2 of .397. Table 4.8 is the ANOVA for *Ra* containing tool diameter and feed rate. The dependent variable is *Ra* with independent variables being the regression equation constant, tool diameter, and feed rate. After completing the ANOVA procedure of the regression model, the regression model proved to be significant. Table 4.9 displays the model summary for the independent variable entered into the regression model with *Vi* as the dependent variable. This model represents the variance associated with *Vi* contributed by tool diameter and feed rate. The dependent variable is vibration (*Vi*) with independent variables being the regression equation constant, tool diameter, and feed rate. The regression model with tool diameter and feed rate entered has values for R of .687, R^2 of .472 and adjusted R^2 of .428. Table 4.10 is the ANOVA for *Vi* containing tool diameter and feed rate. The dependent variable is *Ra* with independent variables being the regression equation constant, tool diameter, and feed rate. After completing the ANOVA procedure of the regression model, the model proved to be significant.

Table 4.7. Regression model for Ra

Model	Entered	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	Tool Diameter, Feed Rate	.666	.444	.397	25.1867

Table 4.8. ANOVA of regression model for Ra. $\alpha = .05$

Model		Sum of Squares	Df	Mean Square	F	Sig.
1	Regression	12140.111	2	6070.056	9.56	.001
	Residual	15224.852	23	634.369		
	Total	27364.963	26			

Table 4.9. Regression model for Vi

Model	Entered	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	Tool Diameter, Feed rate	.687	.472	.428	.0321

Table 4.10. ANOVA of regression model for Vi. $\alpha = .05$

Model		Sum of Squares	Df	Mean Square	F	Sig.
1	Regression	.02211	2	.01105	10.722	.000
	Residual	.02474	24	.00103		
	Total	.04685	26			

A Scheffe' multiple comparison procedure was completed from the vibration and profilometer data. When considering vibration data, the greatest significant difference exists between feed rates of 10 and 30 ipm (0.001*), with the second most significant difference existing between feed rates of 20 and 30 ipm (0.012*). When considering profilometer data, the most significant difference exists between feed rates of 10 and 30 ipm of (0.003*) with the second most significant difference existing between feed rates of 20 and 30 ipm of 0.040 ($\alpha = 0.05$).

Stage One Summary

The purpose of this section of the study was to identify significant effects of tool diameter on tool vibration and work-piece surface smoothness in end mill cutting. The data collected supports the significant effect of tool diameter on vibration generation and surface roughness. The researcher rejects H_{o2} as listed in chapter one. Work-piece vibration and surface smoothness were significantly affected by cutting tool feed rate. The interaction between tool diameter and feed rate did have a significant effect on *Ra* and *Vi*; however, the effect was contributed largely through the factors of the cutting tool feed rate. From the results of stage one, tool diameter was considered as a major contributing factor in the surface roughness recognition model.

Stage Two

The Taguchi experimental design approach was used in this stage. The Taguchi approach simplifies the number of runs necessary when determining the significant effect of independent variables. The dependent variables in stage two were the same as those in stage one, *Ra* and *Vi*; however, the constant independent variables used in stage one were tested at different treatment levels. Work-material type, spindle speed, depth of cut, feed rate, and tool material type were tested at two levels. The two work-materials used were aluminum 6061 and 1018 steel. At spindle speeds of 1500 and 2000 revolutions per minute, 0.01" and 0.03" were used for depths of cut. Using cutter feed speeds of 8" and 16" per minute, high-speed steel (HSS) and carbide were used as the two tool material types. Tool diameter was the only factor to remain fixed at 0.75".

An L16 orthogonal array was used to set up testing parameters for each sample run. Experimental runs were conducted according to design layout in Table 3.2. The *Ra* results collected from the profilometer and the *Vi* data collected from the accelerometer are displayed in Table 4.11. Work material, tool material type, feed rate, and spindle speed were all significant according to their *F* values. The *F*-critical is 4.00 with 79 degrees of freedom (DOF) for the ANOVA with *Ra* as the dependent variable. The *F* value for depth of cut was 3.1, which is insignificant according to the *F*-critical value. Work material, tool material type, feed rate, spindle speed, and depths of cut were found significant according to their *F* values. The *F*-critical is 4.17 with 47 DOF for the ANOVA with *Vi* as the dependent variable. The ANOVAs for *Ra* and *Vi* are displayed with the *F* values in Tables 4.12 and 4.13.

Table 4.11. Taguchi experimental design results

	Ra					Vi		
Run	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 1	Rep 2	Rep 3
1	19	19	21	28	30	0.4156	0.3295	0.4922
2	46	59	64	64	67	1.9091	1.9649	2.0520
3	14	17	17	17	18	0.6783	0.4826	0.4432
4	22	23	29	29	29	0.6809	0.6672	0.7202
5	57	60	60	62	73	2.0104	1.9810	1.8198
6	81	96	97	97	97	0.4346	0.3830	0.4554
7	57	61	63	68	84	0.5280	0.6022	0.4569
8	85	85	86	92	96	1.1077	1.1857	1.2019
9	13	13	14	16	17	0.3348	0.3282	0.2968
10	18	19	20	24	24	0.5278	0.5167	0.6418
11	13	15	17	17	18	0.5294	0.4256	0.4202
12	20	21	22	27	27	0.6876	0.7373	0.6208
13	36	38	41	44	58	0.3948	0.4124	0.4053
14	35	36	37	43	49	0.4664	0.5432	0.5034
15	35	37	37	38	51	0.6624	0.8768	0.9377
16	28	35	35	40	44	0.5868	0.6503	0.5637

The percent contribution due to error provides an estimate of the adequacy of the experiment. Since the percent contribution due to error is low, 15% or less, then it is assumed that no important factors were omitted from the experiment (Ross, 1988). The percent contribution for error is 1.42% for *Vi* ANOVA and 4.38% for *Ra* ANOVA.

Table 4.12. ANOVA for Ra as dependent variable means from Taguchi parameter design. $F^1_{60} = 4.00$

Factor	SS	DOF	Mean Sq.	F
Material	22680.12	1	22680.12	659.2
Tool	12928.59	1	12928.59	375.7
Feed	3577.80	1	3577.80	104.0
3	3162.61	1	3162.61	91.9
9	2679.59	1	2679.59	77.9
7	812.81	1	812.81	23.6
Spin	621.59	1	621.59	18.1
5	437.11	1	437.11	12.7
13	427.80	1	427.80	12.4
12	374.09	1	374.09	10.9
6	255.61	1	255.61	7.4
11	234.61	1	234.61	6.8
Depth	108.12	1	108.12	3.1
14	90.30	1	90.30	2.6
10	56.09	1	56.09	1.6
Error	2202.12	64	34.41	
Total	50648.96	79		

Table 4.13. ANOVA for Vi as dependent variable from the Taguchi parameter design. $F^1_{30} = 4.17$

Factor	SS	DOF	Mean Sq.	F
Depth	2.80	1	2.80	527.1
Tool	2.06	1	2.06	387.8
14	1.98	1	1.98	372.7
10	1.90	1	1.90	357.6
5	1.27	1	1.27	239.1
11	0.75	1	0.75	141.2
Feed	0.26	1	0.26	48.9
13	0.22	1	0.22	41.4
Spindle	0.21	1	0.21	39.5
Material	0.11	1	0.11	20.7
6	0.11	1	0.11	20.7
9	0.05	1	0.05	9.4
12	0.03	1	0.03	5.6
7	0.01	1	0.01	
3	0.00	1	0.00	
Error	0.17	32	0.01	
Total	11.93	47		

Stage Two Summary

The purpose of this stage was to identify significant main and interaction effects of tool material, work-piece material type, feed rate, spindle speed, and depth of cut on tool vibration and work-piece surface smoothness in end mill cutting. In stage one, work-piece material type, spindle speed, depth of cut , feed rate, and tool material type were tested at one treatment level. In stage two, these factors were tested at two treatment levels.

Based on the findings of this state, the researcher rejected null hypotheses 3 - 8 as listed in chapter one. As a result of these findings, all factors were used in the development of the recognition model for both the fuzzy net and multiple regression models. In developing the recognition models, *Vi* was used as an independent variable. Vibration experienced during machining was an important enough variable and should be used in predicting *Ra*. By using the vibration information, an on-line recognition model able to monitor the process in real-time was developed.

Stage Three

In developing the multiple regression model, the significant factors determined from stages one and two were entered into the model. The following four steps were used in developing the regression model.

1. Determine the regression model. The multiple regression equation is (Kirk, 1995):

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots + \beta_{h-1} X_{i,h-1} + \varepsilon_i \quad (i, \ldots, N) \qquad (4.1)$$

2. Determine R, R^2,and adjusted R^2
3. Determine whether the multiple R is statistically significant.
4. Determine the significance of the predictor variables.

The proposed multiple regression models for each of the 8 designs were derived after significant factors were determined from stages one and two. In these designs, the dependent variable was the surface roughness average value Ra (Yi). The structure of the multiple regression, multiple on-line surface roughness recognition (MR-MOSRR) model is depicted in Figure 3.4.

The seven independent variables are comprised of 3 crisp parameters and 4 fuzzy parameters. The 4 fuzzy parameters are (F) feed rate (X_{1i}), (D) depth of cut (X_{2i}), (S) spindle speed (X_{3i}), and (V) vibration average per revolution (X_{4i}) of the accelerometer sensor (see formula 3.0). The three crisp parameters are (TD) tool diameter (CX_{1i}), (TM) tool material (CX_{2i}), and (WM) work material (CX_{3i}).

Eight multiple regression equations were calculated from the training data collected. For each design, 48 samples were used in order to develop the regression models. The samples were cut according to the design parameters in Table 3.4. From each sample, 5 *Ra* readings were taken with the profilometer and 5 (*Vi*) averages were collected.

The average (*Vi*) was calculated from 5 separate revolutions of the spindle according to formula (3.0) located in chapter 3. An average voltage was calculated for each spindle revolution. *Vi* is comprised of five averages. The data collected are displayed in Appendix B. The regression equations for each design use the following factors in order to develop the best-fit model for surface roughness recognition.

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \beta_4 X_{4i} + \beta_5 X_{1i} X_{2i} + \beta_6 X_{1i} X_{3i} + \beta_7 X_{1i} X_4 + \beta_8 X_{2i} X_{3i} + \beta_9 X_{2i} X_{4i} + \beta_{10} X_{3i} X_{4i} + \varepsilon_i.$$

The regression equations for each design are listed in the following sections.

Regression model for Design 1

Enter method was used in developing the best-fit design 1 multiple regression equation.

Tool Diameter = 0.5"

Work-piece material = Aluminum

Tool Material Type = HSS

$R = .907$

$R^2 = .823$

Adjusted $R^2 = .816$

$Ra_1 = -48.674 + 6.034X_{11} + 1390.841X_{12} + 0.03027X_{13} - 197.771X_{14} - 0.002765X_{11}X_{13} - 0.969X_{12}X_{13} + 0.08889X_{13}X_{14} + 33.483X_{11}X_{13} + 0.704X_{12}X_{13}X_{14}$.

The coefficients with the t-values and level of significance are shown in Table 4.14. All of the coefficients are significant, according to the *t*-statistic.

Table 4.14. Design 1 significance of coefficients

Model	Predictors	β	Std. Error	t	Sig.
1	(constant)	-48.674	9.420	-5.167	.000
	Feed rate	6.034	.663	9.108	.000
	Depth	1390.841	320.224	4.343	.000
	Spindle	3.027E-02	.005	5.724	.000
	Vibration	-197.771	39.074	-5.061	.000
	Feed x Spin	-2.765E-03	.000	-7.383	.000
	Dep x Spin	-.969	.190	-5.107	.000
	Vi x Spin	8.889E-02	.028	3.147	.002
	Feed x Dep	33.483	8.614	3.887	.000
	Dep x Spin x Vi	.704	.365	1.927	.055

Regression model for Design 2

Enter method was used in developing the best-fit design 2 multiple regression equation.

Tool Diameter = 0.5"

Work-piece material = Steel

Tool Material Type = HSS

$R = .847$

$R^2 = .718$

Adjusted $R^2 = .705$

$Ra_2 = 77.896 + 12.232X_{21} - 3660.757X_{22} - 0.0572X_{23} - 2680.321X_{24} - 0.003425X_{21}X_{23} + 3.747X_{22}X_{23} + 2.164X_{23}X_{24} - 93.377X_{21}X_{22} - 91.797X_{22}X_{23}X_{24} + 117816.740X_{22}X_{24}$.

The coefficients with the t-values and level of significance are shown in Table 4.15.

Regression model for Design 3

Forward method was used in developing the best-fit design 3 multiple regression equation.

Tool Diameter = 0.5"

Work-piece material = Aluminum

Tool Material Type = Carbide

$R = .782$

$R^2 = .612$

Adjusted $R^2 = .607$

$Ra_3 = 3.927 + 0.04071X_{31} - 0.0001686X_{33} + 144.76X_{32}X_{34}$.

The coefficients with the t-values and level of significance are shown in Table 4.16.

Regression model for Design 4

Enter method was used in developing the design 4 multiple regression equation.

Tool Diameter = 0.5"

Work-piece material = Steel

Tool Material Type = Carbide

R = .765

R^2 = .585

Table 4.15. Design 2 significance of coefficients

Model	Predictors	β	Std. Error	t	Sig.
1	(constant)	77.896	66.715	1.168	.244
	Feed rate	12.232	2.592	4.719	.000
	Depth	-3660.757	3492.960	-1.048	.296
	Spindle	-5.720E-02	.037	-1.528	.128
	Vibration	-2680.321	2659.386	-1.008	.315
	Feed x Spin	-3.425E-03	.002	-2.218	.028
	Dep x Spin	3.747	2.013	1.861	.064
	Vi x Spin	2.164	1.498	1.445	.150
	Vi x Dep	117816.74	131520.566	.896	.371
	Feed x Dep	-93.377	33.480	-2.789	.006
	Dep x Spin x Vi	-91.797	74.60	-1.231	.220

Table 4.16. Design 3 significance of coefficients

Model	Predictors	β	Std. Error	t	Sig.
1	(constant)	3.927	.070	56.146	.000
	Feed rate	4.071E-02	.002	17.946	.000
	Spindle	-1.686E-04	.000	-4.739	.000
	Vibration x depth	144.760	41.987	3.448	.001

Adjusted $R^2 = .565$

$Ra_4 = -617.499 + 14.223X_{41} + 35394.148X_{42} + 0.366X_{43} + 16149.942X_{44} - 0.004116X_{41}X_{43} - 21.013X_{42}X_{43} - 8.746X_{43}X_{44} + 7.753X_{41}X_{42} - 880871.193X_{42}X_{44} - 125.617X_{41}X_{44} + X_{42}X_{43}X_{44}.$

The coefficients with the t-values and level of significance are shown in Table 4.17. The forward method was used in developing the best-fit alternate design 4 multiple regression equation. The dependent variable, *Ra*, was transformed with the natural log function.

$R = .781$

$R^2 = .610$

Adjusted $R^2 = .593$

Table 4.17. Design 4 significance of coefficients

Model	Predictors	β	Std. Error	t	Sig.
1	(constant)	-617.499	85.360	-7.234	.000
	Feed rate	14.223	3.281	4.336	.000
	Depth	35394.148	4430.249	7.989	.000
	Spindle	.366	.046	7.959	.000
	Vibration	16149.942	2856.566	5.654	.000
	Feed x Spin	-4.116E-03	.002	-2.028	.044
	Dep x Spin	-21.013	2.528	-8.311	.000
	Vi x Spin	-8.746	1.476	-5.927	.000
	Vi x Dep	-880871.193	116373.941	-7.569	.000
	Feed x Dep	7.753	38.488	.201	.841
	Feed x Vi	-125.617	32.840	-3.825	.000
	Dep x Spin x Vi	508.985	63.846	7.972	.000

$Ra_4 = e^{**} (-6.618 + 0.162^{*}X_{41} + 573.629X_{42} + 0.005809X_{43} + 271.141X_{44} -$

$0.00003366X_{41}X_{43} - 0.34X_{42}X_{43} - 0.149X_{43}X_{44} - 14249.05X_{42}X_{44} - 1.801X_{41}X_{44} +$

$8.248X_{42}X_{43}X_{44})$.

The coefficients for the alternate method with the t-values and level of significance are shown in Table 4.18.

Regression model for Design 5

Enter method was used in developing the best-fit design 5 multiple regression equation.

Tool Diameter = 0.75"

Work-piece material = Aluminum

Tool Material Type = HSS

R = .620

$R^2 = .384$

Table 4.18. Design 4 alternate method significance of coefficients

Model	Predictors	β	Std. Error	t	Sig.
1	(constant)	-6.618	1.205	-5.491	.000
	Spindle	5.809E-03	.001	8.974	.000
	Feed rate	.162	.044	3.654	.000
	Feed x Vi	-1.801	.440	-4.096	.000
	Feed x Spin	-3.366E-05	.000	-1.183	.238
	Depth	573.629	62.628	9.159	.000
	Dep x Spin x Vi	8.248	.890	9.272	.000
	Dep x Spin	-.340	.035	-9.594	.000
	Vi x Dep	-14249.050	1609.582	-8.853	.000
	Vi x Spin	-.149	.021	-7.231	.000
	Vi	271.141	39.053	6.943	.001

Adjusted $R^2 = .354$

$Ra_5=53.837 - 0.437X_{51} - 1878.232X_{52} - 0.02558X_{53} -204.241X_{54} + 0.0006958X_{51}X_{53} + 0.961X_{52}X_{53} + 0.144X_{53}X_{54} + 3.681X_{51}X_{52} + 18430.247X_{52}X_{54} - 5.646X_{51}X_{54} - 9.806X_{52}X_{53}X_{54}.$

The coefficients with the t-values and level of significance are shown in Table 4.19.

Regression model for Design 6

Enter method was used in developing the design 6 multiple regression equation.

Tool Diameter = 0.75"

Work-piece material = Steel

Tool Material Type = HSS

$R = .794$

$R^2 = .630$

Adjusted $R^2 = .612$

Table 4.19. Design 5 significance of coefficients

Model	Predictors	β	Std. Error	t	Sig.
1	(constant)	53.837	12.018	4.480	.000
	Feed rate	-.437	.736	-.594	.553
	Depth	-1878.232	551.770	-3.404	.001
	Spindle	-2.558E-02	.007	-3.742	.000
	Vibration	-204.241	54.926	-3.718	.000
	Feed x Spin	6.958E-04	.000	1.716	.087
	Dep x Spin	.961	.297	3.231	.001
	Vi x Spin	.144	.033	4.313	.000
	Vi x Dep	18430.247	4754.847	3.876	.000
	Feed x Dep	3.681	9.708	.379	.705
	Feed x Vi	-5.646	2.627	-2.150	.033
	Dep x Spin x Vi	-9.806	2.644	-3.709	.000

Ra_6=161.351 + 6.846X_{61}- 4621.589X_{62} - 0.0007794X_{63} - 3052.133X_{64} - 0.007589$X_{61}X_{63}$ + 3.363$X_{62}X_{63}$ + 0.884$X_{63}X_{64}$ - 343.289$X_{61}X_{62}$ + 134188.744$X_{62}X_{64}$ + 131.22$X_{61}X_{64}$ - 64.467$X_{62}X_{63}X_{64}$.

The coefficients with the t-values and level of significance for design 6 are shown in Table 4.20. The forward method was used in developing the best-fit design 6 multiple regression equation. The dependent variable, *Ra*, was transformed with the natural log function

$R = .792$

$R^2 = .627$

Adjusted $R^2 = .614$

Ra_6 = e**(4.48 + 0.0004797X_3 - 0.00004858X_1X_3 + 0.0106X_2X_3 - 0.009122X_3X_4 - 4.378X_1X_2 + 547.698X_2X_4 + 1.627X_1X_4 - 0.209$X_2X_3X_4$).

The coefficients with the t-values and level of significance are shown in Table 4.21.

Table 4.20. Design 6 significance of coefficients

Model	Predictors	β	Std. Error	*t*	Sig.
1	(constant)	161.351	49.079	3.288	.001
	Feed rate	6.846	3.732	1.834	.068
	Depth	-4621.589	2216.645	-2.085	.038
	Spindle	-7.794E-04	.028	-.028	.978
	Vibration	-3052.133	1014.271	-3.009	.003
	Feed x Spin	-7.589E-03	.002	-3.304	.001
	Dep x Spin	3.363	1.260	2.668	.008
	Vi x Spin	.884	.517	1.710	.089
	Vi x Dep	134188.744	36222.738	3.705	.000
	Feed x Dep	-343.289	49.853	-6.886	.000
	Feed x Vi	131.220	13.497	9.722	.000
	Dep x Spin x Vi	-64.467	18.966	-3.399	.001

Regression model for Design 7

Enter method was used in developing the best-fit design 7 multiple regression equation.

Tool Diameter = 0.75"

Work-piece material = Aluminum

Tool Material Type = Carbide

$R = .733$

$R^2 = .537$

Adjusted $R^2 = .515$

$Ra_7 = 21.399 + 2.078X_{71} + 719.455X_{72} + 0.0004339X_{73} + 562.564X_{74} + 0.00001519X_{71}X_{73} - 0.295X_{72}X_{73} - 0.05761X_{73}X_{74} - 0.146X_{71}X_{72} + 1775.765X_{72}X_{74} - 29.665X_{71}X_{74} - 2.835X_{72}X_{73}X_{74}.$

The coefficients with the t-values and level of significance are shown in Table 4.22.

Table 4.21. Design 6 alternate method significance of coefficients

Model	Predictors	β	Std. Error	t	Sig.
1	(constant)	4.480	.177	25.242	.000
	Dep x Spin x Vi	-.209	.061	-3.401	.001
	Spindle	.0004797	.000	3.508	.001
	Feed x Dep	-4.378	.621	-7.048	.000
	Vi x Dep	547.698	159.401	3.436	.001
	Feed x Vi	1.627	.165	9.852	.000
	Feed x Spin	-.00004858	.000	-4.995	.000
	Vi x Spin	-.009122	.001	-6.232	.000
	Dep x Spin	.01060	.003	3.808	.000

Table 4.22. Design 7 significance of coefficients

Model	Predictors	β	Std. Error	t	Sig.
1	(constant)	21.399	12.518	1.709	.089
	Feed rate	2.078	1.308	1.589	.113
	Depth	719.455	234.012	3.074	.002
	Spindle	4.339E-04	.006	.067	.947
	Vibration	562.564	391.217	1.438	.152
	Feed x Spin	1.519E-05	.001	.021	.983
	Dep x Spin	-.295	.140	-2.106	.036
	Vi x Spin	-5.761E-02	.234	-.246	.806
	Vi x Dep	1775.765	6865.444	.259	.796
	Feed x Dep	-.146	14.030	-.010	.992
	Feed x Vi	-29.665	8.747	-3.391	.001
	Dep x Spin x Vi	-2.835	3.269	-.867	.387

The regression model for Design 8

The forward method was used in developing the best-fit design 8 multiple regression equation.

Tool Diameter = 0.75"

Work-piece material = Steel

Tool Material Type = Carbide

$R = .605$

$R^2 = .366$

Adjusted $R^2 = .336$

$Ra_8 = -48.567+5.364X_{81} + 7684.154X_{82} - 233.178X_{84} - 0.494X_{82}X_{83} + 0.828X_{83}X_{84} - 348.446X_{81}X_{82} - 29.838X_{82}X_{83}X_{84}.$

The coefficients with the t-values and level of significance are shown in Table 4.23. The R, R^2, and adjusted R^2 values for each design listed above is summarized in Table 4.24.

Stage Three Summary

The purpose of this stage was to develop regression equations for each of the eight designs in the regression model. Three methods were used in developing these equations.

Table 4.23. Design 8 significance of coefficients

Model	Predictors	β	Std. Error	t	Sig.
1	(Constant)	-48.567	16.822	-2.887	.004
	Vibration	-233.178	460.960	-.506	.613
	Depth x Spin x Vi	-29.838	4.012	-7.437	.000
	Depth x Spin	-.494	.648	-.763	.446
	Feed x Depth	-348.446	52.098	-6.688	.000
	Depth	7684.154	1372.145	5.600	.000
	Feed	5.364	1.069	5.018	.000
	VI x Spin	.828	.261	3.174	.002

Table 4.24. R, R^2, and adjusted R^2 summarized

Design	Design Configuration	R	R^2	Adjusted R
1	$TD_1TM_1WM_1$	0.907	0.823	0.816
2	$TD_1TM_1WM_2$	0.847	0.718	0.705
3	$TD_1TM_2WM_1$	0.782	.612	0.607
4	$TD_1TM_2WM_2$	0.781	0.610	0.593
5	$TD_2TM_1WM_1$	0.620	0.384	0.354
6	$TD_2TM_1WM_2$	0.792	0.627	0.614
7	$TD_2TM_2WM_1$	0.733	0.537	0.515
8	$TD_2TM_2WM_2$	0.605	0.366	0.336

First is the enter method, which enters all independent variables into the regression model regardless of the their significance. Second is the forward method, which enters the independent variables one at a time base on their significance. The method is built only with the independent variables that are significant. Third the forward method is used again except that the dependent variable *Ra* is transformed with the natural log function (e^x). The method was done in order to smooth the dispersion of the *Ra* values.

The designs with the least amount of deviation from the actual *Ra* value are designs 2 and 7, both using the forward method. Design 4 had the third least deviation from the *Ra* value. The method used for design 4 was the forward method with *Ra* transformed. The percentage deviation will be discussed in stage 5. The development of the fuzzy net designs will be discussed in state 4.

Stage Four

In developing the fuzzy net model, the significant factors determined from stages one and two were entered into the model. The proposed fuzzy net model for the 8 designs was derived after significant factors were determined from stages one and two. In these designs, the dependent variable was the surface roughness average value *Ra* (Yi). The structure of the fuzzy net, multi-level on-line surface roughness recognition (FN-MOSRR) model is depicted in Figure 3.6. The seven independent variables are comprised of 3 crisp parameters and 4 fuzzy parameter. The 4 fuzzy parameters are (F) feed rate (X_{1i}), (D) depth of cut (X_{2i}), (S) spindle speed (X_{3i}), and (V) vibration average per revolution (X_{4i}) of the accelerometer sensor (see formula 3.0). The three crisp parameters are (TD) tool diameter (CX_{1i}), (TM) tool material (CX_{2i}), and (WM) work material (CX_{3i}).

Eight fuzzy net models were calculated from the training data collected. For each design, 48 samples were used to develop the fuzzy model. The samples were cut according to the design parameters in Table 3.4. From each sample, 5 *Ra* readings were taken with the profilometer. These 5 readings were averaged in order to develop the fuzzy net models. The average *Ra* value was considered the resultant *Ra* value. The average Vi was calculated from 3 separate revolutions of the spindle according to formula (3.0) located in chapter 3. An average voltage was calculated for each spindle revolution. *Vi* is comprised of three averages. The following steps were followed in developing the fuzzy models.

1. *Divide the Input Space into Fuzzy Regions (membership function MF)..*

   The input-output space is $X_F\, X_S\, X_D\, X_V\, Y_{Ra}$.

2. *Generate fuzzy rules from given data pairs through experimentation:*
   - Determine the degree of input-output data obtained from the successful experiment.
   - Design input-output pairs to regions with a maximum degree.
   - Obtain one rule from one pair of designed input-output data.

3. *Assign a degree to each rule and resolve conflicting rules.*

4. *Defuzzification*

The number of regions and the ranges for feed rate, depth of cut, and spindle speed are the same for each fuzzy design. The number of regions and their respective ranges are listed for the factors as follows:

Design 1

Feed Speed: $X_1 \in [5, 19]$ ipm

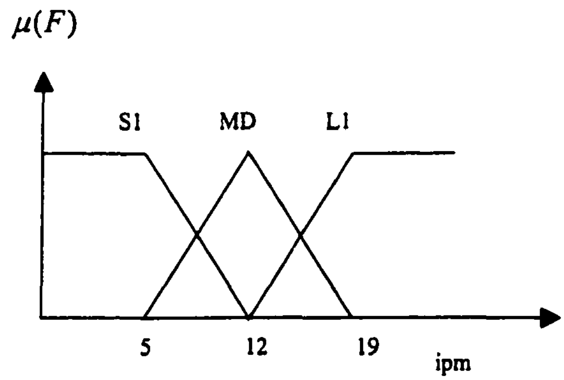


Figure 4.1 Design 1 fuzzy regions for feed rate

3 MFs regions for X_1 shown in Figure 4.1 are denoted by Slow (S1), Medium (MD), Fast (L1)

Depth of Cut: $X_2 \in$ [0.005", .039"]

3 MFs regions for X_2 shown in Figure 4.2 are denoted by Shallow (S1), Medium (MD), Deep (L1)

Spindle Speed: $X_3 \in$ [1400, 2100] in rev/min

3MFs regions for X_3 shown in Figure 4.3 are denoted by.

Slow (S1), Medium (MD), Fast (L1)

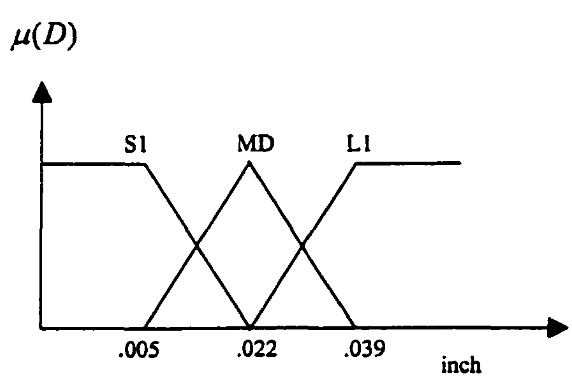


Figure 4.2. Design 1 fuzzy regions for depth if cut

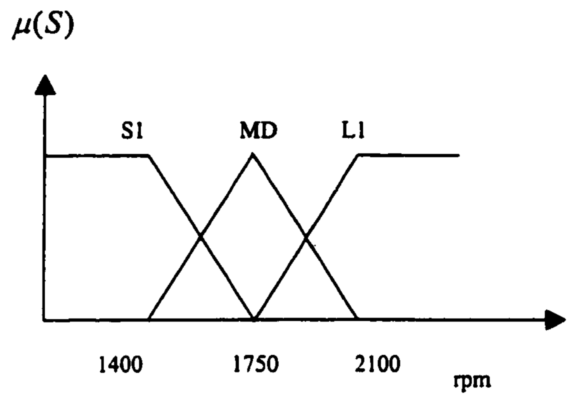


Figure 4.3. Design 1 fuzzy regions for spindle speed

Average Vibration: $X_4 \in [0.0071, 0.3651]$ micro-volts

5 MFs regions of X_4 shown in Figure 4.4 are denoted by: Low (S2), Medium Low (S1), Medium (MD), Medium High (L1), High (L2).

The input range and the number of regions for feed rate, depth of cut, and spindle speed was predetermined. The number of regions was also predetermined for vibration and *Ra*, but the input range was calculated from the data collected for each design set according to formula 3.7.

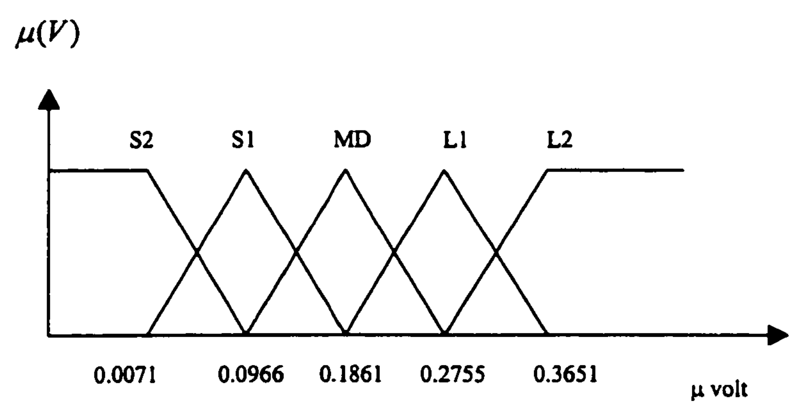


Figure 4.4. Design 1 fuzzy regions for vibration

Ra: $Y \in [11, 39]$ in micro-inches

7 MFs of Y_i shown in Figure 4.5 are denoted by:

High-quality polished finish (S3), Fine (S2), Medium fine (S1)

Medium (MD), Medium course (L1), Course (L2), Low quality finish grit (L3).

Design 2

Feed Speed: *Same as design 1*

Depth of Cut: *Same as design 1*

Spindle Speed: *Same as design 1*

Average Vibration: $X_4 \in [0.0118, 0.0449]$ micro-volts

5 MFs regions of X_4 shown in Figure 4.6 are denoted by: Low (S2), Medium Low (S1), Medium (MD), Medium High (L1), High (L2).

Ra: $Y \in [51, 123]$ in micro-inches

7 MFs of Y_i shown in Figure 4.7 are denoted by:

High-quality polished finish (S3), Fine (S2), Medium fine (S1)

Medium (MD) Medium course (L1), Course (L2), Low quality finish grit (L3).

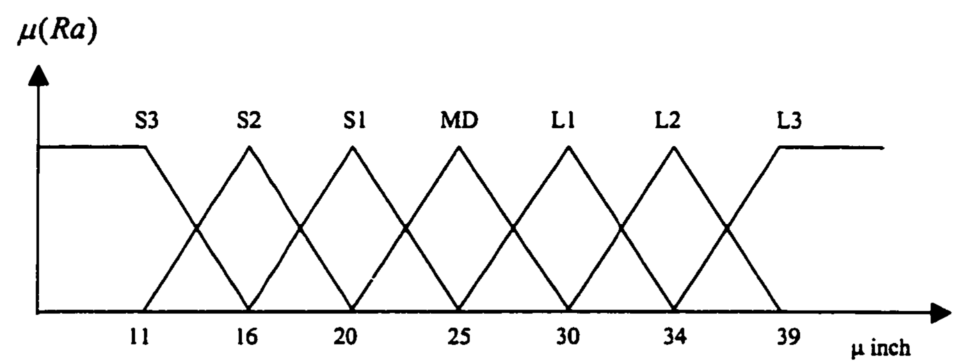


Figure 4.5 Design 1 fuzzy regions and values for Ra

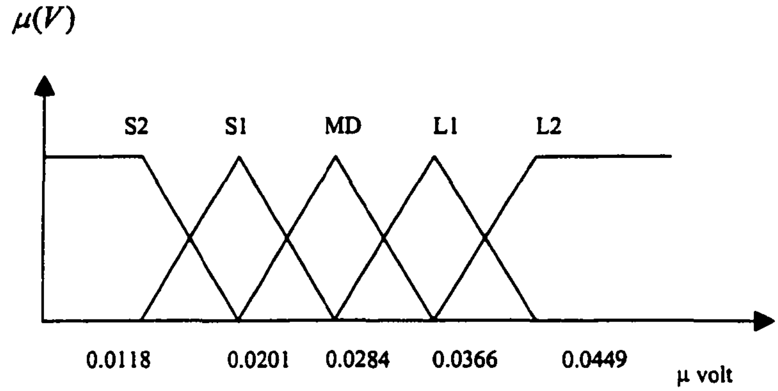


Figure 4.6. Design 2 fuzzy regions for vibration

Design 3

Feed Speed: *Same as design 1*

Depth of Cut: *Same as design 1*

Spindle Speed: *Same as design 1*

Average Vibration: $X_4 \in [0.004, 0.0261]$ micro-volts

5 MFs regions of X_4 shown in Figure 4.8 are denoted by: Low (S2), Medium Low (S1), Medium (MD), Medium High (L1), High (L2).

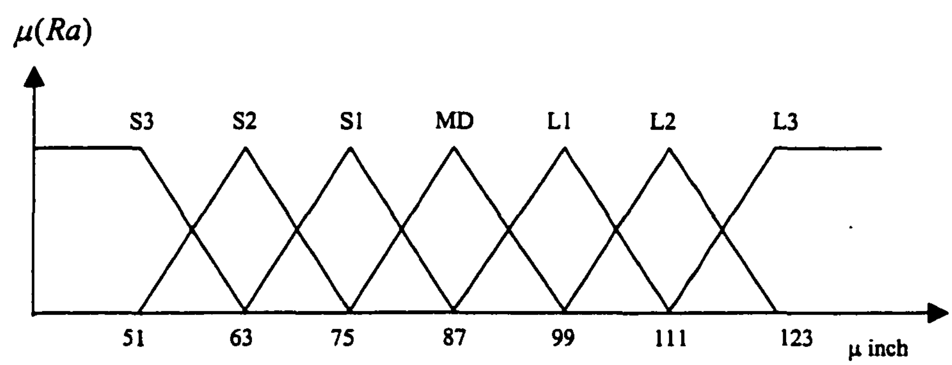


Figure 4.7. Design 2 fuzzy regions and values for Ra

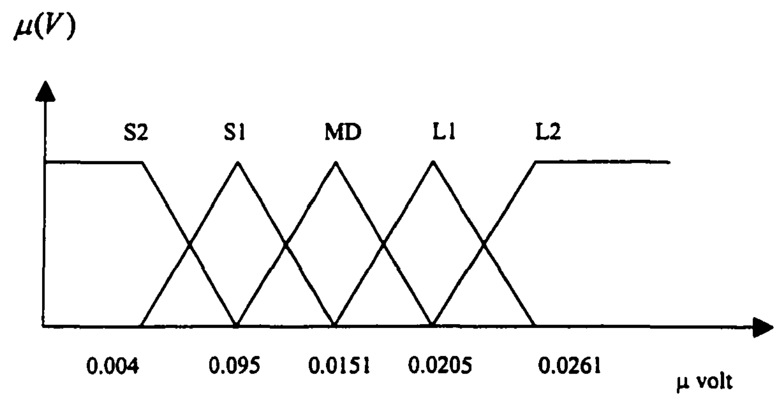


Figure 4.8. Design 3 fuzzy regions for vibration

Ra: Y ∈ [48, 86] in micro-inches

7 MFs of Y_i shown in Figure 4.9 are denoted by:

High-quality polished finish (S3), Fine (S2), Medium fine (S1)

Medium (MD) Medium course (L1), Course (L2), Low quality finish grit (L3).

Design 4

Feed Speed: *Same as design 1*

Depth of Cut: *Same as design 1*

Spindle Speed: *Same as design 1*

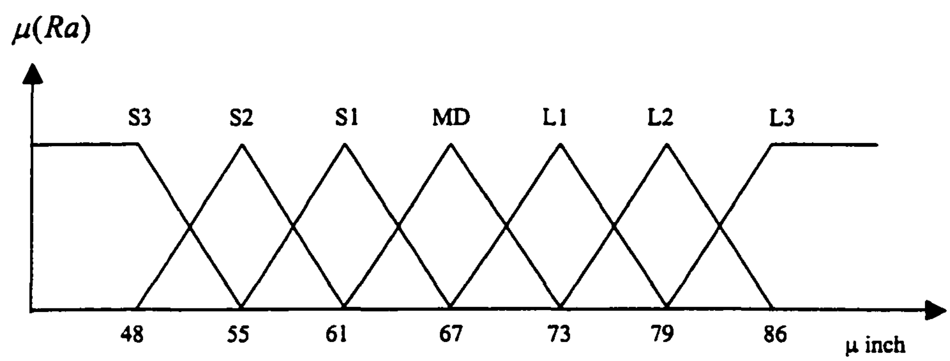


Figure 4.9. Design 3 fuzzy regions and values for Ra

Average Vibration: $X_4 \in [0.0194, 0.0624]$ micro-volts

5 MFs regions of X_4 shown in Figure 4.10 are denoted by: Low (S2), Medium Low (S1), Medium (MD), Medium High (L1), High (L2).

Ra: $(Y) \in [40, 116]$ in micro-inches

7 MFs of Y_i shown in Figure 4.11 are denoted by:

High-quality polished finish (S3), Fine (S2), Medium fine (S1),

Medium (MD), Medium course (L1), Course (L2), Low quality finish grit (L3).

Design 5

Feed Speed: *Same as design 1*

Depth of Cut: *Same as design 1*

Spindle Speed: *Same as design 1*

Average Vibration: $X_4 \in [0.0219, 0.1449]$ micro-volts

5 MFs regions of X_4 shown in Figure 4.12 are denoted by: Low (S2), Medium Low (S1), Medium (MD), Medium High (L1), High (L2).

Ra: $Y \in [10, 21]$ in micro-inches

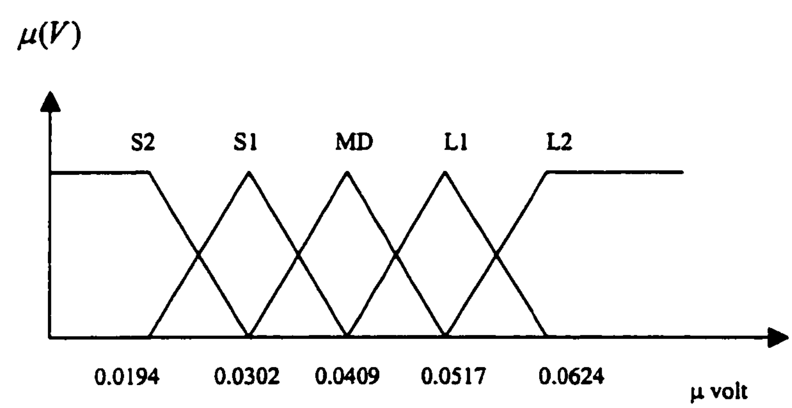


Figure 4.10. Design 4 fuzzy regions for vibration

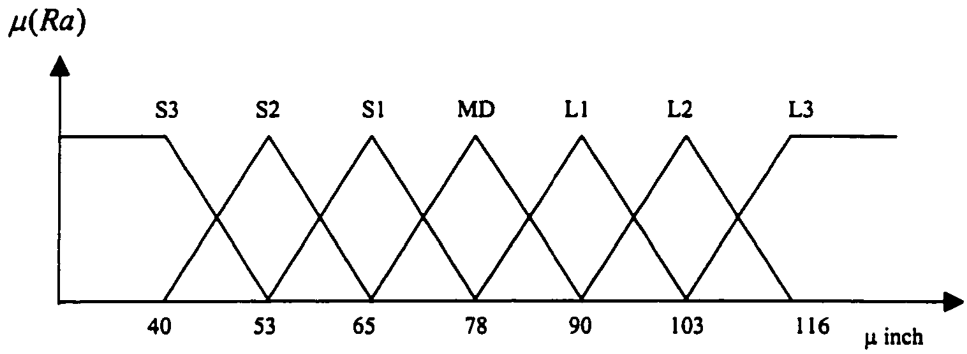


Figure 4.11. Design 4 fuzzy regions and values for Ra

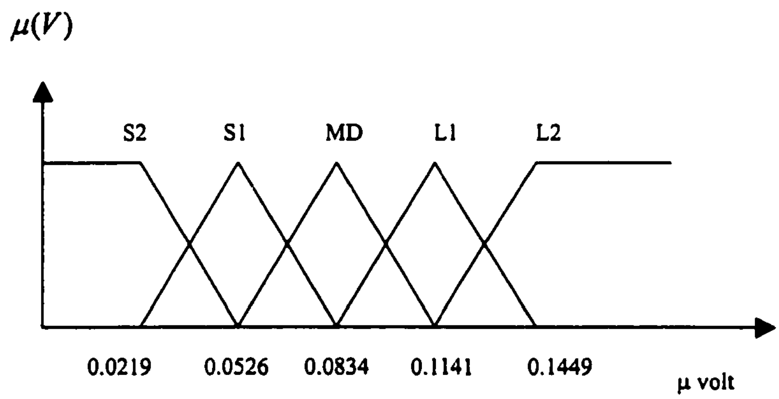


Figure 4.12. Design 5 fuzzy regions for vibration

7 MFs of Y_i shown in Figure 4.13 are denoted by:

High-quality polished finish (S3), Fine (S2), Medium fine (S1),

Medium (MD) Medium course (L1), Course (L2), Low quality finish grit (L3).

Design 6

Feed Speed: *Same as design 1*

Depth of Cut: *Same as design 1*

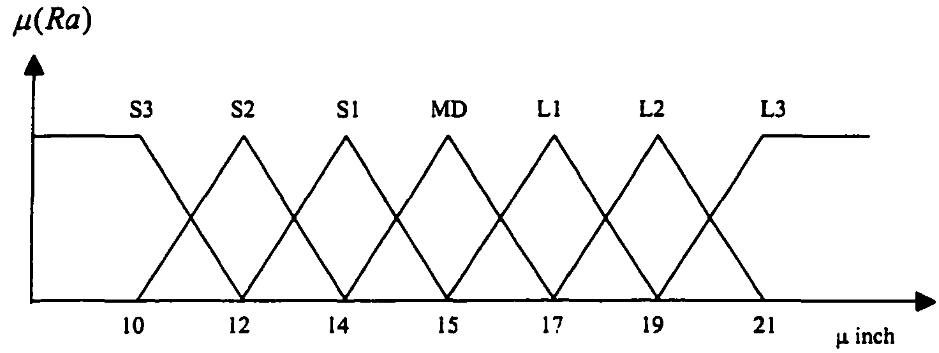


Figure 4.13. Design 5 fuzzy regions and values for Ra

Spindle Speed: *Same as design 1*

Average Vibration: $X_4 \in [0.0306, 0.1283]$ micro-volts

5 MFs regions of X_4 are shown in Figure 4.14 denoted by: Low (S2), Medium Low (S1), Medium (MD), Medium High (L1), High (L2).

Ra: $Y \in [45, 100]$ in micro-inches

7 MFs of Y_i shown in Figure 4.15 are denoted by:

High-quality polished finish (S3), Fine (S2), Medium fine (S1), Medium (MD), Medium course (L1), Course (L2), Low quality finish grit (L3).

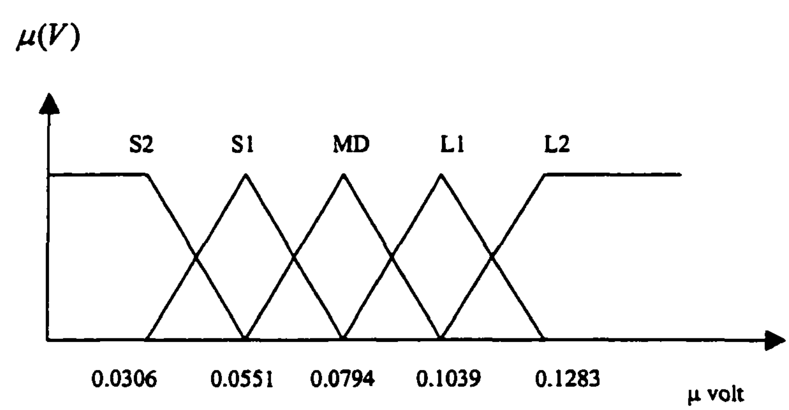


Figure 4.14. Design 6 fuzzy regions for vibration

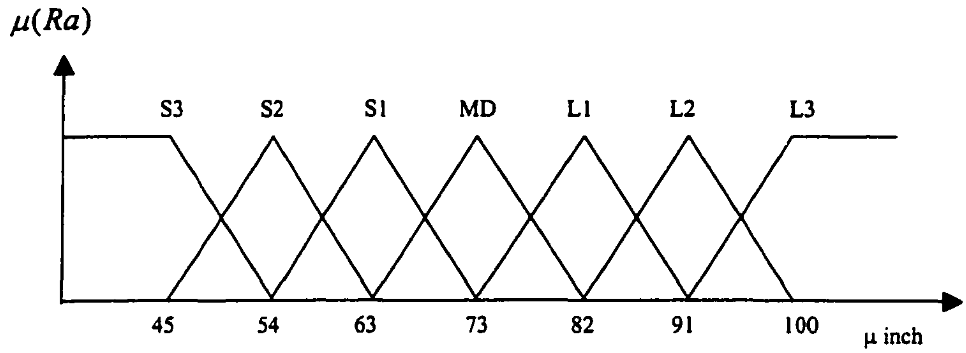


Figure 4.15. Design 6 fuzzy regions and values for Ra

Design 7

Feed Speed: *Same as design 1*

Depth of Cut: *Same as design 1*

Spindle Speed: *Same as design 1*

Average Vibration: $X_4 \in [0.0183, 0.07697]$ micro-volts

5 MFs regions of X_4 shown in Figure 4.16 are denoted by: Low (S2), Medium Low (S1), Medium (MD), Medium High (L1), High (L2).

Ra: $Y \in [43, 60]$ in micro-inches

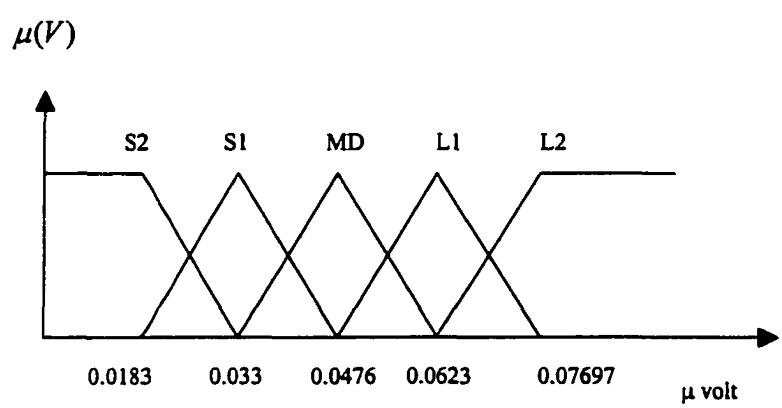


Figure 4.16. Design 7 fuzzy regions for vibration

7 MFs of Y_i shown in Figure 4.17 are denoted by:

High-quality polished finish (S3), Fine (S2), Medium fine (S1)

Medium (MD) Medium course (L1), Course (L2), Low quality finish grit (L3).

Design 8

Feed Speed: *Same as design 1*

Depth of Cut: *Same as design 1*

Spindle Speed: *Same as design 1*

Average Vibration: $X_4 \in [0.0197, 0.0913]$ micro-volts

5 MFs regions of X_4 shown in Figure 4.18 are denoted by: Low (S2), Medium Low (S1), Medium (MD), Medium High (L1), High (L2).

Ra: $Y \in [33, 124]$ in micro-inches

7 MFs of Y_i shown in Figure 4.19 are denoted by:

High-quality polished finish (S3), Fine (S2), Medium fine (S1)

Medium (MD) Medium course (L1), Course (L2), Low quality finish grit (L3)

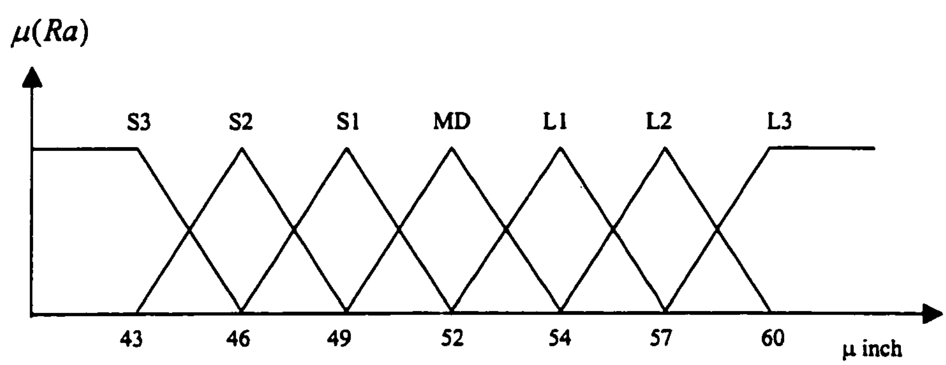


Figure 4.17. Design 7 fuzzy regions and values for Ra

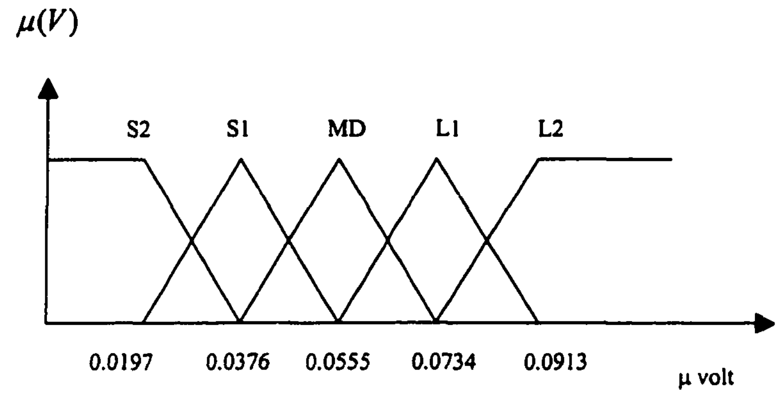


Figure 4.18. Design 8 fuzzy regions for vibration

Generate fuzzy rules from given data pairs through experimentation

The rule base generated for each design is shown in Appendix D.

Assign a degree to each rule and resolve conflicting rules

All conflicts were resolved according to procedure outlined in chapter 3.

Create a combined rule base

A combined rule base consists of two kinds of rules: rules generated from numerical data by means of step 1-3, and linguistic rules determined by a human expert.

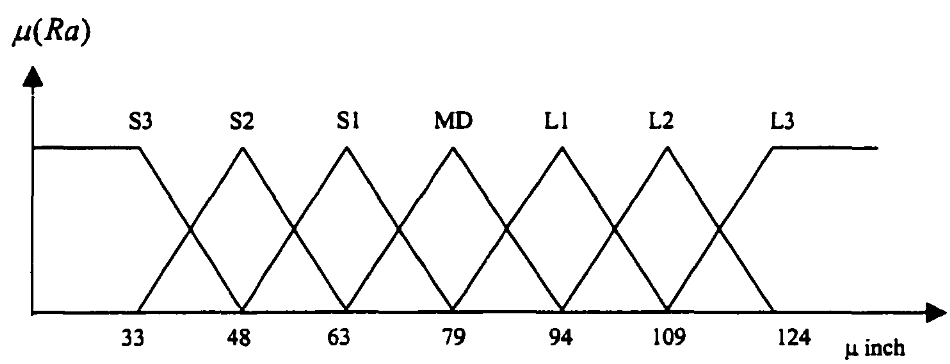


Figure 4.19. Design 8 fuzzy regions and values for Ra

Defuzzification

The centroid of area method was applied:

$$y = \frac{\sum \mu_o^i y^i}{\sum \mu_o^i} \tag{4.2}$$

where $\mu_o^i = \min\{\mu(X_1^i), \mu(X_2^i), ..., \mu(X_n^i)\}, y^i =$ the center value of regions, and y = the output for a given input datum. Defuzzification will be done in stage 5 where the test data will be used in determining the accuracy of the fuzzy net model designs.

Stage Four Summary

Eight fuzzy designs were developed successfully. There are a total of 135 rules for each design. The fuzzy net rule base was developed according to fuzzy net methodology explained in chapter 3. The rules are displayed in Appendix D. Expert input was used in completing the rule base, which was generated from experimental runs enhanced by expert input through refinement. The recognition accuracy of the fuzzy net and the multiple regression designs will be compared in stage five.

Stage Five

In stage 5 the accuracy of the regression model was compared with the accuracy of the fuzzy model. The model resulting in an *Ra* value that deviates the least from the actual *Ra* value is regarded as the most robust surface roughness prediction model. Percentage deviation was the criterion to judge the prediction efficiency of the multiple regression model ($\overline{\overline{\phi}}_{MR}$) and the fuzzy-net model ($\overline{\overline{\phi}}_{FL}$).

To obtain these values, there are three steps:

Step 1. Determine: ϕ_{kMR}, for regression model and ϕ_{kFL}, for fuzzy net model.

Step 2. Determine: $\bar{\phi}_{jMR}$, for regression model and $\bar{\phi}_{jFL}$, for fuzzy net model.

Step 3. Determine $\bar{\bar{\phi}}_{MR}$, overall deviation of MR model and $\bar{\bar{\phi}}_{FL}$, overall deviation of using fuzzy net model

The average deviation for each design and the over-all accuracy for the regression designs, are shown in table 4.28.

In computing the regression equations, *Ra* was the dependent variable with the independent variables listed as follows:

- feed rate
- depth of cut
- spindle speed
- vibration
- feed-depth of cut interaction
- feed-vibration interaction
- feed-spindle speed interaction
- depth of cut-spindle speed interaction
- vibration-spindle speed interaction
- vibration-depth of cut interaction
- depth of cut-spindle speed-vibration interaction.

Three different methods were used in determining the most accurate regression model for each design. The methods and their given accuracies are shown in Table 4.25, with the

Table 4.25.Multiple regression best accuracy model

Design	Enter Method	Forward Method	Forward Method Transformed Ra
1	10.96%	10.82%	**9.06%**
2	**12.10%**	17.38%	12.41%
3	30.26%	31.90%	**27.48%**
4	23.20%	25.04%	**22.00%**
5	**4.82%**	7.54%	8.53
6	26.86%	27.47%	**25.86%**
7	**10.06%**	11.37%	11.63%
8	37.61%	**34.97%**	35.82%

most accurate method highlighted. The accuracy of the multiple regression and the fuzzy net models is compared in Table 4.26.

A *t*-test was conducted between the multiple regression and the fuzzy-nets models. The results in table 4.27 identify a statistical difference between the recognition accuracy of the multiple regression and fuzzy nets models.

Stage Five Summary

The purpose of stage five was to determine the most accurate surface recognition model. Accuracy of the regression model was compared with the accuracy of the fuzzy model. The fuzzy net model resulted in an *Ra* value that deviated the least from the actual *Ra* value, having performed at an overall accuracy of 90%. The fuzzy net design 5 didn't perform as well as the multiple regression design, most likely due to the nature of the test data used. With the exception of designs 1 and 5, all designs were tested with non-training data. The original testing data for designs 1 and 5 exhibited *Ra* values symptomatic of tool wear. The tool material used in both cases was high speed steel. In each of these cases, design 1 and design 5, the rational for the multiple regression model outperforming the fuzzy net model is due to the training data doubling as testing data for each of these designs. By excluding designs 1 and 5 from the overall accuracy calculation, the fuzzy net M-OSRR outperforms the multiple regression M-OSRR, 88% to 78%.

The researcher rejects the hypothesis of there being no significant difference in the accuracy between the multiple regression (M-OSRR) model and the fuzzy net (M-OSRR) model. This conclusion is supported by the *t*-test results for significance displayed in table 4.27. The paired t-test resulted in a significance of 0.045 at $\alpha=0.05$. A summary of findings and recommendations for future study are discussed in chapter 5.

Table 4.26. Model accuracy comparison table

Design (j)	Design Configuration	Average Deviation for MR Model	Average Deviation for Fuzzy net Model	Samples (m)
1	$TD_1TM_1WM_1$	.0906	.0773	8
2	$TD_1TM_1WM_2$	.1211	.0956	8
3	$TD_1TM_2WM_1$	.2748	.1525	8
4	$TD_1TM_2WM_2$	.2200	.1650	8
5	$TD_2TM_1WM_1$	.0482	.0859	8
6	$TD_2TM_1WM_2$	.2586	.0739	8
7	$TD_2TM_2WM_1$	.1006	.0635	8
8	$TD_2TM_2WM_2$	.3497	.1247	8
Total n=8		18.3%	10.5%	64
Accuracy		82%	90%	

Table 4.27. Paired samples t-test MR and FN

MR – FN	t	Df	Sig (2-tailed)
	2.438	7	0.045

CHAPTER V. SUMMARY, DISCUSSION, AND RECOMMENDATIONS

In the preceding four chapters the subject matter of the research was introduced, related literature was reviewed to establish a basis for this research, the methodology was presented and the results of the research were presented. In this chapter, the research will be summarized, conclusion drawn, and recommendations for further study presented.

The purpose of this research was to develop a multi-level on-line surface roughness recognition system. This system is designed to provide the real-time surface roughness values need for on-line decision-making in a more realistic industrial environment. The purpose of proposing the fuzzy net model was to develop an on-line system leading to a more finely tuned prediction model. This research supports the viability of using fuzzy net as a decision making system. In this research a multi-level on-line surface roughness recognition (M-OSRR) system was developed. The important findings drawn from the study are summarized as follows:

Stage One

- Tool diameter is significant with respect to vibration.
- Tool diameter is significant with respect to surface roughness (Ra).
- Feed rate is significant with respect to surface roughness (Ra).
- Feed rate is significant with respect to vibration.

Stage Two

- Work material, tool material type, feed rate, and spindle speed were significant according to their *F* values. The *F*-critical is 4.00 for the ANOVA with R*a* as the dependent variable.
- Depth of cut was insignificant according to the F-critical value. *F*-value for depth of cut was 3.1.

Stage Three

- Developed eight multiple regression equations
- The recognition accuracy of design 1 was 91% with an R = 0.907, R^2 = 0.823, and adjusted R^2 = 0.816.
- The recognition accuracy of design 2 was 88% with an R = 0.847, R^2 = 0.718, and adjusted R^2 = 0.705
- The recognition accuracy of design 3 was 73%with an R = 0.782, R^2 = 0.612, and adjusted R^2 = 0.607.
- The recognition accuracy of design 4 was 78 % with an R = 0.781, R^2 = 0.610, and adjusted R^2 = 0.593.
- The recognition accuracy of design 5 was 95% with and R = 0.620, R^2 = 0.384, and adjusted R^2 = 0.354
- The recognition accuracy of design 6 was 74% with an R = 0.792, R^2 = 0627, and adjusted R^2 = 0.614.
- The recognition accuracy of design 7 was 90% with an R = 0.733, R^2 = 0.537, and adjusted R^2 = 0.515.

- The recognition accuracy of design 8 was 65% with an R = 0.605, R^2 = 0.366, and adjusted R^2 = 0.336.

Stage Four

- Developed eight fuzzy net rules bases with each base having 135 rules through experimentation and expert input
- The recognition accuracy of design 1 was 92.3%
- The recognition accuracy of design 2 was 90%
- The recognition accuracy of design 3 was 85%
- The recognition accuracy of design 4 was 83.5%
- The recognition accuracy of design 5 was 91.4%
- The recognition accuracy of design 6 was 93%
- The recognition accuracy of design 7 was 94%
- The recognition accuracy of design 8 was 88%

Stage Five

- Regression model accuracy was 82%.
- Fuzzy net model accuracy was 90%
- The regression and fuzzy-net recognition accuracy are statistically different at α=0.05 with a *t* of 2.438 with 7 degress of freedom

Limitations of the Study

This study was conducted with the following limitations

1. The test samples were limited to 6061 aluminum and 1018 cold rolled steel.

2. The aluminum and steel samples were of uniform grade.

3. The surface measurement gage was an accurate means of measuring surface roughness.

4. Tool wear is believed to be a contributing factor in the testing data R*a* results for designs 1 and 5.

5. Vibration excitation experienced in the sample is only measured in the z-plane.

6. No coolant or lubricant was used at any stage of the machining process.

Recommendations for Future Studies

1. Measuring vibration

Measuring vibration present in the sample during machining is the purpose of the accelerometer. However, machine vibration is present in spindle and table drives, but was not monitored individually during the machining operation. These external sources of vibration and their contribution to the acceleration measured warrants further study. A spectral analysis of the acceleration signal measured by the accelerometer could prove extremely helpful in accomplishing this task. Through the identification of the frequencies specific to the milling process, the researcher can conduct a more critical analysis of using machine tool vibration in predicting or recognizing surface roughness. As it presently stands, all acceleration (i.e., ground impact forces, motor frequencies, etc.) were used in the development of the surface recognition model.

2. Coolants

Coolants were not used during this research in an effort to concentrate on main controllable factors. In order to experiment with more than one coolant or lubricant type some machine reservoir modifications would be necessary. Therefore, the presence or absence of this factor could have only tested the affect of coolant. The addition of coolant or lubricant in the machining process aids in reducing surface friction, therefore, reducing machine and tool vibration. Surface recognition should improve with the presents of this factor. Coolants or lubricants also are warranted in order to simulate more closely industrial applications

3. Different sample sizes

All the samples in this research were approximately the same size. However, this is not representative of industrial applications. Machine tool dynamics can vary in the mass and size of the workpiece. Further research that incorporates different sizes of samples would be beneficial in developing a more robust surface roughness recognition model.

APPENDIX A. PROGRAMS

- CNC PROGRAM
- MACHINING AND A/D CONVERTING
- REVOLUTION AVERAGE CALCULATION
- RULEBASE DEVELOPMENT
- Ra RECOGNITION PROGRAMS

All "C" programs were writtern with the assistance of Chun Hui from the department of Computer Engineering at Iowa State University

CNC Program

```
N10 O100
N20 G90 G80 G40 G17
N30 T5 M6
N40 E17 G0 X-0.05 Y0.0 Z0.2
N50 M3 S1500
N60 G1 Z-0.02 F8.0
N70 X2.25
N80 G0 G0.2
N90 X-0.5 Y0.0
N100 G1 Z-0.03 F8.0
N110 X2.25
N120 G28 G91 X0.0 Y0.0 Z0.0 M5
N130 M30
```

Machining and A/D Converting Program (Program1)

```
/* Include files */
#ifdef WIN32        // WIN32 Console Application

#include <windows.h>
#include <stdio.h>
#include <conio.h>
#include "cbw.h"
#define number 3000

#else     // DOS text mode application

#include <stdio.h>
#include <conio.h>
#include <dos.h>
#include "cb.h"
#define number 3000
typedef unsigned int WORD;                    // 16-bit unsigned int

#endif    // WIN32 Console, or DOS text mode?

/* Prototypes */
void ClearScreen (void);
void GetTextCursor (int *x, int *y);
void MoveCursor (int x, int y);

void main ()
  {
  /* Variable Declarations */
  FILE *fptr;
  char *filename1;
  int Row,Col;
```

```
        int Row2,Col2;
 int BoardNum = 0;
 int UDStat = 0;
 int Chan0=0;
 int Chan1=1;
 int Gain0 = BIP1PT25VOLTS;
 int Gain1 = BIP10VOLTS;
 int I=0;
 float data[3000][2];
 WORD DataValue0 = 0;
 WORD DataValue1 = 0;
        float   EngUnits;
        float   RevLevel = (float)CURRENTREVNUM;

/* Declare UL Revision Level */
UDStat = cbDeclareRevision(&RevLevel);


 /* Initiate error handling
   Parameters:
          PRINTALL :all warnings and errors encountered will be printed
          STOPALL  :if any error is encountered, the program will stop */

 cbErrHandling (PRINTALL, STOPALL);

 /* set up the screen */
 ClearScreen();
 printf ("Demonstration of cbAIn()\n");
 printf ("Press any key to quit.\n\n");

 GetTextCursor (&Col, &Row);


 /* collect the sample from the channel until a key is pressed */
 for (I=0;I<number;I++)
        {
        /*Parameters:
           BoardNum   :number used by CB.CFG to describe this board
           Chan       :input channel number
           Gain       :gain for the board in BoardNum
           DataValue  :value collected from Chan */

        UDStat = cbAIn (BoardNum, Chan0, Gain0, &DataValue0);
        UDStat = cbToEngUnits (BoardNum, Gain0, DataValue0, &EngUnits);
        data[I][0]=EngUnits;
        UDStat = cbAIn (BoardNum, Chan1, Gain1, &DataValue1);
        UDStat = cbToEngUnits (BoardNum, Gain1, DataValue1, &EngUnits);
        data[I][1]=EngUnits;

        }
 for (I=0; I<number; I++)
 printf("%2.3f %2.3f\n",data[I][0], data[I][1]);
printf(" \n Please keyin filename:");
scanf("%s",filename1);
if((fptr=fopen(filename1,"w"))==NULL)
        {
                printf(" Can't open  file.\n");
                exit(1);
        }

for(I=0; I<number;I++)
{
        fprintf(fptr,"%d %7.4f %7.4f\n",I,data[I][0],data[I][1]);
}
```

```
  }

/**************************************************************************
*
* Name:    ClearScreen
* Arguments: ---
* Returns:  ---
*
* Clears the screen.
*
**************************************************************************/

#define BIOS_VIDEO  0x10

void
ClearScreen (void)
{
#ifdef WIN32      // WIN32 Console Application

        COORD coordOrg = {0, 0};
        DWORD dwWritten = 0;
        HANDLE hConsole = GetStdHandle(STD_OUTPUT_HANDLE);
        if (INVALID_HANDLE_VALUE != hConsole)
                FillConsoleOutputCharacter(hConsole, ' ', 80 * 50, coordOrg, &dwWritten);

        MoveCursor(0, 0);

#else     // DOS text mode application

  union REGS InRegs,OutRegs;

  InRegs.h.ah = 0;
  InRegs.h.al = 2;
  int86 (BIOS_VIDEO, &InRegs, &OutRegs);

#endif    // WIN32 Console, or DOS text mode?

  return;
}

/**************************************************************************
*
* Name:    MoveCursor
* Arguments: x,y - screen coordinates of new cursor position
* Returns:  ---
*
* Positions the cursor on screen.
*
**************************************************************************/


void
MoveCursor (int x, int y)
{
#ifdef WIN32      // WIN32 Console Application

        HANDLE hConsole = GetStdHandle(STD_OUTPUT_HANDLE);

        if (INVALID_HANDLE_VALUE != hConsole)
        {
                COORD coordCursor;
```

```
                    coordCursor.X = (short)x;
                    coordCursor.Y = (short)y;
                    SetConsoleCursorPosition(hConsole, coordCursor);
          }

#else     // DOS text mode application

   union REGS InRegs,OutRegs;

   InRegs.h.ah = 2;
   InRegs.h.dl = (char) x;
   InRegs.h.dh = (char) y;
   InRegs.h.bh = 0;
   int86 (BIOS_VIDEO, &InRegs, &OutRegs);

#endif   // WIN32 Console, or DOS text mode?

   return;
}


/***************************************************************************
 *
 * Name:    GetTextCursor
 * Arguments: x,y - screen coordinates of new cursor position
 * Returns:  *x and *y
 *
 * Returns the current (text) cursor position.
 *
 ***************************************************************************/

void
GetTextCursor (int *x, int *y)
{
#ifdef WIN32       // WIN32 Console Application

          HANDLE hConsole = GetStdHandle(STD_OUTPUT_HANDLE);
          CONSOLE_SCREEN_BUFFER_INFO csbi;

          *x = -1;
          *y = -1;
          if (INVALID_HANDLE_VALUE != hConsole)
          {
                    GetConsoleScreenBufferInfo(hConsole, &csbi);
                    *x = csbi.dwCursorPosition.X;
                    *y = csbi.dwCursorPosition.Y;
          }

#else     // DOS text mode application

   union REGS InRegs,OutRegs;

   InRegs.h.ah = 3;
   InRegs.h.bh = 0;
   int86 (BIOS_VIDEO, &InRegs, &OutRegs);
   *x = OutRegs.h.dl;
   *y = OutRegs.h.dh;

#endif   // WIN32 Console, or DOS text mode?

   return;
}
```

Revolution Average Calculation Program (Readdata)

```
#include <stdio.h>
#include <math.h>

#define number 3000

main(){

int rev = 0;                    /* Number of revolutions */
int peakCount = 0;              /* Count number of peeks */
int lastPeak = 0;               /* Register the postion of last peak */
int pos = 0;                    /* Current postion in dataset */
float acc[number];          /* acc. values */
float prox[number];         /* prox. values */
float accSum = 0;               /* Sum of acc. values */
int rev_index[number];          /* rev. index */
FILE *opf, *ipf;                /* ipf: read data from dataset opf: write avg. to another file */
char *inFile;                   /* Store user-input dataset filename */
char *outFile;                  /* Store user-input rulebase filename */
int fpm = 1;                    /* Set this flag to 0 when the First Peak is Met */
int i = 0;                      /* Number of rows in dataset when fpm = 0 */
int ntbs = 0;                   /* Number to be subtracted from accSum */
int accHit = 0;                 /* Number of acc incremented */
float avgVi;                    /* Avg. Vi */
float avgRev;                   /* Avg Vib per Rev */
int flag=0,rflag=0,total_rev=0;
int nrev,start,rev_start=0;

struct storage {
 float accSum;
 int   total;
} sum[number];

/* initizing the array */
for (i = 0;i<number;i++){
 rev_index[i] = -1;
 sum[i].accSum = 0;
 sum[i].total       = 0;
}
/* Open dataset */
printf("\n Please input the filename of the dataset: ");
scanf("%s", inFile);
if ((ipf=fopen(inFile,"r")) == NULL){
  printf("\n Error opening file/ \n");
  exit(1);
}

/* Start reading dataset */
for (pos = 0; pos < number; pos++){
  fscanf(ipf, "%d %f %f", &pos, &acc[pos], &prox[pos]);
  if(prox[pos]>3 && flag == 0){
   flag = 1;
   if(rflag == 0 || rflag == 1){
    rflag++;
    sum[rev].accSum += (acc[pos]>0? acc[pos] : -1.0*acc[pos]);
    sum[rev].total++;
   }
   else if(rflag==2){
```

```
      rflag = 1;
      sum[rev+1].accSum += (acc[pos]>0? acc[pos] : -1.0*acc[pos]);
      sum[rev+1].total++;

      rev_index[rev+1] = pos;
      rev++;
      total_rev ++;
    }
  }
  else if (rflag != 0){
    sum[rev].accSum += (acc[pos]>0? acc[pos] : -1.0*acc[pos]);
    sum[rev].total++;
    if(prox[pos]<3 && flag == 1)
      flag = 0;

  }
}

rev_index[0] = rev_index[1] - sum[0].total;
sum[rev].accSum = 0;
sum[rev].total = 0;
fclose(ipf);
printf("total # of rev. = %d\n",rev);
printf("please enter # of rev (1 - %d) : ",rev+1);
scanf("%d",&nrev);

printf("please enter the starting point(%d - %d) :",
                                    rev_index[0],rev_index[rev-nrev]);
scanf("%d",&start);

while (rev_index[rev_start] < start)
  rev_start++;

avgVi=0.0;
for(i=0;i<nrev;i++){
  avgVi += sum[rev_start].accSum/(float)sum[rev_start].total;
  rev_start++;
}
avgVi = avgVi/(float)nrev;

/* Write results to output file */
opf = fopen("avgs.res", "a");
fprintf(opf, "%s\t%f\n", inFile,avgVi);

fclose(opf);
```

Rulebase Development Program (Rb-work)

```
#include <stdio.h>

#include <math.h>

#define dtNum 48            /* Number of data per design */
#define min(x, y) (((x) < (y)) ? (x) : (y))
#define max(x, y) (((x) > (y)) ? (x) : (y))
#define tempMaxV 0
#define tempMinV 10
#define tempMaxR 0
#define tempMinR 300
#define numRange 7
#define numRange_Ra 7
```

```
#define numRange_Vi 5
#define spreadFeed  7.0
#define spreadDepth  0.017
#define spreadSpin  250.0

/* Prototype: */

int compute_Feed(int);
int compute_Depth(float);
int compute_Spin(int);
int compute_Vi(float);
int compute_Ra(int);


/* Ranges of member functions */
float feedFn[2][3]={{5.0,12.0,19.0},{12,19,}};
float depthFn[2][3]={{0.005,0.022,0.039},{0.022,0.039,}};
float spinFn[2][3]={{1400.0,1750.0,2100.0},{1750.0,2100.0,}};


float viFn[3][3];
float raFn[5][3];
float Ra[7];                    /* Ra regions 1 - 7 */
float spreadRa;                 /* Spread Ra */
float spreadVi;          /* Spread Vi */
float Vi[5];            /* Vi regions 1 - 5 */

main(){

FILE *opf, *ipf;                /* ipf: Read input file
                                   opf: Output rulebank */
char inFile[20];                /* Store user-input input file */
char outFile[20];               /* Filename of the rulebank */
float floatDt[48][2];           /* Store datasets data */
int intDt[48][3];
int rb[48][5];                  /* Store rulebank */
int dtPos;                     /* Current position in dataset */
int i,j;                        /* Counter */
float maxVi = tempMaxV;         /* Max Vi */
float minVi = tempMinV;         /* Min Vi */
int maxRa = tempMaxR;           /* Max Ra */
int minRa = tempMinR;           /* Min Ra */
int tempF, tempS, tempR;
float tempD, tempV;
int temp_rb[48],rb_flag,max_rb,rb_count[8],max_index;
/* Open input file, which contains F, D, S, Vi and Ra */
printf("\nPlease input the filename that is used to generate rulebank: ");
scanf("%s", inFile);

if ((ipf=fopen(inFile, "r")) == NULL){
  printf("\n Error opening file \n");
  exit(1);
}

/* Start reading input */


/* User inputs the filename of the rulebank*/

printf("\nPlease input the filename of rulebank: ");
scanf("%s", outFile);
opf=fopen(outFile, "w");
```

```
for (dtPos = 1 ; dtPos <=dtNum; dtPos++){

  fscanf(ipf, "%d %4f %d %4f %d\n", &tempF, &tempD, &tempS, &tempV, &tempR);

  intDt[dtPos-1][0] = tempF;
  floatDt[dtPos-1][0] = tempD;
  intDt[dtPos-1][1] = tempS;
  floatDt[dtPos-1][1] = tempV;
  intDt[dtPos-1][2] = tempR ;
/*
  printf("D:%d S:%4f F:%d V:%4f R:%d\n", intDt[dtPos-1][0], floatDt[dtPos-1][0],
          intDt[dtPos-1][1], floatDt[dtPos-1][1], intDt[dtPos-1][2]);
*/
} /* End for */

  /* Find Max and Min Values for Vi and Ra */
for (i = 0; i < dtNum; i++){
  maxVi = max(maxVi, floatDt[i][1]);
  minVi = min(minVi, floatDt[i][1]);
  maxRa = max(maxRa, intDt[i][2]);
  minRa = min(minRa, intDt[i][2]);
}

/*
printf("maxVi: %f\n", maxVi);
printf("minVi: %f\n", minVi);
*/

          spreadVi = (maxVi - minVi)/(numRange - 1);

          /* Find the range for Vi */
          for(i=0;i<numRange_Vi;i++)
                    Vi[i] = minVi +i*spreadVi;

          for(i=0;i<3;i++)
                    for(j=0;j<5;j++)
                              viFn[j][i] = Vi[i+j];

          /* Find the range for Ra */
          spreadRa = (float)(maxRa - minRa)/((float)(numRange_Ra - 1));
          for(i=0;i<numRange_Ra;i++)
                    Ra[i] = minRa +i*spreadRa;

          for(i=0;i<3;i++)
                    for(j=0;j<7;j++)
                              raFn[j][i] = Ra[i+j];



/* Ra values are stored in intDt[i][2] */
  /* Compute input variables, the write to rulebank file */
  /*
*/

for (i = 0; i < dtNum; i++){
  rb[i][0] = compute_Feed(intDt[i][0]);
  rb[i][1] = compute_Depth(floatDt[i][0]);
  rb[i][2] = compute_Spin(intDt[i][1]);

  rb[i][3] = compute_Vi(floatDt[i][1]);
  rb[i][4] = compute_Ra(intDt[i][2]);
/* printf("Ra value at position %d: %d \n", i, rb[i][4]); */
/* printf("Vi value at position %d: %d \n", i, rb[i][3]); */
}
```

```
fprintf(opf,"Index\tFeed\tDepth\tSpin\tVi\tRa\n");

for (i = 0;i < 8; i++)
  rb_count[i] = 0;
rb_flag = 0;
for (i = 0;i < dtNum; i++){
  for (j = i+1; j < dtNum ; j++){
    if(temp_rb[j] != -1&&
       rb[i][0] == rb[j][0]&&
       rb[i][1] == rb[j][1]&&
       rb[i][2] == rb[j][2]&&
       rb[i][3] == rb[j][3]){
      rb_flag = 1;
      temp_rb[j] = -1;
      rb_count[rb[j][4]]++;
    }
  }
  max_rb = rb_count[0];
  max_index = 0;
  rb_count[0] = 0;
  for (j = 1; j < 8; j++){
    max_rb = max(max_rb,rb_count[j]);
    if(max_rb == rb_count[j])
      max_index = j;
    rb_count[j] = 0;
  }
  if(rb_flag){
    rb[i][4] = max_index;
    rb_flag = 0;
  }
}

j=0;
for (i = 0; i < dtNum; i++)
  if(temp_rb[i] != -1)
    fprintf(opf,"%d\t%d\t%d\t%d\t%d\t%d\n",j++,rb[i][0],rb[i][1],
            rb[i][2],rb[i][3],rb[i][4]);

printf("Dt Table\n");
for (i=0;i<dtNum;i++)
printf("%d\t%d\t%f\t%d\t%f\t%d\n",i,intDt[i][0],floatDt[i][0],
                    intDt[i][1],floatDt[i][1],intDt[i][2]);
fclose (ipf);
fclose(opf);

return 0;
} /*---------------------------------------------------- End Main */
/*
/*
 */
int compute_Feed(int f){
  float a, b, miu;                    /* For comparision */
  int vimf;                           /* Vi Membership Function */
  int cond;

  printf("f: %f\n", f);
  if ((feedFn[0][0] <= f) && (f < feedFn[1][0])){
    cond = 1;
    }
  else {
        cond = 2;
    }

  printf("Before SWITCH\n");
```

```
  switch (cond){
    case 1 : /* Between range 1 amd 2 */
          a = (f - feedFn[0][0]) / spreadFeed;
          b = (feedFn[1][0] - f) / spreadFeed;
          miu = max(a, b);
          if(miu == a)
            return 1;
          else
            return 2;

    case 2: /* Between range 2 and 3 */
          a = (f - feedFn[1][0]) / spreadFeed;
          b = (feedFn[1][1] - f) / spreadFeed;
          miu = max(a, b);
          if(miu == a)
            return 2;
          else
            return 3;

    default:
          printf("Error in Switch\n");
          exit(1);
  } /* End SWITCH */

return 0;
}

int compute_Depth(float d){
  float a, b, miu;                    /* For comparision */
/*  int vimf; */                      /* Vi Membership Function */
  int cond;

  printf("d: %f\n", d);
        if ((depthFn[0][0] <= d) && (d < depthFn[1][0])){
                  cond = 1;
        }
        else {
                  cond = 2;
  }

  printf("Before SWITCH\n");
  switch (cond){
    case 1 : /* Between range 1 amd 2 */
          a = (d - depthFn[0][0]) / spreadDepth;
          b = (depthFn[1][0] - d) / spreadDepth;
          miu = max(a, b);
          if(miu == a)
            return 1;
          else
            return 2;

    case 2: /* Between range 2 and 3 */
          a = (d - depthFn[1][0]) / spreadDepth;
          b = (depthFn[1][1] - d) / spreadDepth;
          miu = max(a, b);
          if(miu == a)
            return 2;
          else
            return 3;
    default:
          printf("Error in Switch\n");
          exit(1);
  } /* End SWITCH */
```

```
return 0;
}

int compute_Spin(int s){

  float a, b, miu;                    /* For comparision */
/*  int vimf;          */             /* Vi Membership Function */
  int cond;

 printf("s: %f\n", s);
  if ((spinFn[0][0] <= s) && (s < spinFn[1][0])){
    cond = 1;
    }
  else {
    cond = 2;
    }

  printf("Before SWITCH\n");
  switch (cond){
    case 1 : /* Between range 1 amd 2 */
          a = (s - spinFn[0][0]) / spreadSpin;
          b = (spinFn[1][0] - s) / spreadSpin;
          miu = max(a, b);
          if (miu == a)
            return 1;
          else
            return 2;

    case 2: /* Between range 2 and 3 */
          a = (s - spinFn[1][0]) / spreadSpin;
          b = (spinFn[1][1] - s) / spreadSpin;
          miu = max(a, b);
          if (miu == a)
            return 2;
          else
            return 3;

    default:
          printf("Error in Switch\n");
          exit(1);
  } /* End SWITCH */
         return 0;
}


int compute_Vi(float vi){
  float a, b, miu;                    /* For comparision */
  int vimf;                           /* Vi Membership Function */
  int cond;

  printf("Vi: %f\n", vi);
  if ((viFn[0][0] <= vi) && (vi < viFn[1][0])){
    printf("Cond 1 true\n");
    cond = 1;
    }
  else if ((viFn[1][0] < vi) && (vi < viFn[2][0])){
    cond = 2;
    printf("Cond 2 true\n");
    }
  else if ((viFn[2][0] < vi) && (vi < viFn[2][1])){
    cond = 3;
    printf("Cond 3 true\n");
    }
  else {
```

```
      cond = 4;
      printf("Cond 4 true\n");
      }
    printf("Before SWITCH\n");
    switch (cond){
      case 1 : /* Between range 1 amd 2 */
              a = (vi - viFn[0][0]) / spreadVi;
              b = (viFn[1][0] - vi) / spreadVi;
              miu = max(a, b);
              if (miu == a)
                return 1;
              else
                return 2;

      case 2: /* Between range 2 and 3 */
              a = (vi - viFn[1][0]) / spreadVi;
              b = (viFn[2][0] - vi) / spreadVi;
              miu = max(a, b);
              if (miu == a)
                return 2;
              else
                return 3;

      case 3: /* Between range 3 and 4 */
              a = (vi - viFn[2][0]) / spreadVi;
              b = (viFn[2][1] - vi) / spreadVi;
              miu = max(a, b);
              if (miu == a)
                return 3;
              else
                return 4;

      case 4: /* Between range 4 and 5 */
              a = (vi - viFn[2][1]) / spreadVi;
              b = (viFn[2][2] - vi) / spreadVi;
              miu = max(a, b);
              if (miu == a)
                return 4;
              else
                return 5;
              default:
              printf("Error in Switch\n");
              exit(1);
    } /* End SWITCH */
    return 0;
}

int compute_Ra(int ra){
    float a, b, miu;                    /* For comparision */
    int ramf;                           /* Ra Membership Function */
    int cond;

    printf("Ra: %d\n", ra);
    if ((raFn[0][0] <= (float)ra) && ((float)ra < raFn[1][0])){

      cond = 1;
      }
    else if ((raFn[1][0] < (float)ra) && ((float)ra < raFn[2][0])){
      cond = 2;
      }
    else if ((raFn[2][0] < (float)ra) && ((float)ra < raFn[3][0])){
      cond = 3;
      }
    else if ((raFn[3][0] <(float)ra) && ((float)ra < raFn[4][0])){
```

```
  cond = 4;
  }
else if ((raFn[4][0] < (float)ra) && ((float)ra < raFn[4][1])){
  cond = 5;
  }
else {
  cond = 6;
  }

switch (cond){
  case 1 : /* Between range 1 amd 2 */
        a = (ra - raFn[0][0]) / spreadRa;
        b = (raFn[1][0] - ra) / spreadRa;
        miu = max(a, b);
        if (miu == a)
          return 1;
        else
          return 2;

  case 2: /* Between range 2 and 3 */
        a = (ra - raFn[1][0]) / spreadRa;
        b = (raFn[2][0] - ra) / spreadRa;
        miu = max(a, b);
        if (miu == a)
          return 2;
        else
          return 3;

  case 3: /* Between range 3 and 4 */
        a = (ra - raFn[2][0]) / spreadRa;
        b = (raFn[3][0] - ra) / spreadRa;
        miu = max(a, b);
        if (miu == a)
          return 3;
        else
          return 4;

  case 4: /* Between range 4 and 5 */
        a = (ra - raFn[3][0]) / spreadRa;
        b = (raFn[4][0] - ra) / spreadRa;
        miu = max(a, b);
        if (miu == a)
          return 4;
        else
          return 5;

  case 5: /* Between range 5 and 6 */
        a = (ra - raFn[4][0]) / spreadRa;
        b = (raFn[4][1] - ra) / spreadRa;
        miu = max(a, b);
        if (miu == a)
          return 5;
        else
          return 6;

  case 6: /* Between range 6 and 7 */
        a = (ra - raFn[4][1]) / spreadRa;
        b = (raFn[4][2] - ra) / spreadRa;
        miu = max(a, b);
        if (miu == a)
          return 6;
        else
          return 7;
```

```
    default:
        printf("Error in Switch\n");
        exit(1);
  } /* End SWITCH */
  return 0;
}
```

Ra Recognition Program (Ra)

```
#include <stdio.h>
#include <string.h>
#include <math.h>
#include <stdlib.h>
/*#include <alloc.h>*/


#define dtNum 48            /* Number of data per design */
#define desginNum 8         /* Number of desgin */
#define testingSize 8       /* Number of data per testing data file */
#define MaxRa               16      /* max no. of possible Ra per data */
#define num_rule  135
#define min(x, y) (((x) < (y)) ? (x) : (y))
#define max(x, y) (((x) > (y)) ? (x) : (y))
#define tempMaxV 0
#define tempMinV 10
#define tempMaxR 0
#define tempMinR 300
#define numRange_Ra 7
#define numRange_Vi 5
#define spreadFeed  7.0
#define spreadDepth  0.017
#define spreadSpin  250.0

/* define the data type*/
struct newtype{
  int     reg;
  float   miu;
};
/* define the storage for testing data*/
struct testing{
  int     feed;
  float depth;
  int     spin;
  float   vi;
};
static struct testing tdata[testingSize];
static int rulebank[num_rule][5];

        static struct newtype feed[2];
        static struct newtype depth[2];
        static struct newtype spin[2];
        static struct newtype vi[2];

        static float RA[testingSize];

/* Prototype: */

void compute_Feed(int);
void compute_Depth(float);
void compute_Spin(int);
void compute_Vi(float);
float compute_Ra_value();
```

```
/* Ranges of member functions */
float feedFn[2][3]={{5.0,12.0,19.0},{12,19,}};
float depthFn[2][3]={{0.005,0.022,0.039},{0.022,0.039,}};
float spinFn[2][3]={{1400.0,1750.0,2100.0},{1750.0,2100.0,}};


int rb_total;
float viFn[3][3];
float raFn[5][3];
float Ra[7];                              /* Ra regions 1 - 7 */
float spreadRa;                           /* Spread Ra */
float spreadVi;                /* Spread Vi */
float Vi[5];                  /* Vi regions 1 - 7 */

void main(void){

        FILE *opf, *ipf,*tpf,*rpf;     /* ipf: Read input file
                                               tpf: Read testing data file
                                               rpf: Read rulebank file
                                               opf: Output rulebank */
        char inFile[20];                      /* Store user-input input file */
        char testingFile[20];                 /* Store testing data */
        char rulebankFile[20];                /* Store rulebank data */
        char outFile[20];                     /* Filename of the rulebank */
        static float floatDt[dtNum][2];               /* Store datasets data */
        static int intDt[dtNum][3];
        int rb[num_rule][5];                          /* Store rulebank */
        int dtPos;                     /* Current position in dataset */
        int i;                                /* Counter */
        float maxVi = tempMaxV;               /* Max Vi */
        float minVi = tempMinV;               /* Min Vi */
        int maxRa = tempMaxR;                 /* Max Ra */
        int minRa = tempMinR;                 /* Min Ra */
        int tempF, tempS, tempR,j=0,k;
        float tempD, tempV;
        char  desgin[10];
        char  dump[80];

        /* Open input file, which contains F, D, S, Vi and Ra */
        printf("\nPlease input the filename that is used to generate rulebank: ");
        scanf("%s", inFile);

        if ((ipf=fopen(inFile, "r")) == NULL){
                printf("\n Error opening file \n");
                exit(1);
        }

        printf("\nPlease input the filename for the testing data: ");
        scanf("%s", testingFile);

        if ((tpf=fopen(testingFile, "r")) == NULL){
                printf("\n Error opening file \n");
                exit(1);
        }
        printf("\nPlease input desgin you want to use: ");
        scanf("%s", desgin);

        strcpy(rulebankFile,"Design");
        strcat(rulebankFile,desgin);
        if ((rpf=fopen(rulebankFile, "r")) == NULL){
                printf("\n Error opening file \n");
                exit(1);
        }
```

```
/* Start reading input */


/* User inputs the filename of the rulebank*/

printf("\nPlease input the filename of Ra value: ");
scanf("%s", outFile);


for (dtPos = 0 ; dtPos < dtNum; dtPos++){

        fscanf(ipf, "%d %f %d %f %d\n", &tempF, &tempD, &tempS, &tempV, &tempR);

        intDt[dtPos][0] = tempF;
        floatDt[dtPos][0] = tempD;
        intDt[dtPos][1] = tempS;
        floatDt[dtPos][1] = tempV;
        intDt[dtPos][2] = tempR ;
}
/* Reading the testing data*/
for (dtPos = 0 ; dtPos < testingSize; dtPos++){

        fscanf(tpf, "%d %f %d %f\n", &tempF, &tempD, &tempS, &tempV);
        tdata[dtPos].feed   = tempF;
        tdata[dtPos].depth  = tempD;
        tdata[dtPos].spin   = tempS;
        tdata[dtPos].vi     = tempV;

} /* End for */

/* Reading rulebank */
/*fscanf(rpf,"%s\n",dump);*/
for (i = 0 ; i < num_rule; i++){
        j=fscanf(rpf,"%d %d %d %d %d %d\n",&k,&rulebank[i][0],&rulebank[i][1],
                &rulebank[i][2],&rulebank[i][3],&rulebank[i][4]);
        /*if( j    == EOF){
                rb_total = i;
                i=dtNum;
        }*/

} /* End for */
/* Find Max and Min Values for Vi and Ra */
fclose (ipf);
fclose (tpf);
fclose (rpf);
for (i = 0; i < dtNum; i++){
        maxVi = max(maxVi, floatDt[i][1]);
        minVi = min(minVi, floatDt[i][1]);
        maxRa = max(maxRa, intDt[i][2]);
        minRa = min(minRa, intDt[i][2]);
}


spreadVi = (maxVi - minVi)/((float)(numRange_Vi - 1));

/* Find the range for Vi */
for(i=0;i<numRange_Vi;i++)
        Vi[i] = minVi +i*spreadVi;

for(i=0;i<3;i++)
        for(j=0;j<7;j++)
                viFn[j][i] = Vi[i+j];

/* Find the range for Ra */
```

```
        spreadRa = (float)(maxRa - minRa)/((float)(numRange_Ra - 1));
        for(i=0;i<numRange_Ra;i++)
                Ra[i] = minRa +i*spreadRa;

        for(i=0;i<3;i++)
                for(j=0;j<11;j++)
                        raFn[j][i] = Ra[i+j];

        /* Ra values are stored in intDt[i][2] */
        /* Compute input variables, the write to rulebank file */

        for (i = 0; i < testingSize; i++){
                compute_Feed(tdata[i].feed);
                compute_Depth(tdata[i].depth);
                compute_Spin(tdata[i].spin);
                compute_Vi(tdata[i].vi);
                RA[i] = compute_Ra_value();
        }
        opf=fopen(outFile, "w");
        fprintf(opf,"Index\tFeed\tDepth\t\tSpin\tVi\t\tRa\n");


        for (i = 0; i < testingSize; i++){
                fprintf(opf,"%d\t%d\t%f\t%d\t%f\t%f",i,tdata[i].feed,
                                        tdata[i].depth,tdata[i].spin,tdata[i].vi,RA[i]);
                if(RA[i]>maxRa||RA[i]<minRa)
                        fprintf(opf,"\t RA out of range!!\n");
                else
                        fprintf(opf,"\n");
        }

        fclose (opf);

} /*------------------------------------------------ End Main */


void compute_Feed(int f){
  float a, b, miu;                      /* For comparision */
/*  int vimf;      */                   /* Vi Membership Function */
  int cond;

  printf("f: %f\n", f);
  if(((feedFn[0][0] <= f) && (f < feedFn[1][0]))||f < feedFn[0][0]){
    cond = 1;
    }
  else{
    cond = 2;
    }


  switch (cond){
   case 1 : /* Between range 1 amd 2 */
                if(f<feedFn[0][0]){
                        feed[1].reg = 1;
                        feed[1].miu = 1;
                        feed[0].reg = 1;
                        feed[0].miu = 1;
                        break;
                }

                a = (f - feedFn[0][0]) / spreadFeed;
                b = (feedFn[1][0] - f) / spreadFeed;
                miu = max(a, b);
                if (miu == a){
```

```
                        feed[1].reg = 1:
                        feed[1].miu = a;
                        feed[0].reg = 2;
                        feed[0].miu = b;
                        break;
                }
                else{
                        feed[0].reg = 1:
                        feed[0].miu = b;
                        feed[1].reg = 2;
                        feed[1].miu = a;
                        break;
                }

    case 2: /* Between range 2 and 3 */

                 if(f > feedFn[1][1]){
                        feed[1].reg = 3;
                        feed[1].miu = 1;
                        feed[0].reg = 3;
                        feed[0].miu = 1:
                        break;
                 }

                a = (f - feedFn[1][0]) / spreadFeed;
                b = (feedFn[1][1] - f) / spreadFeed;
                miu = max(a, b);
                if (miu == a){
                   feed[1].reg = 2;
                   feed[1].miu = a;
                        feed[0].reg = 3;
                        feed[0].miu = b;
                        break;
                }

                else{
                        feed[1].reg = 3;
                        feed[1].miu = a;
                        feed[0].reg = 2;
                        feed[0].miu = b;
                        break;
                }
        default:{
                        printf("Error in Switch\n");
                        exit(1);}
        } /* End SWITCH */

}

void compute_Depth(float d){
        float a, b, miu;                        /* For comparision */
        int cond;

        printf("d: %f\n". d);
        if (((depthFn[0][0] <= d) && (d < depthFn[1][0]))||d < depthFn[0][0]){
                cond = 1;
        }
        else {
                cond = 2;
  }


        switch (cond){
                case 1 : /* Between range 1 amd 2 */
```

```
			if(d < depthFn[0][0]){

				depth[1].reg = 1;
				depth[1].miu = 1;
				depth[0].reg = 1;
				depth[0].miu = 1;
				break;
			}

			a = (d - depthFn[0][0]) / spreadDepth;
			b = (depthFn[1][0] - d) / spreadDepth;
			miu = max(a, b);
			if (miu == a){
				depth[1].reg = 1;
				depth[1].miu = a;
				depth[0].reg = 2;
				depth[0].miu = b;
				break;
			}

			else{
				depth[1].reg = 2;
				depth[1].miu = a;
				depth[0].reg = 1;
				depth[0].miu = b;
				break;
			}


		case 2: /* Between range 2 and 3 */

			if(d > depthFn[1][1]){
				depth[1].reg = 3;
				depth[1].miu = 1;
				depth[0].reg = 3;
				depth[0].miu = 1;
				break;
			}
			a = (d - depthFn[1][0]) / spreadDepth;
			b = (depthFn[1][1] - d) / spreadDepth;
			miu = max(a, b);
			if (miu == a){
				depth[1].reg = 2;
				depth[1].miu = a;
				depth[0].reg = 3;
				depth[0].miu = b;
				break;
			}

			else{
				depth[1].reg = 3;
				depth[1].miu = a;
				depth[0].reg = 2;
				depth[0].miu = b;
				break;
			}


		default:{
			printf("Error in Switch\n");
			exit(1);}
	} /* End SWITCH */

}
```

```
void compute_Spin(int s){

  float a, b, miu;                      /* For comparision */
/*  int vimf;         */                /* Vi Membership Function */
  int cond;
  printf("s: %f\n", s);
  if (((spinFn[0][0] <= s) && (s < spinFn[1][0]))||s<spinFn[0][0]){
    cond = 1;
    }
  else {
    cond = 2;
    }
  switch (cond){
    case 1 : /* Between range 1 amd 2 */
                    if (s < spinFn[0][0]){
                              spin[0].reg = 1;
                              spin[0].miu = 1;
                              spin[1].reg = 1;
                              spin[1].miu = 1;
                              break;
                    }

            a = (s - spinFn[0][0]) / spreadSpin;
                   b = (spinFn[1][0] - s) / spreadSpin;
                   miu = max(a, b);
                   if (miu == a){
                             spin[1].reg = 1;
                             spin[1].miu = a;
                             spin[0].reg = 2;
                             spin[0].miu = b;
                             break;
          }
          else{
            spin[1].reg = 2;
            spin[1].miu = a;
            spin[0].reg = 1;
            spin[0].miu = b;
                   break;
          }


    case 2: /* Between range 2 and 3 */

                    if(s > spinFn[1][1]){
                              spin[0].reg = 3;
                              spin[0].miu = 1;
                              spin[1].reg = 3;
                              spin[1].miu = 1;
                              break;
                    }
          a = (s - spinFn[1][0]) / spreadSpin;
          b = (spinFn[1][1] - s) / spreadSpin;
          miu = max(a, b);
          if (miu == a){
            spin[1].reg = 2;
            spin[1].miu = a;
            spin[0].reg = 3;
            spin[0].miu = b;
                   break;
          }

          else{
            spin[1].reg = 3;
```

```
            spin[1].miu = a;
            spin[0].reg = 2;
            spin[0].miu = b;
                    break;

          }


    default:
            printf("Error in Switch\n");
            exit(1);
  } /* End SWITCH */
}


void compute_Vi(float v){
  float a, b, miu;                          /* For comparision */
/*  int vimf;*/                             /* Vi Membership Function */
  int cond;


  if (((viFn[0][0] <= v) && (v < viFn[1][0]))||v < viFn[0][0]){
    printf("Cond 1 true\n");
    cond = 1;
    }
  else if ((viFn[1][0] < v) && (v < viFn[2][0])){
    cond = 2;
    printf("Cond 2 true\n");
    }
  else if ((viFn[2][0] < v) && (v < viFn[2][1])){
    cond = 3;
    printf("Cond 3 true\n");
    }
  else {
    cond = 4;
    printf("Cond 4 true\n");
    }
  switch (cond){
    case 1 : /* Between range 1 amd 2 */
                  if(v < viFn[0][0]){
                            vi[0].reg = 1;
                            vi[0].miu = 1;
                            vi[1].reg = 1;
                            vi[1].miu = 1;
                            break;
                  }
          a = (v - viFn[0][0]) / spreadVi;
          b = (viFn[1][0] - v) / spreadVi;
          miu = max(a, b);
          if (miu == a){
            vi[1].reg = 1;
            vi[1].miu = a;
            vi[0].reg = 2;
            vi[0].miu = b;
                    break;
          }

          else{
            vi[1].reg = 2;
            vi[1].miu = a;
            vi[0].reg = 1;
            vi[0].miu = b;
                    break;
          }
```

```
case 2: /* Between range 2 and 3 */
        a = (v - viFn[1][0]) / spreadVi;
        b = (viFn[2][0] - v) / spreadVi;
        miu = max(a, b);
        if(miu == a){
          vi[1].reg = 2;
          vi[1].miu = a;
          vi[0].reg = 3;
          vi[0].miu = b;
                break;
        }

        else{
          vi[1].reg = 3;
          vi[1].miu = a;
          vi[0].reg = 2;
          vi[0].miu = b;
                break;
        }

case 3: /* Between range 3 and 4 */
        a = (v - viFn[2][0]) / spreadVi;
        b = (viFn[2][1] - v) / spreadVi;
        miu = max(a, b);
        if(miu == a){
          vi[1].reg = 3;
          vi[1].miu = a;
          vi[0].reg = 4;
          vi[0].miu = b;
                break;
        }

        else {
          vi[1].reg = 4;
          vi[1].miu = a;
          vi[0].reg = 3;
          vi[0].miu = b;
                break;
        }

case 4: /* Between range 4 and 5 */

                if(v > viFn[2][2]){
                        vi[0].reg=5;
                        vi[0].miu=1;
                        vi[1].reg=5;
                        vi[1].miu=1;
                        break;

                }

                a = (v - viFn[2][1]) / spreadVi;

                b = (viFn[2][2] - v) / spreadVi;
        miu = max(a, b);
        if(miu == a){
          vi[1].reg = 4;
          vi[1].miu = a;
          vi[0].reg = 5;
          vi[0].miu = b;
```

```
                break;
            }

            else{
              vi[1].reg = 5;
              vi[1].miu = a;
              vi[0].reg = 4;
              vi[0].miu = b;
                break;
            }


    default:
            printf("Error in Switch\n");
            exit(1);
  } /* End SWITCH */
}

float compute_Ra_value()
{
        float a,b,miu,miu_total=0.0;
        float temp;
        float ra=0.0;
        int i,j,k,l,m;

        for(i = 0; i<2;i++)
                for(j = 0; j<2;j++)
                        for(k = 0; k < 2; k++)
                                for(l = 0; l < 2;l ++){
                                        m = 0;
                                        while(!(feed[i].reg  == rulebank[m][0] &&
                                                        depth[j].reg == rulebank[m][1] &&
                                                        spin[k].reg  == rulebank[m][2] &&
                                                        vi[l].reg    == rulebank[m][3])&&
                                                        m<num_rule)
                                                        /*
                                                        (rb_total == 0?m<dtNum:m<rb_total))
                                                        */
                                                m++;

                                        temp = raFn[0][0]+(float)(rulebank[m][4]-1)*(float)spreadRa;
                                        a = min(feed[i].miu,depth[j].miu);
                                        b = min(spin[k].miu,vi[l].miu);
                                        miu = min(a,b);
                                        miu_total += miu;
                                        ra +=temp*miu;

                                }

        if(ra!=0.0)
                ra=ra/miu_total;
        return ra;
}
```

APPENDIX B. TRAINING DATA SET

Training Data Set 384 Samples (8 Designs)

Design 1

Tool Mat'l	Tool Dia.	Workpiece Mat'l	Feed Rate	Depth of Cut	Spindle Speed	Measured Ra Average	Measured VI
HSS	0.5	AL	8	0.01	1500	13	0.027895
HSS	0.5	AL	8	0.01	1667	11	0.036229
HSS	0.5	AL	8	0.01	1833	13	0.036641
HSS	0.5	AL	8	0.01	2000	14	0.020386
HSS	0.5	AL	8	0.02	1500	18	0.007045
HSS	0.5	AL	8	0.02	1667	12	0.130970
HSS	0.5	AL	8	0.02	1833	13	0.016078
HSS	0.5	AL	8	0.02	2000	12	0.035993
HSS	0.5	AL	8	0.03	1500	17	0.012934
HSS	0.5	AL	8	0.03	1667	14	0.028949
HSS	0.5	AL	8	0.03	1833	12	0.317928
HSS	0.5	AL	8	0.03	2000	14	0.315197
HSS	0.5	AL	11	0.01	1500	16	0.061292
HSS	0.5	AL	11	0.01	1667	17	0.067297
HSS	0.5	AL	11	0.01	1833	13	0.035852
HSS	0.5	AL	11	0.01	2000	15	0.045985
HSS	0.5	AL	11	0.02	1500	17	0.170229
HSS	0.5	AL	11	0.02	1667	19	0.107315
HSS	0.5	AL	11	0.02	1833	17	0.029973
HSS	0.5	AL	11	0.02	2000	14	0.030177
HSS	0.5	AL	11	0.03	1500	23	0.103221
HSS	0.5	AL	11	0.03	1667	20	0.066835
HSS	0.5	AL	11	0.03	1833	19	0.222886
HSS	0.5	AL	11	0.03	2000	18	0.283938
HSS	0.5	AL	13	0.01	1500	26	0.024550
HSS	0.5	AL	13	0.01	1667	19	0.049736
HSS	0.5	AL	13	0.01	1833	15	0.055171
HSS	0.5	AL	13	0.01	2000	20	0.055899
HSS	0.5	AL	13	0.02	1500	24	0.132362
HSS	0.5	AL	13	0.02	1667	18	0.147852
HSS	0.5	AL	13	0.02	1833	18	0.082295
HSS	0.5	AL	13	0.02	2000	17	0.097648
HSS	0.5	AL	13	0.03	1500	28	0.126577
HSS	0.5	AL	13	0.03	1667	21	0.134839
HSS	0.5	AL	13	0.03	1833	22	0.365079
HSS	0.5	AL	13	0.03	2000	19	0.272762
HSS	0.5	AL	16	0.01	1500	30	0.052344
HSS	0.5	AL	16	0.01	1667	26	0.048164
HSS	0.5	AL	16	0.01	1833	23	0.050382
HSS	0.5	AL	16	0.01	2000	20	0.040876
HSS	0.5	AL	16	0.02	1500	38	0.008714
HSS	0.5	AL	16	0.02	1667	27	0.074357
HSS	0.5	AL	16	0.02	1833	25	0.190230
HSS	0.5	AL	16	0.02	2000	22	0.081882

HSS	0.5	AL	16	0.03	1500	39	0.085834
HSS	0.5	AL	16	0.03	1667	31	0.145809
HSS	0.5	AL	16	0.03	1833	30	0.296731
HSS	0.5	AL	16	0.03	2000	24	0.193531

Design 2

Tool Mat'l	**Tool Dia.**	**Workpiece Mat'l**	**Feed Rate**	**Depth of Cut**	**Spindle Speed**	**Measured Ra Average**	**Measured VI**
HSS	0.5	STEEL	8	0.01	1500	65	0.011826
HSS	0.5	STEEL	8	0.01	1667	58	0.012581
HSS	0.5	STEEL	8	0.01	1833	51	0.012160
HSS	0.5	STEEL	8	0.01	2000	55	0.013389
HSS	0.5	STEEL	8	0.02	1500	71	0.013564
HSS	0.5	STEEL	8	0.02	1667	71	0.020986
HSS	0.5	STEEL	8	0.02	1833	70	0.020953
HSS	0.5	STEEL	8	0.02	2000	76	0.020852
HSS	0.5	STEEL	8	0.03	1500	87	0.020719
HSS	0.5	STEEL	8	0.03	1667	83	0.026688
HSS	0.5	STEEL	8	0.03	1833	76	0.039637
HSS	0.5	STEEL	8	0.03	2000	76	0.026873
HSS	0.5	STEEL	11	0.01	1500	82	0.026151
HSS	0.5	STEEL	11	0.01	1667	109	0.024006
HSS	0.5	STEEL	11	0.01	1833	77	0.019062
HSS	0.5	STEEL	11	0.01	2000	71	0.026475
HSS	0.5	STEEL	11	0.02	1500	89	0.025386
HSS	0.5	STEEL	11	0.02	1667	97	0.023711
HSS	0.5	STEEL	11	0.02	1833	108	0.030977
HSS	0.5	STEEL	11	0.02	2000	112	0.028416
HSS	0.5	STEEL	11	0.03	1500	105	0.028900
HSS	0.5	STEEL	11	0.03	1667	99	0.028316
HSS	0.5	STEEL	11	0.03	1833	97	0.029418
HSS	0.5	STEEL	11	0.03	2000	95	0.033099
HSS	0.5	STEEL	13	0.01	1500	93	0.023805
HSS	0.5	STEEL	13	0.01	1667	83	0.023484
HSS	0.5	STEEL	13	0.01	1833	73	0.024822
HSS	0.5	STEEL	13	0.01	2000	71	0.018768
HSS	0.5	STEEL	13	0.02	1500	102	0.024053
HSS	0.5	STEEL	13	0.02	1667	111	0.021101
HSS	0.5	STEEL	13	0.02	1833	98	0.024319
HSS	0.5	STEEL	13	0.02	2000	102	0.026842
HSS	0.5	STEEL	13	0.03	1500	114	0.024592
HSS	0.5	STEEL	13	0.03	1667	113	0.039436
HSS	0.5	STEEL	13	0.03	1833	108	0.022456
HSS	0.5	STEEL	13	0.03	2000	110	0.027413
HSS	0.5	STEEL	16	0.01	1500	123	0.015071
HSS	0.5	STEEL	16	0.01	1667	115	0.017266
HSS	0.5	STEEL	16	0.01	1833	107	0.026472
HSS	0.5	STEEL	16	0.01	2000	98	0.036336
HSS	0.5	STEEL	16	0.02	1500	114	0.020469
HSS	0.5	STEEL	16	0.02	1667	119	0.027419
HSS	0.5	STEEL	16	0.02	1833	120	0.044919
HSS	0.5	STEEL	16	0.02	2000	110	0.028422

HSS	0.5	STEEL	16	0.03	1500	106	0.029248
HSS	0.5	STEEL	16	0.03	1667	107	0.042989
HSS	0.5	STEEL	16	0.03	1833	99	0.022027
HSS	0.5	STEEL	16	0.03	2000	105	0.035542

Design 3

Tool Mat'l	Tool Dia.	Workpiece Mat'l	Feed Rate	Depth of Cut	Spindle Speed	Measured Ra Average	Measured VI
CAR	0.5	AL	8	0.01	1500	53	0.007828
CAR	0.5	AL	8	0.01	1667	51	0.008417
CAR	0.5	AL	8	0.01	1833	52	0.011870
CAR	0.5	AL	8	0.01	2000	48	0.011954
CAR	0.5	AL	8	0.02	1500	56	0.011333
CAR	0.5	AL	8	0.02	1667	55	0.008768
CAR	0.5	AL	8	0.02	1833	50	0.013109
CAR	0.5	AL	8	0.02	2000	54	0.006991
CAR	0.5	AL	8	0.03	1500	62	0.011892
CAR	0.5	AL	8	0.03	1667	58	0.015903
CAR	0.5	AL	8	0.03	1833	54	0.020819
CAR	0.5	AL	8	0.03	2000	51	0.010881
CAR	0.5	AL	11	0.01	1500	62	0.019341
CAR	0.5	AL	11	0.01	1667	62	0.011881
CAR	0.5	AL	11	0.01	1833	58	0.026071
CAR	0.5	AL	11	0.01	2000	56	0.011589
CAR	0.5	AL	11	0.02	1500	72	0.016076
CAR	0.5	AL	11	0.02	1667	63	0.012542
CAR	0.5	AL	11	0.02	1833	60	0.012092
CAR	0.5	AL	11	0.02	2000	61	0.013316
CAR	0.5	AL	11	0.03	1500	62	0.019028
CAR	0.5	AL	11	0.03	1667	63	0.019401
CAR	0.5	AL	11	0.03	1833	64	0.014040
CAR	0.5	AL	11	0.03	2000	62	0.016634
CAR	0.5	AL	13	0.01	1500	81	0.019163
CAR	0.5	AL	13	0.01	1667	69	0.016338
CAR	0.5	AL	13	0.01	1833	59	0.008545
CAR	0.5	AL	13	0.01	2000	65	0.012924
CAR	0.5	AL	13	0.02	1500	73	0.019104
CAR	0.5	AL	13	0.02	1667	78	0.024630
CAR	0.5	AL	13	0.02	1833	74	0.016848
CAR	0.5	AL	13	0.02	2000	66	0.019269
CAR	0.5	AL	13	0.03	1500	66	0.014224
CAR	0.5	AL	13	0.03	1667	81	0.015090
CAR	0.5	AL	13	0.03	1833	75	0.017823
CAR	0.5	AL	13	0.03	2000	66	0.014654
CAR	0.5	AL	16	0.01	1500	77	0.008500
CAR	0.5	AL	16	0.01	1667	86	0.013721
CAR	0.5	AL	16	0.01	1833	64	0.013803
CAR	0.5	AL	16	0.01	2000	83	0.017440
CAR	0.5	AL	16	0.02	1500	72	0.020103
CAR	0.5	AL	16	0.02	1667	67	0.014522
CAR	0.5	AL	16	0.02	1833	66	0.012922
CAR	0.5	AL	16	0.02	2000	76	0.004043

CAR	0.5	AL	16	0.03	1500	84	0.016997
CAR	0.5	AL	16	0.03	1667	70	0.011657
CAR	0.5	AL	16	0.03	1833	70	0.017508
CAR	0.5	AL	16	0.03	2000	72	0.014127

Design 4

Tool Mat'l	Tool Dia.	Workpiece Mat'l	Feed Rate	Depth of Cut	Spindle Speed	Measured Ra Average	Measured VI
CAR	0.5	STEEL	8	0.01	1500	50	0.022936
CAR	0.5	STEEL	8	0.01	1667	90	0.032797
CAR	0.5	STEEL	8	0.01	1833	59	0.021085
CAR	0.5	STEEL	8	0.01	2000	78	0.019483
CAR	0.5	STEEL	8	0.02	1500	62	0.020299
CAR	0.5	STEEL	8	0.02	1667	54	0.034000
CAR	0.5	STEEL	8	0.02	1833	48	0.028861
CAR	0.5	STEEL	8	0.02	2000	50	0.029843
CAR	0.5	STEEL	8	0.03	1500	67	0.032454
CAR	0.5	STEEL	8	0.03	1667	59	0.032510
CAR	0.5	STEEL	8	0.03	1833	57	0.056517
CAR	0.5	STEEL	8	0.03	2000	63	0.053756
CAR	0.5	STEEL	11	0.01	1500	104	0.032559
CAR	0.5	STEEL	11	0.01	1667	68	0.027680
CAR	0.5	STEEL	11	0.01	1833	67	0.038162
CAR	0.5	STEEL	11	0.01	2000	51	0.041244
CAR	0.5	STEEL	11	0.02	1500	57	0.046091
CAR	0.5	STEEL	11	0.02	1667	57	0.050306
CAR	0.5	STEEL	11	0.02	1833	43	0.057429
CAR	0.5	STEEL	11	0.02	2000	42	0.039385
CAR	0.5	STEEL	11	0.03	1500	51	0.048164
CAR	0.5	STEEL	11	0.03	1667	49	0.053592
CAR	0.5	STEEL	11	0.03	1833	51	0.058326
CAR	0.5	STEEL	11	0.03	2000	40	0.041439
CAR	0.5	STEEL	13	0.01	1500	63	0.033887
CAR	0.5	STEEL	13	0.01	1667	73	0.041058
CAR	0.5	STEEL	13	0.01	1833	62	0.046451
CAR	0.5	STEEL	13	0.01	2000	49	0.049501
CAR	0.5	STEEL	13	0.02	1500	68	0.036331
CAR	0.5	STEEL	13	0.02	1667	56	0.039483
CAR	0.5	STEEL	13	0.02	1833	48	0.050183
CAR	0.5	STEEL	13	0.02	2000	48	0.056196
CAR	0.5	STEEL	13	0.03	1500	78	0.034014
CAR	0.5	STEEL	13	0.03	1667	57	0.033275
CAR	0.5	STEEL	13	0.03	1833	52	0.058633
CAR	0.5	STEEL	13	0.03	2000	59	0.052197
CAR	0.5	STEEL	16	0.01	1500	94	0.043115
CAR	0.5	STEEL	16	0.01	1667	87	0.034131
CAR	0.5	STEEL	16	0.01	1833	95	0.042213
CAR	0.5	STEEL	16	0.01	2000	52	0.044329
CAR	0.5	STEEL	16	0.02	1500	70	0.048465
CAR	0.5	STEEL	16	0.02	1667	82	0.045517
CAR	0.5	STEEL	16	0.02	1833	58	0.056440
CAR	0.5	STEEL	16	0.02	2000	53	0.046780

CAR	0.5	STEEL	16	0.03	1500	116	0.034047
CAR	0.5	STEEL	16	0.03	1667	63	0.040933
CAR	0.5	STEEL	16	0.03	1833	58	0.036411
CAR	0.5	STEEL	16	0.03	2000	58	0.062450

Design 5

Tool Mat'l	Tool Dia.	Workpiece Mat'l	Feed Rate	Depth of Cut	Spindle Speed	Measured Ra Average	Measured VI
HSS	0.75	AL	8	0.01	1500	18	0.021874
HSS	0.75	AL	8	0.01	1667	10	0.045451
HSS	0.75	AL	8	0.01	1833	11	0.030353
HSS	0.75	AL	8	0.01	2000	11	0.049318
HSS	0.75	AL	8	0.02	1500	15	0.042009
HSS	0.75	AL	8	0.02	1667	13	0.068430
HSS	0.75	AL	8	0.02	1833	12	0.072337
HSS	0.75	AL	8	0.02	2000	12	0.077484
HSS	0.75	AL	8	0.03	1500	16	0.072625
HSS	0.75	AL	8	0.03	1667	12	0.082501
HSS	0.75	AL	8	0.03	1833	12	0.060496
HSS	0.75	AL	8	0.03	2000	12	0.043178
HSS	0.75	AL	11	0.01	1500	16	0.058295
HSS	0.75	AL	11	0.01	1667	17	0.057847
HSS	0.75	AL	11	0.01	1833	19	0.081686
HSS	0.75	AL	11	0.01	2000	17	0.051495
HSS	0.75	AL	11	0.02	1500	16	0.085316
HSS	0.75	AL	11	0.02	1667	16	0.073322
HSS	0.75	AL	11	0.02	1833	17	0.087465
HSS	0.75	AL	11	0.02	2000	16	0.072604
HSS	0.75	AL	11	0.03	1500	16	0.090319
HSS	0.75	AL	11	0.03	1667	16	0.081486
HSS	0.75	AL	11	0.03	1833	16	0.066694
HSS	0.75	AL	11	0.03	2000	16	0.089280
HSS	0.75	AL	13	0.01	1500	15	0.068106
HSS	0.75	AL	13	0.01	1667	18	0.065458
HSS	0.75	AL	13	0.01	1833	17	0.067093
HSS	0.75	AL	13	0.01	2000	17	0.067364
HSS	0.75	AL	13	0.02	1500	14	0.082745
HSS	0.75	AL	13	0.02	1667	16	0.089907
HSS	0.75	AL	13	0.02	1833	16	0.073419
HSS	0.75	AL	13	0.02	2000	16	0.091126
HSS	0.75	AL	13	0.03	1500	15	0.107949
HSS	0.75	AL	13	0.03	1667	15	0.095374
HSS	0.75	AL	13	0.03	1833	15	0.082945
HSS	0.75	AL	13	0.03	2000	16	0.114872
HSS	0.75	AL	16	0.01	1500	21	0.064547
HSS	0.75	AL	16	0.01	1667	16	0.070625
HSS	0.75	AL	16	0.01	1833	15	0.100317
HSS	0.75	AL	16	0.01	2000	17	0.064406
HSS	0.75	AL	16	0.02	1500	21	0.109645
HSS	0.75	AL	16	0.02	1667	16	0.090754
HSS	0.75	AL	16	0.02	1833	15	0.080975
HSS	0.75	AL	16	0.02	2000	16	0.122039

HSS	0.75	AL	16	0.03	1500	20	0.144894
HSS	0.75	AL	16	0.03	1667	17	0.112761
HSS	0.75	AL	16	0.03	1833	15	0.112008
HSS	0.75	AL	16	0.03	2000	19	0.079299

Design 6

Tool Mat'l	Tool Dia.	Workpiece Mat'l	Feed Rate	Depth of Cut	Spindle Speed	Measured Ra Average	Measured VI
HSS	0.75	STEEL	8	0.01	1500	92	0.032578
HSS	0.75	STEEL	8	0.01	1667	100	0.039932
HSS	0.75	STEEL	8	0.01	1833	75	0.044872
HSS	0.75	STEEL	8	0.01	2000	79	0.030638
HSS	0.75	STEEL	8	0.02	1500	76	0.044872
HSS	0.75	STEEL	8	0.02	1667	86	0.031289
HSS	0.75	STEEL	8	0.02	1833	68	0.034336
HSS	0.75	STEEL	8	0.02	2000	95	0.044954
HSS	0.75	STEEL	8	0.03	1500	75	0.046256
HSS	0.75	STEEL	8	0.03	1667	81	0.056966
HSS	0.75	STEEL	8	0.03	1833	66	0.046850
HSS	0.75	STEEL	8	0.03	2000	66	0.069429
HSS	0.75	STEEL	11	0.01	1500	67	0.034367
HSS	0.75	STEEL	11	0.01	1667	84	0.051804
HSS	0.75	STEEL	11	0.01	1833	52	0.043752
HSS	0.75	STEEL	11	0.01	2000	62	0.071156
HSS	0.75	STEEL	11	0.02	1500	64	0.039902
HSS	0.75	STEEL	11	0.02	1667	62	0.054635
HSS	0.75	STEEL	11	0.02	1833	55	0.060786
HSS	0.75	STEEL	11	0.02	2000	49	0.077093
HSS	0.75	STEEL	11	0.03	1500	57	0.053924
HSS	0.75	STEEL	11	0.03	1667	52	0.071903
HSS	0.75	STEEL	11	0.03	1833	47	0.074961
HSS	0.75	STEEL	11	0.03	2000	46	0.098174
HSS	0.75	STEEL	13	0.01	1500	78	0.049599
HSS	0.75	STEEL	13	0.01	1667	69	0.052642
HSS	0.75	STEEL	13	0.01	1833	78	0.057953
HSS	0.75	STEEL	13	0.01	2000	63	0.077643
HSS	0.75	STEEL	13	0.02	1500	80	0.091827
HSS	0.75	STEEL	13	0.02	1667	73	0.077512
HSS	0.75	STEEL	13	0.02	1833	77	0.099260
HSS	0.75	STEEL	13	0.02	2000	55	0.094965
HSS	0.75	STEEL	13	0.03	1500	90	0.092275
HSS	0.75	STEEL	13	0.03	1667	66	0.093795
HSS	0.75	STEEL	13	0.03	1833	64	0.105460
HSS	0.75	STEEL	13	0.03	2000	60	0.126006
HSS	0.75	STEEL	16	0.01	1500	88	0.061495
HSS	0.75	STEEL	16	0.01	1667	80	0.077886
HSS	0.75	STEEL	16	0.01	1833	79	0.085417
HSS	0.75	STEEL	16	0.01	2000	67	0.089577
HSS	0.75	STEEL	16	0.02	1500	79	0.092653
HSS	0.75	STEEL	16	0.02	1667	76	0.079203
HSS	0.75	STEEL	16	0.02	1833	67	0.099086
HSS	0.75	STEEL	16	0.02	2000	61	0.110423

HSS	0.75	STEEL	16	0.03	1500	57	0.081481
HSS	0.75	STEEL	16	0.03	1667	52	0.093869
HSS	0.75	STEEL	16	0.03	1833	48	0.102970
HSS	0.75	STEEL	16	0.03	2000	45	0.128340

Design 7

Tool Mat'l	Tool Dia.	Workpiece Mat'l	Feed Rate	Depth of Cut	Spindle Speed	Measured Ra Average	Measured VI
CAR	0.75	AL	8	0.01	1500	48	0.032427
CAR	0.75	AL	8	0.01	1667	44	0.025771
CAR	0.75	AL	8	0.01	1833	44	0.022897
CAR	0.75	AL	8	0.01	2000	44	0.020063
CAR	0.75	AL	8	0.02	1500	47	0.031232
CAR	0.75	AL	8	0.02	1667	52	0.024138
CAR	0.75	AL	8	0.02	1833	52	0.024188
CAR	0.75	AL	8	0.02	2000	45	0.027179
CAR	0.75	AL	8	0.03	1500	48	0.018318
CAR	0.75	AL	8	0.03	1667	46	0.021718
CAR	0.75	AL	8	0.03	1833	46	0.033998
CAR	0.75	AL	8	0.03	2000	43	0.029728
CAR	0.75	AL	11	0.01	1500	54	0.041989
CAR	0.75	AL	11	0.01	1667	52	0.041521
CAR	0.75	AL	11	0.01	1833	51	0.020769
CAR	0.75	AL	11	0.01	2000	49	0.031109
CAR	0.75	AL	11	0.02	1500	57	0.043044
CAR	0.75	AL	11	0.02	1667	53	0.064287
CAR	0.75	AL	11	0.02	1833	55	0.032096
CAR	0.75	AL	11	0.02	2000	46	0.031798
CAR	0.75	AL	11	0.03	1500	60	0.034354
CAR	0.75	AL	11	0.03	1667	59	0.029681
CAR	0.75	AL	11	0.03	1833	53	0.030696
CAR	0.75	AL	11	0.03	2000	50	0.045323
CAR	0.75	AL	13	0.01	1500	51	0.037338
CAR	0.75	AL	13	0.01	1667	54	0.026969
CAR	0.75	AL	13	0.01	1833	57	0.042663
CAR	0.75	AL	13	0.01	2000	49	0.029463
CAR	0.75	AL	13	0.02	1500	57	0.035567
CAR	0.75	AL	13	0.02	1667	56	0.042147
CAR	0.75	AL	13	0.02	1833	54	0.052984
CAR	0.75	AL	13	0.02	2000	51	0.035860
CAR	0.75	AL	13	0.03	1500	56	0.029064
CAR	0.75	AL	13	0.03	1667	55	0.025920
CAR	0.75	AL	13	0.03	1833	55	0.051001
CAR	0.75	AL	13	0.03	2000	53	0.044868
CAR	0.75	AL	16	0.01	1500	57	0.040501
CAR	0.75	AL	16	0.01	1667	57	0.047024
CAR	0.75	AL	16	0.01	1833	53	0.034375
CAR	0.75	AL	16	0.01	2000	56	0.048419
CAR	0.75	AL	16	0.02	1500	60	0.045772
CAR	0.75	AL	16	0.02	1667	57	0.049949
CAR	0.75	AL	16	0.02	1833	56	0.076975
CAR	0.75	AL	16	0.02	2000	47	0.065240

CAR	0.75	AL	16	0.03	1500	57	0.053346
CAR	0.75	AL	16	0.03	1667	58	0.036564
CAR	0.75	AL	16	0.03	1833	57	0.041629
CAR	0.75	AL	16	0.03	2000	53	0.041694

Design 8

Tool Mat'l	Tool Dia.	Workpiece Mat'l	Feed Rate	Depth of Cut	Spindle Speed	Measured Ra Average	Measured VI
CAR	0.75	STEEL	8	0.01	1500	52	0.016952
CAR	0.75	STEEL	8	0.01	1667	50	0.036747
CAR	0.75	STEEL	8	0.01	1833	75	0.062593
CAR	0.75	STEEL	8	0.01	2000	82	0.043988
CAR	0.75	STEEL	8	0.02	1500	92	0.064152
CAR	0.75	STEEL	8	0.02	1667	81	0.060910
CAR	0.75	STEEL	8	0.02	1833	83	0.069300
CAR	0.75	STEEL	8	0.02	2000	83	0.074339
CAR	0.75	STEEL	8	0.03	1500	80	0.067588
CAR	0.75	STEEL	8	0.03	1667	81	0.075522
CAR	0.75	STEEL	8	0.03	1833	85	0.091361
CAR	0.75	STEEL	8	0.03	2000	70	0.072815
CAR	0.75	STEEL	11	0.01	1500	79	0.063089
CAR	0.75	STEEL	11	0.01	1667	91	0.066292
CAR	0.75	STEEL	11	0.01	1833	89	0.073593
CAR	0.75	STEEL	11	0.01	2000	99	0.074915
CAR	0.75	STEEL	11	0.02	1500	93	0.081317
CAR	0.75	STEEL	11	0.02	1667	37	0.031000
CAR	0.75	STEEL	11	0.02	1833	91	0.061328
CAR	0.75	STEEL	11	0.02	2000	77	0.071810
CAR	0.75	STEEL	11	0.03	1500	83	0.076349
CAR	0.75	STEEL	11	0.03	1667	76	0.072240
CAR	0.75	STEEL	11	0.03	1833	88	0.069325
CAR	0.75	STEEL	11	0.03	2000	79	0.089199
CAR	0.75	STEEL	13	0.01	1500	49	0.019761
CAR	0.75	STEEL	13	0.01	1667	55	0.019860
CAR	0.75	STEEL	13	0.01	1833	78	0.030244
CAR	0.75	STEEL	13	0.01	2000	52	0.026989
CAR	0.75	STEEL	13	0.02	1500	47	0.039513
CAR	0.75	STEEL	13	0.02	1667	120	0.038471
CAR	0.75	STEEL	13	0.02	1833	85	0.042902
CAR	0.75	STEEL	13	0.02	2000	110	0.028063
CAR	0.75	STEEL	13	0.03	1500	124	0.031262
CAR	0.75	STEEL	13	0.03	1667	70	0.056180
CAR	0.75	STEEL	13	0.03	1833	77	0.034918
CAR	0.75	STEEL	13	0.03	2000	67	0.036054
CAR	0.75	STEEL	16	0.01	1500	66	0.034568
CAR	0.75	STEEL	16	0.01	1667	67	0.027813
CAR	0.75	STEEL	16	0.01	1833	80	0.040682
CAR	0.75	STEEL	16	0.01	2000	69	0.036635
CAR	0.75	STEEL	16	0.02	1500	87	0.024372
CAR	0.75	STEEL	16	0.02	1667	65	0.037552
CAR	0.75	STEEL	16	0.02	1833	67	0.032681
CAR	0.75	STEEL	16	0.02	2000	64	0.033025

CAR	0.75	STEEL	16	0.03	1500	34	0.041685
CAR	0.75	STEEL	16	0.03	1667	48	0.043844
CAR	0.75	STEEL	16	0.03	1833	52	0.076615
CAR	0.75	STEEL	16	0.03	2000	33	0.042749

APPENDIX C. TESTING DATA SET

Training Data Set 64 Samples (8 Designs)

Design 1 old

Tool Mat'l	Tool Dia.	Workpiece Mat'l	Feed Rate	Depth of Cut	Spindle Speed	Measured Ra Avg.	Measured Vi
HSS	0.5	AL	10	0.015	1583	45	0.074005
HSS	0.5	AL	10	0.015	1917	48	0.083071
HSS	0.5	AL	10	0.025	1583	46	0.082082
HSS	0.5	AL	10	0.025	1917	35	0.111917
HSS	0.5	AL	14	0.015	1583	60	0.089972
HSS	0.5	AL	14	0.015	1917	43	0.045687
HSS	0.5	AL	14	0.025	1583	68	0.143090
HSS	0.5	AL	14	0.025	1917	96	0.082533

Design 1 replacement

HSS	0.5	AL	11	0.01	1667	17	0.067297
HSS	0.5	AL	11	0.01	1833	13	0.035852
HSS	0.5	AL	11	0.02	1667	19	0.107315
HSS	0.5	AL	11	0.02	1833	17	0.029973
HSS	0.5	AL	13	0.01	1667	19	0.049736
HSS	0.5	AL	13	0.01	1833	15	0.055171
HSS	0.5	AL	13	0.02	1667	18	0.147852
HSS	0.5	AL	13	0.02	1833	18	0.082295

Design 2

HSS	0.5	STEEL	10	0.015	1583	121	0.039013
HSS	0.5	STEEL	10	0.015	1917	100	0.051130
HSS	0.5	STEEL	10	0.025	1583	127	0.045163
HSS	0.5	STEEL	10	0.025	1917	116	0.051896
HSS	0.5	STEEL	14	0.015	1583	114	0.041261
HSS	0.5	STEEL	14	0.015	1917	112	0.038684
HSS	0.5	STEEL	14	0.025	1583	115	0.067469
HSS	0.5	STEEL	14	0.025	1917	138	0.046849

Design 3

CAR	0.5	AL	10	0.015	1583	53	0.025988
CAR	0.5	AL	10	0.015	1917	41	0.025079
CAR	0.5	AL	10	0.025	1583	43	0.030685
CAR	0.5	AL	10	0.025	1917	35	0.024974
CAR	0.5	AL	14	0.015	1583	65	0.031418
CAR	0.5	AL	14	0.015	1917	67	0.032304
CAR	0.5	AL	14	0.025	1583	64	0.032074
CAR	0.5	AL	14	0.025	1917	44	0.039749

Design 4

CAR	0.5	STEEL	10	0.015	1583	66	0.030246
CAR	0.5	STEEL	10	0.015	1917	85	0.040331
CAR	0.5	STEEL	10	0.025	1583	86	0.042672
CAR	0.5	STEEL	10	0.025	1917	74	0.039562
CAR	0.5	STEEL	14	0.015	1583	79	0.052529
CAR	0.5	STEEL	14	0.015	1917	51	0.045131
CAR	0.5	STEEL	14	0.025	1583	45	0.041114
CAR	0.5	STEEL	14	0.025	1917	45	0.047443

Design 5 old

HSS	0.75	AL	10	0.015	1583	51	0.053463
HSS	0.75	AL	10	0.015	1917	42	0.060989
HSS	0.75	AL	10	0.025	1583	54	0.063705
HSS	0.75	AL	10	0.025	1917	50	0.068671
HSS	0.75	AL	14	0.015	1583	44	0.074193
HSS	0.75	AL	14	0.015	1917	38	0.074559
HSS	0.75	AL	14	0.025	1583	50	0.078998
HSS	0.75	AL	14	0.025	1917	42	0.070106

Design 5 replacement

HSS	0.75	AL	11	0.01	1667	17	0.057847
HSS	0.75	AL	11	0.01	1833	19	0.081686
HSS	0.75	AL	11	0.02	1667	16	0.073322
HSS	0.75	AL	11	0.02	1833	17	0.087465
HSS	0.75	AL	13	0.01	1667	18	0.065458
HSS	0.75	AL	13	0.01	1833	17	0.067093
HSS	0.75	AL	13	0.02	1667	16	0.089907
HSS	0.75	AL	13	0.02	1833	16	0.073419

Design 6

HSS	0.75	STEEL	10	0.015	1583	28	0.039587
HSS	0.75	STEEL	10	0.015	1917	26	0.063742
HSS	0.75	STEEL	10	0.025	1583	35	0.045810
HSS	0.75	STEEL	10	0.025	1917	25	0.050177
HSS	0.75	STEEL	14	0.015	1583	55	0.082344
HSS	0.75	STEEL	14	0.015	1917	58	0.067212
HSS	0.75	STEEL	14	0.025	1583	63	0.055368
HSS	0.75	STEEL	14	0.025	1917	74	0.064248

Design 7

CAR	0.75	AL	10	0.015	1583	56	0.033547
CAR	0.75	AL	10	0.015	1917	58	0.041877
CAR	0.75	AL	10	0.025	1583	57	0.047646
CAR	0.75	AL	10	0.025	1917	66	0.050182
CAR	0.75	AL	14	0.015	1583	62	0.048540
CAR	0.75	AL	14	0.015	1917	60	0.066656
CAR	0.75	AL	14	0.025	1583	63	0.042287
CAR	0.75	AL	14	0.025	1917	58	0.055368

Design 8

CAR	0.75	STEEL	10	0.015	1583	62	0.065757
CAR	0.75	STEEL	10	0.015	1917	61	0.078400
CAR	0.75	STEEL	10	0.025	1583	51	0.084584
CAR	0.75	STEEL	10	0.025	1917	53	0.082142
CAR	0.75	STEEL	14	0.015	1583	61	0.074269
CAR	0.75	STEEL	14	0.015	1917	64	0.067714
CAR	0.75	STEEL	14	0.025	1583	62	0.083270
CAR	0.75	STEEL	14	0.025	1917	44	0.124153

APPENDIX D. FUZZY RULE BASE

Fuzzy Rules Per Design: 135 total rules.
Fuzzy Regions Designation: 1 = S3, 2 = S2, 3 = S1, 4 = MD, 5 = L1, 6 = L2, 7 = L3.

Design 1 (135 rules)

Index	Feed	Depth	Spin	Vi	Ra
1	1	1	1	1	2
2	1	1	1	2	3
3	1	1	1	3	3
4	1	1	1	4	2
5	1	1	1	5	3
6	1	1	2	1	2
7	1	1	2	2	3
8	1	1	2	3	3
9	1	1	2	4	3
10	1	1	2	5	4
11	1	1	3	1	1
12	1	1	3	2	2
13	1	1	3	3	2
14	1	1	3	4	4
15	1	1	3	5	4
16	1	2	1	1	3
17	1	2	1	2	3
18	1	2	1	3	3
19	1	2	1	4	5
20	1	2	1	5	5
21	1	2	2	1	2
22	1	2	2	2	3
23	1	2	2	3	3
24	1	2	2	4	5
25	1	2	2	5	5
26	1	2	3	1	1
27	1	2	3	2	1
28	1	2	3	3	2
29	1	2	3	4	2
30	1	2	3	5	2
31	1	3	1	1	2
32	1	3	1	2	3
33	1	3	1	3	5
34	1	3	1	4	6
35	1	3	1	5	6
36	1	3	2	1	2
37	1	3	2	2	3
38	1	3	2	3	4
39	1	3	2	4	5
40	1	3	2	5	5
41	1	3	3	1	1
42	1	3	3	2	2
43	1	3	3	3	2
44	1	3	3	4	2
45	1	3	3	5	3
46	2	1	1	1	2
47	2	1	1	2	2
48	2	1	1	3	3
49	2	1	1	4	3
50	2	1	1	5	4
51	2	1	2	1	2
52	2	1	2	2	2
53	2	1	2	3	2
54	2	1	2	4	3
55	2	1	2	5	4
56	2	1	3	1	1
57	2	1	3	2	2
58	2	1	3	3	2
59	2	1	3	4	4
60	2	1	3	5	4
61	2	2	1	1	2
62	2	2	1	2	2
63	2	2	1	3	3
64	2	2	1	4	3
65	2	2	1	5	5
66	2	2	2	1	2
67	2	2	2	2	3
68	2	2	2	3	3
69	2	2	2	4	4
70	2	2	2	5	4
71	2	2	3	1	3
72	2	2	3	2	3
73	2	2	3	3	3
74	2	2	3	4	4
75	2	2	3	5	4
76	2	3	1	1	3
77	2	3	1	2	3
78	2	3	1	3	4
79	2	3	1	4	5
80	2	3	1	5	5
81	2	3	2	1	4
82	2	3	2	2	4
83	2	3	2	3	4
84	2	3	2	4	6
85	2	3	2	5	6
86	2	3	3	1	3
87	2	3	3	2	4
88	2	3	3	3	5
89	2	3	3	4	5
90	2	3	3	5	5
91	3	1	1	1	2
92	3	1	1	2	3
93	3	1	1	3	3
94	3	1	1	4	3
95	3	1	1	5	3
96	3	1	2	1	3
97	3	1	2	2	3
98	3	1	2	3	3
99	3	1	2	4	4
100	3	1	2	5	3
101	3	1	3	1	3
102	3	1	3	2	2
103	3	1	3	3	3
104	3	1	3	4	2
105	3	1	3	5	3
106	3	2	1	1	3
107	3	2	1	2	4
108	3	2	1	3	4
109	3	2	1	4	4
110	3	2	1	5	4

111	3	2	2	1	4
112	3	2	2	2	5
113	3	2	2	3	3
114	3	2	2	4	3
115	3	2	2	5	4
116	3	2	3	1	3
117	3	2	3	2	3
118	3	2	3	3	2
119	3	2	3	4	3
120	3	2	3	5	3
121	3	3	1	1	2
122	3	3	1	2	2
123	3	3	1	3	3
124	3	3	1	4	4
125	3	3	1	5	4
126	3	3	2	1	2
127	3	3	2	2	2
128	3	3	2	3	3
129	3	3	2	4	4
130	3	3	2	5	4
131	3	3	3	1	2
132	3	3	3	2	2
133	3	3	3	3	3
134	3	3	3	4	3
135	3	3	3	5	3

Design 2 (135 rules)

Index	Feed	Depth	Spin	Vi	Ra
1	1	1	1	1	1
2	1	1	1	2	1
3	1	1	1	3	2
4	1	1	1	4	2
5	1	1	1	5	2
6	1	1	2	1	2
7	1	1	2	2	3
8	1	1	2	3	3
9	1	1	2	4	4
10	1	1	2	5	4
11	1	1	3	1	3
12	1	1	3	2	3
13	1	1	3	3	2
14	1	1	3	4	2
15	1	1	3	5	2
16	1	2	1	1	3
17	1	2	1	2	3
18	1	2	1	3	3
19	1	2	1	4	4
20	1	2	1	5	4
21	1	2	2	1	2
22	1	2	2	2	2
23	1	2	2	3	3
24	1	2	2	4	3
25	1	2	2	5	4
26	1	2	3	1	2
27	1	2	3	2	2
28	1	2	3	3	2
29	1	2	3	4	2
30	1	2	3	5	2
31	1	3	1	1	3
32	1	3	1	2	3
33	1	3	1	3	3
34	1	3	1	4	4
35	1	3	1	5	4
36	1	3	2	1	2
37	1	3	2	2	2
38	1	3	2	3	3
39	1	3	2	4	3
40	1	3	2	5	4
41	1	3	3	1	2
42	1	3	3	2	2
43	1	3	3	3	2
44	1	3	3	4	2
45	1	3	3	5	2
46	2	1	1	1	4
47	2	1	1	2	4
48	2	1	1	3	4
49	2	1	1	4	5
50	2	1	1	5	5
51	2	1	2	1	4
52	2	1	2	2	4
53	2	1	2	3	5
54	2	1	2	4	6
55	2	1	2	5	6
56	2	1	3	1	3
57	2	1	3	2	4
58	2	1	3	3	4
59	2	1	3	4	5
60	2	1	3	5	5
61	2	2	1	1	5
62	2	2	1	2	6
63	2	2	1	3	6
64	2	2	1	4	6
65	2	2	1	5	7
66	2	2	2	1	6
67	2	2	2	2	6
68	2	2	2	3	6
69	2	2	2	4	7
70	2	2	2	5	7
71	2	2	3	1	3
72	2	2	3	2	4
73	2	2	3	3	4
74	2	2	3	4	5
75	2	2	3	5	4
76	2	3	1	1	5
77	2	3	1	2	5
78	2	3	1	3	6
79	2	3	1	4	6
80	2	3	1	5	6
81	2	3	2	1	5
82	2	3	2	2	5
83	2	3	2	3	6
84	2	3	2	4	6
85	2	3	2	5	6
86	2	3	3	1	4
87	2	3	3	2	4
88	2	3	3	3	4
89	2	3	3	4	5
90	2	3	3	5	5
91	3	1	1	1	7
92	3	1	1	2	7
93	3	1	1	3	7
94	3	1	1	4	7
95	3	1	1	5	7
96	3	1	2	1	6
97	3	1	2	2	6
98	3	1	2	3	7
99	3	1	2	4	7

100	3	1	2	5	7
101	3	1	3	1	5
102	3	1	3	2	5
103	3	1	3	3	5
104	3	1	3	4	5
105	3	1	3	5	6
106	3	2	1	1	5
107	3	2	1	2	5
108	3	2	1	3	6
109	3	2	1	4	7
110	3	2	1	5	7
111	3	2	2	1	4
112	3	2	2	2	4
113	3	2	2	3	5
114	3	2	2	4	5
115	3	2	2	5	5
116	3	2	3	1	3
117	3	2	3	2	4
118	3	2	3	3	4
119	3	2	3	4	5
120	3	2	3	5	5
121	3	3	1	1	7
122	3	3	1	2	7
123	3	3	1	3	7
124	3	3	1	4	7
125	3	3	1	5	7
126	3	3	2	1	5
127	3	3	2	2	5
128	3	3	2	3	6
129	3	3	2	4	6
130	3	3	2	5	4
131	3	3	3	1	3
132	3	3	3	2	4
133	3	3	3	3	4
134	3	3	3	4	4
135	3	3	3	5	5

Design 3 (135 rules)

Index	Feed	Depth	Spin	Vi	Ra
1	1	1	1	1	1
2	1	1	1	2	1
3	1	1	1	3	1
4	1	1	1	4	1
5	1	1	1	5	1
6	1	1	2	1	1
7	1	1	2	2	1
8	1	1	2	3	1
9	1	1	2	4	1
10	1	1	2	5	1
11	1	1	3	1	1
12	1	1	3	2	1
13	1	1	3	3	1
14	1	1	3	4	1
15	1	1	3	5	1
16	1	2	1	1	1
17	1	2	1	2	1
18	1	2	1	3	1
19	1	2	1	4	1
20	1	2	1	5	2
21	1	2	2	1	1
22	1	2	2	2	1
23	1	2	2	3	1
24	1	2	2	4	1
25	1	2	2	5	1
26	1	2	3	1	1
27	1	2	3	2	1
28	1	2	3	3	1
29	1	2	3	4	1
30	1	2	3	5	1
31	1	3	1	1	1
32	1	3	1	2	1
33	1	3	1	3	1
34	1	3	1	4	1
35	1	3	1	5	1
36	1	3	2	1	1
37	1	3	2	2	1
38	1	3	2	3	1
39	1	3	2	4	1
40	1	3	2	5	2
41	1	3	3	1	1
42	1	3	3	2	1
43	1	3	3	3	1
44	1	3	3	4	1
45	1	3	3	5	2
46	2	1	1	1	1
47	2	1	1	2	1
48	2	1	1	3	1
49	2	1	1	4	1
50	2	1	1	5	2
51	2	1	2	1	1
52	2	1	2	2	1
53	2	1	2	3	1
54	2	1	2	4	1
55	2	1	2	5	2
56	2	1	3	1	1
57	2	1	3	2	1
58	2	1	3	3	1
59	2	1	3	4	1
60	2	1	3	5	2
61	2	2	1	1	1
62	2	2	1	2	1
63	2	2	1	3	1
64	2	2	1	4	2
65	2	2	1	5	2
66	2	2	2	1	1
67	2	2	2	2	1
68	2	2	2	3	1
69	2	2	2	4	2
70	2	2	2	5	2
71	2	2	3	1	1
72	2	2	3	2	1
73	2	2	3	3	1
74	2	2	3	4	1
75	2	2	3	5	1
76	2	3	1	1	1
77	2	3	1	2	1
78	2	3	1	3	1
79	2	3	1	4	1
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82	2	3	2	2	1
83	2	3	2	3	1
84	2	3	2	4	2
85	2	3	2	5	2
86	2	3	3	1	1
87	2	3	3	2	1
88	2	3	3	3	1

89	2	3	3	4	2
90	2	3	3	5	2
91	3	1	1	1	3
92	3	1	1	2	3
93	3	1	1	3	4
94	3	1	1	4	4
95	3	1	1	5	5
96	3	1	2	1	2
97	3	1	2	2	2
98	3	1	2	3	3
99	3	1	2	4	3
100	3	1	2	5	4
101	3	1	3	1	2
102	3	1	3	2	2
103	3	1	3	3	2
104	3	1	3	4	3
105	3	1	3	5	4
106	3	2	1	1	2
107	3	2	1	2	2
108	3	2	1	3	3
109	3	2	1	4	4
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111	3	2	2	1	2
112	3	2	2	2	3
113	3	2	2	3	3
114	3	2	2	4	4
115	3	2	2	5	5
116	3	2	3	1	2
117	3	2	3	2	3
118	3	2	3	3	3
119	3	2	3	4	4
120	3	2	3	5	5
121	3	3	1	1	3
122	3	3	1	2	4
123	3	3	1	3	4
124	3	3	1	4	5
125	3	3	1	5	6
126	3	3	2	1	3
127	3	3	2	2	4
128	3	3	2	3	4
129	3	3	2	4	5
130	3	3	2	5	6
131	3	3	3	1	2
132	3	3	3	2	3
133	3	3	3	3	3
134	3	3	3	4	4
135	3	3	3	5	5

Design 4 (135 rules)

Index	Feed	Depth	Spin	Vi	Ra
1	1	1	1	1	1
2	1	1	1	2	2
3	1	1	1	3	3
4	1	1	1	4	3
5	1	1	1	5	3
6	1	1	2	1	2
7	1	1	2	2	2
8	1	1	2	3	3
9	1	1	2	4	3
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12	1	1	3	2	3
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14	1	1	3	4	4
15	1	1	3	5	4
16	1	2	1	1	1
17	1	2	1	2	2
18	1	2	1	3	3
19	1	2	1	4	4
20	1	2	1	5	4
21	1	2	2	1	2
22	1	2	2	2	3
23	1	2	2	3	4
24	1	2	2	4	5
25	1	2	2	5	5
26	1	2	3	1	2
27	1	2	3	2	2
28	1	2	3	3	3
29	1	2	3	4	3
30	1	2	3	5	3
31	1	3	1	1	3
32	1	3	1	2	4
33	1	3	1	3	5
34	1	3	1	4	6
35	1	3	1	5	6
36	1	3	2	1	3
37	1	3	2	2	3
38	1	3	2	3	3
39	1	3	2	4	5
40	1	3	2	5	6
41	1	3	3	1	1
42	1	3	3	2	2
43	1	3	3	3	2
44	1	3	3	4	2
45	1	3	3	5	2
46	2	1	1	1	2
47	2	1	1	2	3
48	2	1	1	3	3
49	2	1	1	4	3
50	2	1	1	5	4
51	2	1	2	1	3
52	2	1	2	2	3
53	2	1	2	3	4
54	2	1	2	4	4
55	2	1	2	5	4
56	2	1	3	1	3
57	2	1	3	2	4
58	2	1	3	3	5
59	2	1	3	4	4
60	2	1	3	5	4
61	2	2	1	1	3
62	2	2	1	2	4
63	2	2	1	3	3
64	2	2	1	4	4
65	2	2	1	5	5
66	2	2	2	1	2
67	2	2	2	2	3
68	2	2	2	3	3
69	2	2	2	4	3
70	2	2	2	5	4
71	2	2	3	1	3
72	2	2	3	2	4
73	2	2	3	3	5
74	2	2	3	4	3
75	2	2	3	5	4
76	2	3	1	1	2
77	2	3	1	2	3

78	2	3	1	3	4
79	2	3	1	4	5
80	2	3	1	5	4
81	2	3	2	1	3
82	2	3	2	2	4
83	2	3	2	3	5
84	2	3	2	4	6
85	2	3	2	5	6
86	2	3	3	1	3
87	2	3	3	2	4
88	2	3	3	3	5
89	2	3	3	4	5
90	2	3	3	5	5
91	3	1	1	1	2
92	3	1	1	2	2
93	3	1	1	3	2
94	3	1	1	4	3
95	3	1	1	5	3
96	3	1	2	1	1
97	3	1	2	2	1
98	3	1	2	3	2
99	3	1	2	4	3
100	3	1	2	5	3
101	3	1	3	1	1
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103	3	1	3	3	1
104	3	1	3	4	2
105	3	1	3	5	2
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112	3	2	2	2	2
113	3	2	2	3	3
114	3	2	2	4	4
115	3	2	2	5	4
116	3	2	3	1	1
117	3	2	3	2	1
118	3	2	3	3	2
119	3	2	3	4	3
120	3	2	3	5	3
121	3	3	1	1	1
122	3	3	1	2	2
123	3	3	1	3	3
124	3	3	1	4	4
125	3	3	1	5	4
126	3	3	2	1	2
127	3	3	2	2	2
128	3	3	2	3	3
129	3	3	2	4	4
130	3	3	2	5	4
131	3	3	3	1	1
132	3	3	3	2	2
133	3	3	3	3	3
134	3	3	3	4	3
135	3	3	3	5	3

Design 5 (135 rules)

Index	Feed	Depth	Spin	Vi	Ra
1	1	1	1	1	3
2	1	1	1	2	4
3	1	1	1	3	5
4	1	1	1	4	5
5	1	1	1	5	5
6	1	1	2	1	2
7	1	1	2	2	3
8	1	1	2	3	4
9	1	1	2	4	4
10	1	1	2	5	4
11	1	1	3	1	2
12	1	1	3	2	3
13	1	1	3	3	4
14	1	1	3	4	4
15	1	1	3	5	5
16	1	2	1	1	3
17	1	2	1	2	4
18	1	2	1	3	6
19	1	2	1	4	6
20	1	2	1	5	6
21	1	2	2	1	2
22	1	2	2	2	3
23	1	2	2	3	4
24	1	2	2	4	4
25	1	2	2	5	5
26	1	2	3	1	2
27	1	2	3	2	3
28	1	2	3	3	3
29	1	2	3	4	3
30	1	2	3	5	3
31	1	3	1	1	3
32	1	3	1	2	4
33	1	3	1	3	4
34	1	3	1	4	5
35	1	3	1	5	5
36	1	3	2	1	3
37	1	3	2	2	3
38	1	3	2	3	4
39	1	3	2	4	5
40	1	3	2	5	5
41	1	3	3	1	2
42	1	3	3	2	3
43	1	3	3	3	3
44	1	3	3	4	4
45	1	3	3	5	4
46	2	1	1	1	3
47	2	1	1	2	4
48	2	1	1	3	5
49	2	1	1	4	5
50	2	1	1	5	5
51	2	1	2	1	2
52	2	1	2	2	3
53	2	1	2	3	4
54	2	1	2	4	4
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58	2	1	3	3	3
59	2	1	3	4	3
60	2	1	3	5	4
61	2	2	1	1	4
62	2	2	1	2	5
63	2	2	1	3	6
64	2	2	1	4	6
65	2	2	1	5	6
66	2	2	2	1	4

67	2	2	2	2	5
68	2	2	2	3	5
69	2	2	2	4	6
70	2	2	2	5	6
71	2	2	3	1	3
72	2	2	3	2	4
73	2	2	3	3	5
74	2	2	3	4	5
75	2	2	3	5	5
76	2	3	1	1	3
77	2	3	1	2	4
78	2	3	1	3	5
79	2	3	1	4	5
80	2	3	1	5	5
81	2	3	2	1	3
82	2	3	2	2	4
83	2	3	2	3	5
84	2	3	2	4	6
85	2	3	2	5	6
86	2	3	3	1	3
87	2	3	3	2	3
88	2	3	3	3	4
89	2	3	3	4	7
90	2	3	3	5	6
91	3	1	1	1	5
92	3	1	1	2	6
93	3	1	1	3	7
94	3	1	1	4	5
95	3	1	1	5	5
96	3	1	2	1	4
97	3	1	2	2	5
98	3	1	2	3	6
99	3	1	2	4	6
100	3	1	2	5	6
101	3	1	3	1	4
102	3	1	3	2	5
103	3	1	3	3	5
104	3	1	3	4	5
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108	3	2	1	3	7
109	3	2	1	4	7
110	3	2	1	5	7
111	3	2	2	1	4
112	3	2	2	2	5
113	3	2	2	3	6
114	3	2	2	4	6
115	3	2	2	5	6
116	3	2	3	1	5
117	3	2	3	2	6
118	3	2	3	3	6
119	3	2	3	4	6
120	3	2	3	5	7
121	3	3	1	1	4
122	3	3	1	2	5
123	3	3	1	3	5
124	3	3	1	4	5
125	3	3	1	5	6
126	3	3	2	1	3
127	3	3	2	2	4
128	3	3	2	3	4
129	3	3	2	4	4
130	3	3	2	5	5
131	3	3	3	1	3
132	3	3	3	2	4
133	3	3	3	3	4
134	3	3	3	4	5
135	3	3	3	5	5

Design 6 (135 rules)

Index	Feed	Depth	Spin	Vi	Ra
1	1	1	1	1	1
2	1	1	1	2	1
3	1	1	1	3	1
4	1	1	1	4	1
5	1	1	1	5	1
6	1	1	2	1	1
7	1	1	2	2	1
8	1	1	2	3	1
9	1	1	2	4	1
10	1	1	2	5	1
11	1	1	3	1	1
12	1	1	3	2	1
13	1	1	3	3	1
14	1	1	3	4	1
15	1	1	3	5	1
16	1	2	1	1	1
17	1	2	1	2	1
18	1	2	1	3	1
19	1	2	1	4	1
20	1	2	1	5	1
21	1	2	2	1	1
22	1	2	2	2	1
23	1	2	2	3	1
24	1	2	2	4	1
25	1	2	2	5	1
26	1	2	3	1	1
27	1	2	3	2	1
28	1	2	3	3	2
29	1	2	3	4	2
30	1	2	3	5	2
31	1	3	1	1	2
32	1	3	1	2	3
33	1	3	1	3	3
34	1	3	1	4	3
35	1	3	1	5	4
36	1	3	2	1	1
37	1	3	2	2	2
38	1	3	2	3	2
39	1	3	2	4	2
40	1	3	2	5	2
41	1	3	3	1	1
42	1	3	3	2	2
43	1	3	3	3	2
44	1	3	3	4	2
45	1	3	3	5	2
46	2	1	1	1	1
47	2	1	1	2	2
48	2	1	1	3	1
49	2	1	1	4	2
50	2	1	1	5	2
51	2	1	2	1	1
52	2	1	2	2	2
53	2	1	2	3	2
54	2	1	2	4	2
55	2	1	2	5	2

56	2	1	3	1	2
57	2	1	3	2	1
58	2	1	3	3	1
59	2	1	3	4	2
60	2	1	3	5	2
61	2	2	1	1	2
62	2	2	1	2	3
63	2	2	1	3	1
64	2	2	1	4	2
65	2	2	1	5	3
66	2	2	2	1	3
67	2	2	2	2	3
68	2	2	2	3	3
69	2	2	2	4	3
70	2	2	2	5	3
71	2	2	3	1	2
72	2	2	3	2	2
73	2	2	3	3	2
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78	2	3	1	3	2
79	2	3	1	4	3
80	2	3	1	5	3
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82	2	3	2	2	3
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84	2	3	2	4	2
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86	2	3	3	1	2
87	2	3	3	2	2
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89	2	3	3	4	4
90	2	3	3	5	4
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92	3	1	1	2	2
93	3	1	1	3	4
94	3	1	1	4	4
95	3	1	1	5	4
96	3	1	2	1	1
97	3	1	2	2	2
98	3	1	2	3	2
99	3	1	2	4	2
100	3	1	2	5	2
101	3	1	3	1	2
102	3	1	3	2	3
103	3	1	3	3	3
104	3	1	3	4	3
105	3	1	3	5	3
106	3	2	1	1	2
107	3	2	1	2	3
108	3	2	1	3	3
109	3	2	1	4	4
110	3	2	1	5	4
111	3	2	2	1	1
112	3	2	2	2	2
113	3	2	2	3	3
114	3	2	2	4	3
115	3	2	2	5	3
116	3	2	3	1	1
117	3	2	3	2	2
118	3	2	3	3	2
119	3	2	3	4	2
120	3	2	3	5	2
121	3	3	1	1	3
122	3	3	1	2	4
123	3	3	1	3	4
124	3	3	1	4	4
125	3	3	1	5	4
126	3	3	2	1	3
127	3	3	2	2	4
128	3	3	2	3	4
129	3	3	2	4	4
130	3	3	2	5	4
131	3	3	3	1	5
132	3	3	3	2	5
133	3	3	3	3	6
134	3	3	3	4	6
135	3	3	3	5	6

Design 7 (135 rules)

Index	Feed	Depth	Spin	Vi	Ra
1	1	1	1	1	2
2	1	1	1	2	5
3	1	1	1	3	4
4	1	1	1	4	2
5	1	1	1	5	3
6	1	1	2	1	5
7	1	1	2	2	6
8	1	1	2	3	7
9	1	1	2	4	7
10	1	1	2	5	7
11	1	1	3	1	5
12	1	1	3	2	6
13	1	1	3	3	6
14	1	1	3	4	6
15	1	1	3	5	7
16	1	2	1	1	4
17	1	2	1	2	4
18	1	2	1	3	7
19	1	2	1	4	7
20	1	2	1	5	7
21	1	2	2	1	4
22	1	2	2	2	5
23	1	2	2	3	5
24	1	2	2	4	6
25	1	2	2	5	6
26	1	2	3	1	3
27	1	2	3	2	3
28	1	2	3	3	6
29	1	2	3	4	7
30	1	2	3	5	7
31	1	3	1	1	5
32	1	3	1	2	6
33	1	3	1	3	6
34	1	3	1	4	7
35	1	3	1	5	7
36	1	3	2	1	5
37	1	3	2	2	6
38	1	3	2	3	6
39	1	3	2	4	7
40	1	3	2	5	7
41	1	3	3	1	5
42	1	3	3	2	6
43	1	3	3	3	6
44	1	3	3	4	7

45	1	3	3	5	7
46	2	1	1	1	2
47	2	1	1	2	5
48	2	1	1	3	4
49	2	1	1	4	2
50	2	1	1	5	3
51	2	1	2	1	5
52	2	1	2	2	6
53	2	1	2	3	7
54	2	1	2	4	7
55	2	1	2	5	7
56	2	1	3	1	5
57	2	1	3	2	5
58	2	1	3	3	6
59	2	1	3	4	6
60	2	1	3	5	7
61	2	2	1	1	4
62	2	2	1	2	4
63	2	2	1	3	7
64	2	2	1	4	7
65	2	2	1	5	7
66	2	2	2	1	4
67	2	2	2	2	5
68	2	2	2	3	5
69	2	2	2	4	6
70	2	2	2	5	6
71	2	2	3	1	3
72	2	2	3	2	3
73	2	2	3	3	6
74	2	2	3	4	7
75	2	2	3	5	7
76	2	3	1	1	5
77	2	3	1	2	6
78	2	3	1	3	6
79	2	3	1	4	7
80	2	3	1	5	7
81	2	3	2	1	5
82	2	3	2	2	6
83	2	3	2	3	6
84	2	3	2	4	7
85	2	3	2	5	7
86	2	3	3	1	5
87	2	3	3	2	6
88	2	3	3	3	7
89	2	3	3	4	7
90	2	3	3	5	7
91	3	1	1	1	4
92	3	1	1	2	4
93	3	1	1	3	4
94	3	1	1	4	5
95	3	1	1	5	5
96	3	1	2	1	5
97	3	1	2	2	5
98	3	1	2	3	5
99	3	1	2	4	5
100	3	1	2	5	6
101	3	1	3	1	3
102	3	1	3	2	4
103	3	1	3	3	4
104	3	1	3	4	4
105	3	1	3	5	4
106	3	2	1	1	6
107	3	2	1	2	6
108	3	2	1	3	6
109	3	2	1	4	6
110	3	2	1	5	6
111	3	2	2	1	6
112	3	2	2	2	6
113	3	2	2	3	6
114	3	2	2	4	7
115	3	2	2	5	7
116	3	2	3	1	5
117	3	2	3	2	6
118	3	2	3	3	6
119	3	2	3	4	7
120	3	2	3	5	7
121	3	3	1	1	6
122	3	3	1	2	6
123	3	3	1	3	6
124	3	3	1	4	6
125	3	3	1	5	6
126	3	3	2	1	5
127	3	3	2	2	5
128	3	3	2	3	6
129	3	3	2	4	7
130	3	3	2	5	6
131	3	3	3	1	5
132	3	3	3	2	6
133	3	3	3	3	6
134	3	3	3	4	7
135	3	3	3	5	7

Design 8 (135 rules)

Index	Feed	Depth	Spin	Vi	Ra
1	1	1	1	1	2
2	1	1	1	2	3
3	1	1	1	3	3
4	1	1	1	4	3
5	1	1	1	5	3
6	1	1	2	1	2
7	1	1	2	2	2
8	1	1	2	3	3
9	1	1	2	4	3
10	1	1	2	5	3
11	1	1	3	1	1
12	1	1	3	2	2
13	1	1	3	3	2
14	1	1	3	4	2
15	1	1	3	5	3
16	1	2	1	1	2
17	1	2	1	2	2
18	1	2	1	3	3
19	1	2	1	4	4
20	1	2	1	5	4
21	1	2	2	1	1
22	1	2	2	2	1
23	1	2	2	3	1
24	1	2	2	4	2
25	1	2	2	5	3
26	1	2	3	1	1
27	1	2	3	2	1
28	1	2	3	3	2
29	1	2	3	4	2
30	1	2	3	5	2
31	1	3	1	1	1
32	1	3	1	2	1
33	1	3	1	3	2

34	1	3	1	4	3
35	1	3	1	5	4
36	1	3	2	1	1
37	1	3	2	2	1
38	1	3	2	3	2
39	1	3	2	4	3
40	1	3	2	5	3
41	1	3	3	1	1
42	1	3	3	2	1
43	1	3	3	3	1
44	1	3	3	4	2
45	1	3	3	5	2
46	2	1	1	1	1
47	2	1	1	2	1
48	2	1	1	3	2
49	2	1	1	4	3
50	2	1	1	5	3
51	2	1	2	1	1
52	2	1	2	2	1
53	2	1	2	3	1
54	2	1	2	4	2
55	2	1	2	5	3
56	2	1	3	1	1
57	2	1	3	2	1
58	2	1	3	3	2
59	2	1	3	4	2
60	2	1	3	5	2
61	2	2	1	1	1
62	2	2	1	2	2
63	2	2	1	3	3
64	2	2	1	4	4
65	2	2	1	5	4
66	2	2	2	1	1
67	2	2	2	2	2
68	2	2	2	3	3
69	2	2	2	4	2
70	2	2	2	5	3
71	2	2	3	1	2
72	2	2	3	2	2
73	2	2	3	3	3
74	2	2	3	4	2
75	2	2	3	5	3
76	2	3	1	1	2
77	2	3	1	2	2
78	2	3	1	3	3
79	2	3	1	4	4
80	2	3	1	5	4
81	2	3	2	1	2
82	2	3	2	2	2
83	2	3	2	3	2
84	2	3	2	4	3
85	2	3	2	5	3
86	2	3	3	1	1
87	2	3	3	2	1
88	2	3	3	3	1
89	2	3	3	4	2
90	2	3	3	5	2
91	3	1	1	1	1
92	3	1	1	2	1
93	3	1	1	3	1
94	3	1	1	4	2
95	3	1	1	5	3
96	3	1	2	1	1
97	3	1	2	2	1
98	3	1	2	3	1
99	3	1	2	4	2
100	3	1	2	5	3
101	3	1	3	1	1
102	3	1	3	2	1
103	3	1	3	3	1
104	3	1	3	4	2
105	3	1	3	5	2
106	3	2	1	1	2
107	3	2	1	2	2
108	3	2	1	3	3
109	3	2	1	4	4
110	3	2	1	5	4
111	3	2	2	1	2
112	3	2	2	2	2
113	3	2	2	3	3
114	3	2	2	4	3
115	3	2	2	5	3
116	3	2	3	1	2
117	3	2	3	2	2
118	3	2	3	3	3
119	3	2	3	4	3
120	3	2	3	5	2
121	3	3	1	1	2
122	3	3	1	2	2
123	3	3	1	3	2
124	3	3	1	4	3
125	3	3	1	5	3
126	3	3	2	1	1
127	3	3	2	2	1
128	3	3	2	3	1
129	3	3	2	4	2
130	3	3	2	5	2
131	3	3	3	1	1
132	3	3	3	2	1
133	3	3	3	3	1
134	3	3	3	4	1
135	3	3	3	5	1

APPENDIX E. CALCULATIONS

Determine the degree of input-output data obtained from the successful experiment.

1. Set parameters
2. Run sample
3. Collect vibration signal during machining
4. Measure surface of sample with profilometer.

Testing data setup and results

Feed is 13 ipm

Depth of cut is 0.03 inches

Spindle speed is 2000 rpm

Average vibration is 0.027413 μv

Average Ra is 110 μi

Design input-output pairs to regions with a maximum degree

Calculate the maximum degree for factors

Feed (F) = 13

degree for region MD = (19-13)/7* = 0.8571

degree for region L1 = (13-12)/7* = 0.1428

feed value of 13 is assigned to region MD

Depth of cut (D) is 0.03

degree for region MD = (0.039- 0.03)/0.017 = 0.5294

degree for region L1 = (0.03 - 0.022)/0.017 = 0.4705

depth value of 0.03 is assigned to region MD

Spindle speed (S) is 2000 rpm

degree for region MD = (2100 - 2000)/350 = 0.2857

degree for region L1 = (2000 - 1750)/350 = 0.7142

depth value of 2000 is assigned to region L1

Vibration (V) of 0.027413 micro-volts

degree for region S1 = (0.0284 - 0.027413)/0.008273 = 0.1193

degree for region MD = (0.027413 - .0201)/0.008273 = 0.8839

vibration value of 0.027413 is assigned to region MD

Surface roughness (Ra) of 110 micro-inches

degree for region L1 = (111 - 110)/12 = 0.0833

degree for region L2 = (110 - 99)/12 = 0.9166

Ra value of 110 is assigned to region L2

Obtain one rule from one pair of designed input-output data

The resultant rule from the input-output pair is: If feed is MD, depth of cut is MD, spindle speed is L1, vibration is MD, then Ra is L2. For design 2 135 rules were develop in the proceeding manner.

Defuzzification (example calculation)

Input parameters

Feed = 13

Depth = 0.03

Spindle = 2000

Vibration (on-line) = 0.027413

The database has two possibilities for each input-output factor for feed the two possibilities are MD or L1, for depth they are MD or L1, for spindle they are MD or L1, for vibration they are S1 or MD, and for Ra the are L1 or L2. When establishing the rule for the rule base the region with the maximum degree was chosen. In order to defuzzify the output a combination table is made. There are 16 combination that are used in calculating Ra.

Defuzzification Matrix

μ_o'	(F)	(D)	(S)	(Vi)	Ra (value)	Ra * μ_o'
0.1193	MD = 0.8571	MD = 0.5294	MD = 0.2857	S1 = 0.1193	117	13.9581
0.2857	MD = 0.8571	MD = 0.5294	MD = 0.2857	MD = 0.8839	116	33.1412
0.1193	MD = 0.8571	MD = 0.5294	L1 = 0.7142	S1 = 0.1193	115	13.7195
0.5294	MD = 0.8571	MD = 0.5294	L1 = 0.7142	MD = 0.8839	114	60.3516
0.1193	MD = 0.8571	L1 = 0.4705	MD = 0.2857	S1 = 0.1193	113	13.4809
0.2857	MD = 0.8571	L1 = 0.4705	MD = 0.2857	MD = 0.8839	112	31.9984
0.1193	MD = 0.8571	L1 = 0.4705	L1 = 0.7142	S1 = 0.1193	111	13.2423
0.4705	MD = 0.8571	L1 = 0.4705	L1 = 0.7142	MD = 0.8839	109	51.2845
0.1193	L1 = 0.1428	MD = 0.5294	MD = 0.2857	S1 = 0.1193	108	12.8844
0.1428	L1 = 0.1428	MD = 0.5294	MD = 0.2857	MD = 0.8839	107	15.2796
0.1193	L1 = 0.1428	MD = 0.5294	L1 = 0.7142	S1 = 0.1193	106	12.6458
0.1428	L1 = 0.1428	MD = 0.5294	L1 = 0.7142	MD = 0.8839	105	14.994
0.1193	L1 = 0.1428	L1 = 0.4705	MD = 0.2857	S1 = 0.1193	104	12.4072
0.1428	L1 = 0.1428	L1 = 0.4705	MD = 0.2857	MD = 0.8839	103	14.7084
0.1193	L1 = 0.1428	L1 = 0.4705	L1 = 0.7142	S1 = 0.1193	102	12.1686
0.1428	L1 = 0.1428	L1 = 0.4705	L1 = 0.7142	MD = 0.8839	100	14.28
3.0969						340.5445

$$y = \frac{340.5445}{3.0969} = 109.9630$$

$$y = \frac{\sum \begin{matrix} 0.1193(117) + 0.2857(116) + 0.1193(115) + 0.5294(114) + \\ 0.1193(113) + 0.2857(112) + 0.1193(111) + 0.4705(109) + \\ 0.1193(108) + 0.1428(107) + 0.1193(106) + 0.1428(105) + \\ 0.1193(104) + 0.1428(103) + 0.1193(102) + 0.1428(100) \end{matrix}}{\sum \begin{matrix} 0.1193 + 0.2857 + .01193 + .05294 + .01193 + .02857 + .01193 + \\ .04705 + .01193 + .01428 + .01193 + .01428 + .01193 + .01428 + \\ .01193 + .01428 \end{matrix}} = 110$$

Regression calculations

Design 1

Original Testing Data

Feed	Depth	Spindle	Vibration	Feeddep	Feedspin	FeedVi	depspin	Videp	Vispin	dspv
X1	X2	X3	X4	X1X2	X1X3	X1X4	X2X3	X2X4	X3X4	X2X3X4
10	0.015	1583	0.074005	0.15	15830	0.740050	23.745	0.001110	117.1499	1.757249
10	0.015	1917	0.083071	0.15	19170	0.830710	28.755	0.001246	159.2471	2.388707
10	0.025	1583	0.082082	0.25	15830	0.820820	39.575	0.002052	129.9358	3.248395
10	0.025	1917	0.111917	0.25	19170	1.119170	47.925	0.002798	214.5449	5.363622
14	0.015	1583	0.089972	0.21	22162	1.259608	23.745	0.001350	142.4257	2.136385
14	0.015	1917	0.045687	0.21	26838	0.639618	28.755	0.000685	87.58198	1.313730
14	0.025	1583	0.143090	0.35	22162	2.003260	39.575	0.003577	226.5115	5.662787
14	0.025	1917	0.082533	0.35	26838	1.155462	47.925	0.002063	158.2158	3.955394

ENTER METHOD			FORWARD			FORWARD TRANSFORMED			
Rec Ra	ACTUAL	DIFF	Rec RA	ACTUAL	DIFF		Rec RA	ACTUAL	DIFF
15.62274	44.57143	64.94897	15.70414	44.57143	64.76636	2.758158	15.77077	44.57143	64.61687
14.11594	48.42857	70.85204	14.11810	48.42857	70.84758	2.656622	14.24808	48.42857	70.57919
18.17995	46.28571	60.72234	18.21048	46.28571	60.65636	2.878628	17.78985	46.28571	61.56514
14.11138	34.85714	59.51653	14.10394	34.85714	59.53788	2.733672	15.38929	34.85714	55.85039
23.79613	59.57143	60.05445	23.69700	59.57143	60.22086	3.168729	23.77724	59.57143	60.08618
19.18209	42.57143	54.94140	19.32743	42.57143	54.59999	2.956331	19.22730	42.57143	54.83519
26.45287	68.28571	61.26148	26.40553	68.28571	61.33081	3.289199	26.82136	68.28571	60.72186
19.94487	53.00000	62.36817	20.19903	53.00000	61.88862	3.033381	20.76734	53.00000	60.81635
Average Deviation		54.03715	Average Deviation		53.99498		Average Deviation		53.53185

Training data replacement

Feed	Depth	Spindle	Vibration	Feeddep	Feedspin	FeedVi	depspin	Videp	Vispin	dspv
X1	X2	X3	X4	X1X2	X1X3	X1X4	X2X3	X2X4	X3X4	X2X3X4
11	0.01	1667	0.067297	0.11	18337	0.740267	16.67	0.000673	112.1841	1.121841
11	0.01	1833	0.035852	0.11	20163	0.394372	18.33	0.000359	65.71672	0.657167
11	0.02	1667	0.107315	0.22	18337	1.180465	33.34	0.002146	178.8941	3.577882
11	0.02	1833	0.029973	0.22	20163	0.329703	36.66	0.000599	54.94051	1.09881
13	0.01	1667	0.049736	0.13	21671	0.646568	16.67	0.000497	82.90991	0.829099
13	0.01	1833	0.055171	0.13	23829	0.717223	18.33	0.000552	101.1284	1.011284
13	0.02	1667	0.147852	0.26	21671	1.922076	33.34	0.002957	246.4693	4.929386
13	0.02	1833	0.082295	0.26	23829	1.069835	36.66	0.001646	150.8467	3.016935

ENTER METHOD			FORWARD			FORWARD TRANSFORMED			
Ra	ACTUAL	DIFF	RA	ACTUAL	DIFF		RA	ACTUAL	DIFF
16.31721	17	4.016391	16.34902	17	3.82929	2.773519	16.0149	17	5.794725
16.47021	13	26.69396	16.4777	13	26.75157	2.720071	15.18139	13	16.77996
17.48415	19	7.978163	17.53184	19	7.727178	2.883069	17.86904	19	5.952446
16.79014	17	1.234451	16.82319	17	1.040065	2.808041	16.57741	17	2.485849
20.56707	19	8.247727	20.53295	19	8.068181	2.964864	19.39207	19	2.063506
18.66412	15	24.42749	18.65518	15	24.36788	2.883866	17.88328	15	19.22184
20.72247	18	15.12484	20.66182	18	14.78788	3.074414	21.6372	18	20.20666
19.53478	18	8.526546	19.62171	18	9.009494	2.971836	19.52774	18	8.48744
Average Deviation		10.96538	Average Deviation		10.82151		Average Deviation		9.063124

Design 2

Feed X1	Depth X2	Spindle X3	Vibration X4	Feeddep X1X2	Feedspin X1X3	FeedVi X1X4	depspin X2X3	Videp X2X4	Vispin X3X4	Dspv X2X3X4
16	0.02	1500	0.020469	0.32	24000	0.327504	30.00	0.000409	30.7035	0.61407
16	0.02	1667	0.027419	0.32	26672	0.438704	33.34	0.000548	45.70747	0.914149
16	0.02	1833	0.044919	0.32	29328	0.718704	36.66	0.000898	82.33653	1.646731
16	0.02	2000	0.028422	0.32	32000	0.454752	40.00	0.000568	56.844	1.13688
16	0.03	1500	0.029248	0.48	24000	0.467968	45.00	0.000877	43.872	1.31616
16	0.03	1667	0.042989	0.48	26672	0.687824	50.01	0.00129	71.66266	2.14988
16	0.03	1833	0.022027	0.48	29328	0.352432	54.99	0.000661	40.37549	1.211265
16	0.03	2000	0.035542	0.48	32000	0.568672	60.00	0.001066	71.084	2.13252

ENTER METHOD			FORWARD			FORWARD TRANSFORMED			
Ra	ACTUAL	DIFF	RA	ACTUAL	DIFF		RA	ACTUAL	DIFF
118.3631	114	3.645479	118.9060	114	4.120806	4.766641	117.5239	114	2.910572
114.8446	119	3.491919	114.7483	119	3.572834	4.756907	116.3854	119	2.197174
115.0394	120	4.293324	110.6156	120	7.973717	4.786324	119.8600	120	0.282879
105.8321	110	3.613728	106.4580	110	3.043752	4.690046	108.8582	110	0.857736
118.6819	106	12.388150	118.3674	106	12.090380	4.751530	115.7613	106	9.622444
114.0937	107	6.629602	115.8330	107	8.255185	4.719239	112.0829	107	4.750377
114.7130	99	15.40544	113.3138	99	13.99782	4.763998	117.2136	99	17.92109
108.2105	105	3.451698	110.7794	105	5.907686	4.732208	113.5460	105	8.552558
Average Deviation		6.183455	Average Deviation		6.631811		Average Deviation		4.817784

Design 3

Feed X1	Depth X2	Spindle X3	Vibration X4	Feeddep X1X2	Feedspin X1X3	FeedVi X1X4	depspin X2X3	Videp X2X4	Vispin X3X4	Dspv X2X3X4
10	0.015	1583	0.025988	0.15	15830	0.259880	23.745	0.000390	41.13900	0.617085
10	0.015	1917	0.025079	0.15	19170	0.250790	28.755	0.000376	48.07644	0.721147
10	0.025	1583	0.030685	0.25	15830	0.306850	39.575	0.000767	48.57436	1.214359
10	0.025	1917	0.024974	0.25	19170	0.249740	47.925	0.000624	47.87516	1.196879
14	0.015	1583	0.031418	0.21	22162	0.439852	23.745	0.000471	49.73469	0.746020
14	0.015	1917	0.032304	0.21	26838	0.452256	28.755	0.000485	61.92677	0.928902
14	0.025	1583	0.032074	0.35	22162	0.449036	39.575	0.000802	50.77314	1.269329
14	0.025	1917	0.039749	0.35	26838	0.556486	47.925	0.000994	76.19883	1.904971

ENTER METHOD			FORWARD			FORWARD TRANSFORMED			
Ra	ACTUAL	DIFF	RA	ACTUAL	DIFF		RA	ACTUAL	DIFF
64.60325	121.4286	46.79732	65.4242	121.4286	46.12125	4.123637	61.78351	121.4286	49.11946
56.50047	99.71429	43.33764	61.59972	99.71429	38.22377	4.06535	58.28532	99.71429	41.54767
66.997	127.4286	47.42388	66.90935	127.4286	47.49266	4.178255	65.2519	127.4286	48.79335
58.4377	116.1429	49.68464	61.56652	116.1429	46.99069	4.101275	60.41725	116.1429	47.98023
81.40674	114.2857	28.7691	77.41712	114.2857	32.26002	4.298267	73.5722	114.2857	35.62432
73.61353	112	34.27363	74.1602	112	33.78553	4.243879	69.67759	112	37.78787
80.34535	114.7143	29.96047	77.62454	114.7143	32.33228	4.346122	77.17858	114.7143	32.72104
74.54905	138.1429	46.03481	76.51425	138.1429	44.61223	4.317585	75.0073	138.1429	45.70309

Average Deviation	35.03083	Average Deviation	34.65078	Average Deviation	36.69674

Design 4

Feed	Depth	Spindle	Vibration	Feeddep	Feedspin	FeedVi	depspin	Videp	Vispin	Dspv
X1	X2	X3	X4	X1X2	X1X3	X1X4	X2X3	X2X4	X3X4	X2X3X4
10	0.015	1583	0.030246	0.15	15830	0.30246	23.745	0.000454	47.87942	0.718191
10	0.015	1917	0.040331	0.15	19170	0.40331	28.755	0.000605	77.31453	1.159718
10	0.025	1583	0.042672	0.25	15830	0.42672	39.575	0.001067	67.54978	1.688744
10	0.025	1917	0.039562	0.25	19170	0.39562	47.925	0.000989	75.84035	1.896009
14	0.015	1583	0.052529	0.21	22162	0.735406	23.745	0.000788	83.15341	1.247301
14	0.015	1917	0.045131	0.21	26838	0.631834	28.755	0.000677	86.51613	1.297742
14	0.025	1583	0.041114	0.35	22162	0.575596	39.575	0.001028	65.08346	1.627087
14	0.025	1917	0.047443	0.35	26838	0.664202	47.925	0.001186	90.94823	2.273706

ENTER METHOD			FORWARD			FORWARD TRANSFORMED			
Ra	ACTUAL	DIFF	RA	ACTUAL	DIFF		RA	ACTUAL	DIFF
69.70398	65.57143	6.302359	68.67269	65.57143	4.729591	4.177101	65.17665	65.57143	0.602062
57.16628	85	32.74556	57.39763	85	32.47337	3.954664	52.17818	85	38.61391
58.74407	85.57143	31.35083	54.51079	85.57143	36.29791	4.014601	55.40118	85.57143	35.25739
46.93529	74.14286	36.69614	48.23751	74.14286	34.93977	3.79823	44.62212	74.14286	39.81602
72.85829	78.85714	7.607238	61.81517	78.85714	21.6112	4.219665	68.01071	78.85714	13.75454
58.12742	51.14286	13.65696	57.1252	51.14286	11.69731	3.975917	53.29894	51.14286	4.215814
70.98329	45.14286	57.24146	71.58707	45.14286	58.57896	4.17283	64.89884	45.14286	43.76325
53.13526	45.28571	17.33338	51.09037	45.28571	12.81785	3.898022	49.30485	45.28571	8.875059
Average Deviation		23.20007	Average Deviation		25.04101		Average Deviation		22.00287

Design 5 origianal testing data

Feed	Depth	Spindle	Vibration	Feeddep	Feedspin	FeedVi	depspin	Videp	Vispin	Dspv
X1	X2	X3	X4	X1X2	X1X3	X1X4	X2X3	X2X4	X3X4	X2X3X4
10	0.015	1583	0.053463	0.15	15830	0.53463	23.745	0.000802	84.63193	1.269479
10	0.015	1917	0.060989	0.15	19170	0.60989	28.755	0.000915	116.9159	1.753739
10	0.025	1583	0.063705	0.25	15830	0.63705	39.575	0.001593	100.845	2.521125
10	0.025	1917	0.068671	0.25	19170	0.68671	47.925	0.001717	131.6423	3.291058
14	0.015	1583	0.074193	0.21	22162	1.038702	23.745	0.001113	117.4475	1.761713
14	0.015	1917	0.074559	0.21	26838	1.043826	28.755	0.001118	142.9296	2.143944
14	0.025	1583	0.078998	0.35	22162	1.105972	39.575	0.001975	125.0538	3.126346
14	0.025	1917	0.070106	0.35	26838	0.981484	47.925	0.001753	134.3932	3.35983

ENTER METHOD			FORWARD			FORWARD TRANSFORMED			
Ra	ACTUAL	DIFF	RA	ACTUAL	DIFF		RA	ACTUAL	DIFF
15.76666	27.6	42.87441	15.15287	27.6	45.09828	2.695673	14.81549	27.6	46.32069
14.38032	25.6	43.82687	14.11013	25.6	44.88232	2.630577	13.88177	25.6	45.77432
14.52844	35.2	58.72602	15.15287	35.2	56.95206	2.695673	14.81549	35.2	57.91054
14.21137	24.6	42.2302	14.11013	24.6	42.64176	2.630577	13.88177	24.6	43.57003
17.19491	44.2	61.09749	17.17687	44.2	61.13829	2.835753	17.04323	44.2	61.44065
16.63812	38.4	56.67157	16.13413	38.4	57.98405	2.770657	15.96912	38.4	58.41376
16.38098	50.4	67.49806	17.17687	50.4	65.9189	2.835753	17.04323	50.4	66.18406
16.59242	41.6	60.11438	16.13413	41.6	61.21604	2.770657	15.96912	41.6	61.6127

Average Deviation	46.61558	Average Deviation	46.82696		Average Deviation	47.45175

Training data replacement

Feed X1	Depth X2	Spindle X3	Vibration X4	Feeddep X1X2	Feedspin X1X3	FeedVi X1X4	depspin X2X3	Videp X2X4	Vispin X3X4	dspv X2X3X4
10	0.015	1583	0.039587	0.15	15830	0.39587	23.745	0.000594	62.66622	0.939993
10	0.015	1917	0.063742	0.15	19170	0.63742	28.755	0.000956	122.1934	1.832901
10	0.025	1583	0.04581	0.25	15830	0.4581	39.575	0.001145	72.51723	1.812931
10	0.025	1917	0.050177	0.25	19170	0.50177	47.925	0.001254	96.18931	2.404733
14	0.015	1583	0.082344	0.21	22162	1.152816	23.745	0.001235	130.3506	1.955258
14	0.015	1917	0.067212	0.21	26838	0.940968	28.755	0.001008	128.8454	1.932681
14	0.025	1583	0.055368	0.35	22162	0.775152	39.575	0.001384	87.64754	2.191189
14	0.025	1917	0.064248	0.35	26838	0.899472	47.925	0.001606	123.1634	3.079085

ENTER METHOD			FORWARD			FORWARD TRANSFORMED			
Ra	ACTUAL	DIFF	RA	ACTUAL	DIFF		RA	ACTUAL	DIFF
73.0822	51.4	42.18327	72.93692	51.4	41.90063	4.266547	71.27511	51.4	38.66752
65.97405	42.4	55.59918	66.51913	42.4	56.88474	4.179437	65.32909	42.4	54.07805
61.37644	54.4	12.82434	63.13358	54.4	16.05437	4.127514	62.02353	54.4	14.01384
53.6761	49.8	7.783337	55.20529	49.8	10.854	4.005209	54.8833	49.8	10.20743
81.0862	55	47.42945	84.52585	55	53.68336	4.449472	85.58172	55	55.60313
50.2413	57.6	12.77552	53.35913	57.6	7.362619	3.985093	53.79028	57.6	6.614091
39.86372	62.6	36.31994	41.9126	62.6	33.04696	3.811747	45.22937	62.6	27.74861
25.3545	74.2	65.82951	31.13446	74.2	58.03981	3.647628	38.3835	74.2	48.27021
Average Deviation		26.86438	Average Deviation		27.47334		Average Deviation		25.86658

Design 6

Feed X1	Depth X2	Spindle X3	Vibration X4	Feeddep X1X2	Feedspin X1X3	FeedVi X1X4	depspin X2X3	Videp X2X4	Vispin X3X4	Dspv X2X3X4
10	0.015	1583	0.039587	0.15	15830	0.39587	23.745	0.000594	62.66622	0.939993
10	0.015	1917	0.063742	0.15	19170	0.63742	28.755	0.000956	122.1934	1.832901
10	0.025	1583	0.04581	0.25	15830	0.4581	39.575	0.001145	72.51723	1.812931
10	0.025	1917	0.050177	0.25	19170	0.50177	47.925	0.001254	96.18931	2.404733
14	0.015	1583	0.082344	0.21	22162	1.152816	23.745	0.001235	130.3506	1.955258
14	0.015	1917	0.067212	0.21	26838	0.940968	28.755	0.001008	128.8454	1.932681
14	0.025	1583	0.055368	0.35	22162	0.775152	39.575	0.001384	87.64754	2.191189
14	0.025	1917	0.064248	0.35	26838	0.899472	47.925	0.001606	123.1634	3.079085

ENTER METHOD			FORWARD			FORWARD TRANSFORMED			
Ra	ACTUAL	DIFF	RA	ACTUAL	DIFF		RA	ACTUAL	DIFF
73.0822	51.4	42.18327	72.93692	51.4	41.90063	4.266547	71.27511	51.4	38.66752
65.97405	42.4	55.59918	66.51913	42.4	56.88474	4.179437	65.32909	42.4	54.07805
61.37644	54.4	12.82434	63.13358	54.4	16.05437	4.127514	62.02353	54.4	14.01384
53.6761	49.8	7.783337	55.20529	49.8	10.854	4.005209	54.8833	49.8	10.20743
81.0862	55	47.42945	84.52585	55	53.68336	4.449472	85.58172	55	55.60313
50.2413	57.6	12.77552	53.35913	57.6	7.362619	3.985093	53.79028	57.6	6.614091
39.86372	62.6	36.31994	41.9126	62.6	33.04696	3.811747	45.22937	62.6	27.74861
25.3545	74.2	65.82951	31.13446	74.2	58.03981	3.647628	38.3835	74.2	48.27021
Average Deviation		26.86438	Average Deviation		27.47334		Average Deviation		25.86658

Design 7

Feed X1	Depth X2	Spindle X3	Vibration X4	Feeddep X1X2	Feedspin X1X3	FeedVi X1X4	depspin X2X3	Videp X2X4	Vispin X3X4	Dspv X2X3X4
10	0.015	1583	0.033547	0.15	15830	0.33547	23.745	0.000503	53.1049	0.796574
10	0.015	1917	0.041877	0.15	19170	0.41877	28.755	0.000628	80.27821	1.204173
10	0.025	1583	0.047646	0.25	15830	0.47646	39.575	0.001191	75.42362	1.88559
10	0.025	1917	0.050182	0.25	19170	0.50182	47.925	0.001255	96.19889	2.404972
14	0.015	1583	0.04854	0.21	22162	0.67956	23.745	0.000728	76.83882	1.152582
14	0.015	1917	0.066656	0.21	26838	0.933184	28.755	0.001	127.7796	1.916693
14	0.025	1583	0.042287	0.35	22162	0.592018	39.575	0.001057	66.94032	1.673508
14	0.025	1917	0.055368	0.35	26838	0.775152	47.925	0.001384	106.1405	2.653511

ENTER METHOD			FORWARD			FORWARD TRANSFORMED			
Ra	ACTUAL	DIFF	RA	ACTUAL	DIFF		RA	ACTUAL	DIFF
51.368	56.4	8.921981	51.26729	56.4	9.10055	3.93135	50.97575	56.4	9.617468
49.80166	58.4	14.72319	48.20284	58.4	17.46089	3.872488	48.06179	58.4	17.70241
54.47571	56.6	3.753165	52.54404	56.6	7.166007	3.955127	52.20232	56.6	7.769754
50.32575	65.6	23.28392	48.60451	65.6	25.90776	3.880136	48.43078	65.6	26.17259
56.01728	62	9.649544	55.65529	62	10.2334	4.01775	55.57592	62	10.36142
52.80453	59.6	11.40179	52.59084	59.6	11.76034	3.958888	52.399	59.6	12.08221
57.27855	62.8	8.792115	56.93204	62.8	9.343885	4.041527	56.91318	62.8	9.373919
52.50157	57.8	9.16683	52.99251	57.8	8.317457	3.966536	52.80129	57.8	8.648292
Average Deviation		10.06571	Average Deviation		11.3716		Average Deviation		11.63497

Design 8

Feed X1	Depth X2	Spindle X3	Vibration X4	Feeddep X1X2	Feedspin X1X3	FeedVi X1X4	depspin X2X3	Videp X2X4	Vispin X3X4	Dspv X2X3X4
10	0.015	1583	0.065757	0.15	15830	0.65757	23.745	0.000986	104.0933	1.5614
10	0.015	1917	0.0784	0.15	19170	0.784	28.755	0.001176	150.2928	2.254392
10	0.025	1583	0.084584	0.25	15830	0.84584	39.575	0.002115	133.8965	3.347412
10	0.025	1917	0.082142	0.25	19170	0.82142	47.925	0.002054	157.4662	3.936655
14	0.015	1583	0.074269	0.21	22162	1.039766	23.745	0.001114	117.5678	1.763517
14	0.015	1917	0.067714	0.21	26838	0.947996	28.755	0.001016	129.8077	1.947116
14	0.025	1583	0.08327	0.35	22162	1.16578	39.575	0.002082	131.8164	3.29541
14	0.025	1917	0.124153	0.35	26838	1.738142	47.925	0.003104	238.0013	5.950033

ENTER METHOD			FORWARD			FORWARD TRANSFORMED			
Ra	ACTUAL	DIFF	RA	ACTUAL	DIFF		RA	ACTUAL	DIFF
82.98254	62.2	33.41244	80.60552	62.2	29.59087	4.39894	81.36454	62.2	30.81116
88.87379	61.4	44.74559	92.75817	61.4	51.07195	4.468577	87.23252	61.4	42.07251
77.41151	51	51.78727	81.77838	51	60.34976	4.443139	85.04144	51	66.74792
80.44576	52.8	52.3594	80.1568	52.8	51.81211	4.429688	83.90525	52.8	58.91145
96.04147	61	57.44503	84.29605	61	38.19025	4.410124	82.27964	61	34.88465
91.97497	64	43.71089	88.00602	64	37.50941	4.374019	79.36192	64	24.00301
72.36468	61.6	17.47512	68.5255	61.6	11.2427	4.376401	79.55123	61.6	29.1416
75.0139	43.8	71.26461	63.58006	43.8	45.15995	4.601585	99.6421	43.8	127.4934

Average Deviation	37.61697	Average Deviation	34.97088	Average Deviation	35.82154

Fuzzy-Net calculations

Design 1

Feed	Depth	Spin	Vi	Ra	Recognized Ra	Difference
11	0.01	1667	0.067297	17	17.63615	3.60708
11	0.01	1833	0.035852	13	15.64486	16.90561
11	0.02	1667	0.107315	19	19.48989	2.513545
11	0.02	1833	0.029973	17	15.69163	8.337984
13	0.01	1667	0.049736	19	17.85225	6.429179
13	0.01	1833	0.055171	15	17.98508	16.59751
13	0.02	1667	0.147852	18	19.03442	5.434471
13	0.02	1833	0.082295	18	17.64438	2.015474
					Average Deviation	7.730106

Design 2

Feed	Depth	Spin	Vi	Ra	Recognized Ra	Difference
10	0.015	1583	0.039013	121.4286	104.26200	14.13715
10	0.015	1917	0.051130	99.71429	95.59893	4.127148
10	0.025	1583	0.045163	127.4286	115.17070	9.619400
10	0.025	1917	0.051896	116.1429	103.68290	10.72814
14	0.015	1583	0.041261	114.2857	110.74340	3.099564
14	0.015	1917	0.038684	112	102.75400	8.255325
14	0.025	1583	0.067469	114.7143	114.84810	0.116669
14	0.025	1917	0.046849	138.1429	101.63540	26.42729
					Average Deviation	9.563837

Design 3

Feed	Depth	Spin	Vi	Ra	Recognized Ra	Difference
10	0.015	1583	0.025988	53.43	51.1328	4.492621
10	0.015	1917	0.025079	41.14	49.72728	17.26874
10	0.025	1583	0.030685	42.86	51.90214	17.42152
10	0.025	1917	0.024974	34.86	50.36129	30.78017
14	0.015	1583	0.031418	64.71	60.66668	6.664806
14	0.015	1917	0.032304	67.29	59.26115	13.54825
14	0.025	1583	0.032074	64.43	61.35721	5.008031
14	0.025	1917	0.039749	43.71	59.7665	26.86539
					Average Deviation	15.25619

Design 4

Feed	Depth	Spin	Vi	Ra	Recognized Ra	Difference
10	0.015	1583	0.030246	65.57143	54.32188	20.70905
10	0.015	1917	0.040331	85	61.18533	38.9222
10	0.025	1583	0.042672	85.57143	85.284	0.33702
10	0.025	1917	0.039562	74.14286	64.54705	14.86638
14	0.015	1583	0.052529	78.85714	78.50803	0.444689
14	0.015	1917	0.045131	51.14286	74.61319	31.45601
14	0.025	1583	0.041114	45.14286	83.60308	46.00336
14	0.025	1917	0.047443	45.28571	74.95832	39.58547
					Average Deviation	24.04052

Design 5

Feed	Depth	Spin	Vi	Ra	Recognized Ra	Difference
11	0.01	1667	0.057847	17	15.81755	6.211152
11	0.01	1833	0.081686	19	14.27119	33.13539
11	0.02	1667	0.073322	16	15.90522	1.918993
11	0.02	1833	0.087465	17	16.28009	1.965013
13	0.01	1667	0.065458	18	17.26803	3.080664
13	0.01	1833	0.067093	17	16.14571	7.768592
13	0.02	1667	0.089907	16	18.02229	12.3308
13	0.02	1833	0.073419	16	15.82329	2.380712
					Average Deviation	8.598914

Design 6

Feed	Depth	Spin	Vi	Ra	Recognized Ra	Difference
10	0.015	1583	0.039587	51.4	49.09851	4.687501
10	0.015	1917	0.063742	42.4	49.24209	13.8948
10	0.025	1583	0.04581	54.4	53.2872	2.088304
10	0.025	1917	0.050177	49.8	50.9251	2.209327
14	0.015	1583	0.082344	55	60.73531	9.443127
14	0.015	1917	0.067212	57.6	55.21838	4.3131
14	0.025	1583	0.055368	62.6	64.06007	2.279226
14	0.025	1917	0.064248	74.2	61.72662	20.20745
					Average Deviation	7.390355

Design 7

Feed	Depth	Spin	Vi	Ra	Recognized Ra	Difference
10	0.015	1583	0.033547	56	54.66794	2.436642
10	0.015	1917	0.041877	58	55.67945	4.167694
10	0.025	1583	0.047646	57	54.02033	5.515833
10	0.025	1917	0.050182	66	58.93466	11.98843
14	0.015	1583	0.04854	62	56.47729	9.778644
14	0.015	1917	0.066656	60	58.5985	2.391708
14	0.025	1583	0.042287	63	55.87272	12.75628
14	0.025	1917	0.055368	58	59.05105	1.779904
					Average Deviation	6.351892

Design 8

Feed	Depth	Spin	Vi	Ra	Recognized Ra	Difference
10	0.015	1583	0.065757	62.2	66.69921	6.745524
10	0.015	1917	0.0784	61.4	59.96748	2.388835
10	0.025	1583	0.084584	51	71.04864	28.21819
10	0.025	1917	0.082142	52.8	57.51129	8.191943
14	0.015	1583	0.074269	61	66.69921	8.544645
14	0.015	1917	0.067714	64	57.73709	10.8473
14	0.025	1583	0.08327	61.6	69.03595	10.77113
14	0.025	1917	0.124153	43.8	57.67864	24.062
					Average Deviation	12.47119

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REFERENCES

Altintas, Y. (1992). Prediction of cutting forces and tool breakage in milling from feed drive current measurements. *Transcations of the ASME, 114,* 386-392.

Atlintas, Y. & Munasinghe, W. K. (1996). Modular CNC design for intelligent machining, Part 2: Modular integration of sensor based milling process monitoring and control tasks. *Transactions of the ASME, 118,* 514-521.

Anderson, J. S. & Bratos-Anderson, M. (1987). *Solving problems in vibrations.* Singapore: Longman Scientific & Technical Publishers Ltd.

Beak, Dae K., Ko, Tae, J., & Kim, Hee S. (1997). A dynamic surface roughness model for face milling. *Precision Engineering, 20,* 171-178.

Bonde, A. (1996, December). Fuzzy Logic Basics. GTE Government Systems Corporation [On-line]. Accessed: January 1, 1999 <http://www.austinlinks.com/Fuzzy/basics.html> .

Bradley, C., Bohlmann, J., & Kurada, S. (May 1998). A fiber optic sensor for surface roughness measurement. *Journal of Manufacturing Science and Engineering, 120,* 359-367.

Chen, J. C., & Lin, N.-H. (1997). Optimizing the fuzzy-nets training scheme using the Taguchi parameter design. *International Journal for Advance Manufacturing Technology, 13,* 587-599.

Coker, S. A., & Shin, Y. C. (1996), In-process control of surface roughness due to tool wear using a new ultrasonic system. *International Journal of Machine Tools Manufacturing, 36*(3), 411- 422.

Coker, S. A., Oh, S. J., & Shin, Y. C. (1998). In-process monitoring of surface roughness utilizing ultrasound. *Journal of Manufacturing Science and Engineering, 120,* 197-200.

Cook, N. H. (1980). Tool wear sensors. *Wear, 62,* 49-57.

Dalpiaz, R., & Remondi. (1988). Use of accoustic emission for cutting process monitoring in turning, *Journal of Condioning Monitoring, 1,* 1-26.

Devoe, D. L., & Zhang, G. (1993). Optical area-based surface quality assessment for in-process measurement. *Manufacturing Science in Engineering, 64,* 413- 420.

Dontamsetti, S. K., & Fischer, G. W. (1988). Factors affecting surface roughness in finish turning of gray iron. *Advance Material Manufacturing Processes, 3(4),* 689-725.

Dornfield, D. A., & Fei, R.,Y. (1986). In-process surface finish characterization. *Manufacturing Simulation Processes, 20,* 191- 204.

Emel, E., & Kannatey-Asibu. (1988). Tool failure monitoring in turning by pattern recognition analysis of AE signals. *Journal of Engineering for Industry, 110,* 137 - 145.

Fowlkes, W. Y., Creveling, C. M. (1995). *Engineering methods for robust product design: Using Taguchi methods in technology and product cevelopment.* Reading, MA: Addison-Wesley Publishing Company.

Freund, J. E. (1984). *Modern elementary statistics.* Englewood Cliffs, NJ: Prentice-Hall. Inc.

Frost-Smith, E. H. (1970). Optimization of the machining process and overall system concepts. *Proceedings of the MTIRA Conference on Adaptive Control of Machine Tools.*

Garbini, J. L., Koh, S., Jorgensen, J. E., & Ramulu, M. (1992). Surface profile measurement during turning using fringe-field capacitive profilometry. *Transactions of the ASME, 114,* 234-243.

Giusti, F., & Santochi, M. (1979). Development of a fibre optic sensor for in-process measurement of tool flank wear. *Proceedings of the 20th International Machine Tool Design and Research Conference.* 351-360.

Goldman, S. (1991), *Vibration spectrum analysis: A practical approach.* New York: Industrial Press, Inc.

Ham, I., Schmidt, A. O., & Babcock, R. J. (1968). Experimental evaluation of tool wear mechanism and rate using electron microprobe analysis. *Proceedings of the 9th International Machine Tool Design and Research Conference,* 973-987.

Inasaki, I. (1982). Development of in-process sensor for surface roughness measurement. *Proceedings of the 23th International Machine Tool Design and Research Conference,* 109-113.

Inasaki, I. (1985). In-process measurement of surface roughness during cylindrical grinding process. *Precision Engineering, 7(2),* 73-76.

Ismall, F., Elbestawi, M. A., Du, R., & Urbasik, K. (1993). Generation of milled surfaces including tool dynamics and wear. *Journal of Engineering for Industry, 115,* 245-252.

Iwata, K., & Moriwaki, T. (1977). An application of acoustic emission measurement to in-process sensing of tool wear. *Annals of the CIRP, 25,* 21-26.

Jang, J.S. R, Sun, C.T., & Mizutani, E. (1997). *Neuro-fuzzy and soft computing: A computational approach to learning and machine intelligence.* Upper Saddle River, NJ: Prentice-Hall, Inc.

Joen, J. U., & Kim, S. W. (1988). Optical flank wear monitoring of cutting tools by image processing. *Wear, 107,* 207-217.

Kannatey-Asibu, E. (1984). A study of tool wear using statistical analysis of metal-cutting acoustic emission. *Wear, 76,* 106-118.

Kannatey-Asibu, E. (1981). Quantitative relationships for acoustic emission from orthogonal metal cutting. *Transactions of the ASME, 103,* 330-341.

Kim, J.-D., & Choi, In-Hye. (1996). Development of a tool failure detection system using multi-sensors. *International Journal of Machine Tools Manufacturing, 36*(8), 861-870.

Kirk, R. E. (1995). *Experimental design: Procedures for the behavioral sciences* (3rd ed.). Pacific Grove, CA: Brooks/Cole Publishing Co.

Koren, Y. (1989). Adaptive control systems for machining. *Manufacturing Review, 2*(1), 6-15.

Lahidji, B. (1997). Determining deflection for metal turning operation. *Journal of Industrial Technology, 13*(2).

Lane, D. (1999, January 1). Introduction to Multiple Regression. Rice University. [On-line] Accessed: January 24, 1999. <http://www.ruf.rice.edu/~lane/hyperstate/B123219.html>.

Liao, T. S., & Young, T. C. (1994). A new on-line spindle speed regulation strategy for chatter control. *International Journal of Machine Tools Manufacturing,* 651-660.

Lin, S.C., DeVor, R.E., & Kapoor, S.G. (1990). The Effects of Variable Speed Cutting on Vibration Control in Face Milling. *Journal of Engineering for Industry, 112,* 1-11.

Lin, S. C., & Chang, M. F. (1998). A study on the effects of vibrations on the surface finish using a surface topography simulation model for turning. *International Journal of Machine Tools Manufacturing, 38,* 763-782.

Lister, P. M., & Barrow, G. (1986). Tool condition monitoring systems. *Proceedings of the 26th International Machine Tool Design and Research Conference,* 271-288.

Lou, S.-J., & Chen, J. C. (1997). *Development of four in-process surface recognition systems to predict surface rougness in end milling.* Doctoral dissertation, Iowa State University, Ames.

Luk, F., Huynh, V., & North, W. (1987). Measureemnt of surface roughness by vision system. *Computers in Engineering, Procedures from the International Computer Engineering Conference, 2,* 61-64.

Mamdani, E. H. (1974). Applications of fuzzy algorithms for simple dynamic plant. *Proceedings of IEEE, 121*(12), 1585-1588.

Mitsui, K. (1986). In-process sensors for surface roughness and their applications. *Precision Engineering, 9,* 212-220.

Montgomery, D., & Altintas, Y. (1991). Mechanism of cutting force and surface generation in dynamic milling. *Journal of Engineering for Industry, 113,* 160-168.

Nayfeh, T. H., Abu-Zahra, N. H. (1996). Multifunctional ultrasonic sensor for on-line tool condition monitoring in turning operations. *Materials Evaluation,* 443-448.

Olivo, C. T. (1982). *Advanced machne technology.* North Scituate, MA: Breton Publishers.

Pedersen, K. B. (1990). Wear measurement of cutting tools by computer vision. *International Journal of Machine Tools Manufacturing, 30(4),* 129-131.

Ross, P. J. (1988). *Taguchi techniques for quality engineering: Loss function, orthogonal experiments, parameter and tolerance design.* New York: McGraw-Hill.

Sathyanarayanan, G., & Radhakrishnan, V. (1988). Roughness measurement with non-contacting inductive pickup. *Manufacturing Metrology, 29,* 75-100.

Scott, W., & Donovan, A. (1998). Comparison of surface texture measurement by stylus and fiber optic transducers. *Journal of Testing and Evaluation, 26(1),* 70-78.

Shin, Y. C., Oh, S. J. , & Coker, S. A. (1995). Surface roughness measurement by ultrasonic sensing for in-process monitoring. *Journal of Engineering for Industry, 117,* 439-447.

Spurgeon, D., & Slater, R. A. C. (1974). In-process indication of surface roughness using a fibre-optics transducer. *Proceedings of the 15th International Machine Tool Design and Research Conference,* 339-347.

Sundar, S. M., & Raman, S. (1993). Analysis for vision assisted optical characterization of machined surfaces. *Manufacturing Science in Engineering, 64,* 43-58.

Sundaram, R. M., & Lambert, B. K. (1979). Surface roughness variablility of AISI 4140 steel in fine turning using carbide tools. *International Journal of Production Research, 17(3),* 249-258.

Sutherland, J. W., & DeVor, R. E. (1986). An improved method for cutting force and surface error prediction in flexible end milling systems. *Journal of Engineering for Industry, 108,* 269-279.

Takeyama, H., Sekiguchi, H., Murata, R., & Matsuzaki, H. (1976). In-process detection of surface roughness in machining. *Annals of the CIRP, 25(1),* 467-471.

Tlutsy, J. & Andrews, G. C. (1983) A critical review of sensors for unmanned machining. *Annals of the CIRP, 32,* 563-572.

Tlusty, J. & Smith, S. (1992). Stabilizing Chatter by Automatic Spindle Speed Regulation. *Annals of the CIRP, 41(1)*, 433-436.

Vajpayee, S. (1981). Analytical study of surface roughness in turning. *Wear, 70*, 165-175.

Wang, L.-X. (1994). *Adaptive fuzzy systems and control*. Englewood Cliffs, NJ: Prentice Hall.

Wilson, F. W., & Cox, R. W. (1965). *Machining the space-age metals*. Washington, DC: American Society of Tool and Manufacturing Engineers (SME).

You, S. J., & Ehmann, K. F. (1991). Synthesis and generation of surfaces milled by ball nose end mills under tertiary cutter motion. *Journal of Engineering for Industry, 113*, 17-24.

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