DEVELOPMENT OF 1ST AND 2ND ORDER TOOL LIFE MODEL WHEN MACHINING MODIFIED AISI P20 TOOL STEEL

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We certify that the project entitled "Ddevelopment of 1^{st} and 2^{nd} order tool life model when machining modified AISI P20 tool steel" is written by Afiq Zainorul Bin Zainal. We have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. We herewith recommend that it be accepted in partial fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering with Manufacturing Engineering.

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To my Beloved Family

NORLAILA BINTI MOHAMED

ZAINAL BIN AHMAD

NURHAMIM BIN ZAINAL

MOHD. HAZIQ BIN ZAINAL

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ABSTRACT

This thesis deals with tool life durability when performing end-milling operation on modified AISI P20 tool steel using TiN coated inserts. The objectives of this thesis is to develop the 1st and 2nd order tool life model when machining modified AISI P20 tool steel and to investigate the relationship between cutting parameters; cutting speed, feedrate, axial depth, radial depth with tool life. This prediction model was then compared with the results obtained experimentally. By using Response Surface Method (RSM) of experiment, first and second order models were developed with 95% confidence level. The 1st order and 2nd order tool life prediction model was developed with the aid of MINITAB software. Modified AISI P20 tool steel were selected as the material in this thesis which commonly used to make plastic injection mold, zinc die-casting, extrusion dies, blow molds, and other structural components. From the results, it is observed that the 2nd order tool life model gives less error percentage compared to the 1st order. Comparing with the 1st order model, 2nd order model gives more accurate value because the average error % shows it has smaller value, which is 0.59%. From both generated regression equation, the relationship between the four cutting parameters with tool life for 1st and 2nd order model are, the tool life increase with reduction of cutting speed, feedrate, and radial depth excluding the axial depth. For end-milling of P20 tool steel, the optimum conditions that is required to maximize the coated carbide tool life are as follow: cutting speed of 140 m/s, federate of 0.1 mm/rev, axial depth of 1.5 mm and radial depth of 2 mm. Using these parameters, a tool life of 39.46 min was obtained. This value for tool life was obtained from the 2nd order model. Tool life optimization can help to overcome the cutting tool's costs and production time problem.

ABSTRAK

Tesis ini membentangkan mengenai ketahanan jangka hayat mata alat apabila melakukan operasi “end-milling” terhadap besi AISI P20 yang di ubah suai. Objektif tesis ini adalah untuk meberbitkan persamaan urutan pertama dan urutan kedua jangka hayat mata alat apabila memesin besi AISI P20 yang telah di ubah suai dan mengkaji kaitan di antara parameter-parameter pemotongan iaitu, kelajuan memotong, kadar suapan, kedalaman berpaksi, dan kedalaman jejari dengan jangka hayat mata alat. Model ramalan kemudian dibandingkan dengan nilai yang diperoleh dalam eksperimen. Dengan menggunakan eksperimen “Response Surface Methodology (RSM)”, model urutan pertama dan urutan keduadi terbitkan dengan tahap keyakinan 95%. Model-model tersebut diterbitkan dengan bantuan perisian MINITAB. Besi AISI P20 yang di ubah suai yang dipilih sebagai material di dalam eksperimen ini lazimnya digunakan untuk membuat acuan suntikan plastik, acuan tuangan zink, tuangan penonjolan, acuan tiupan, dan komponen-komponen struktur yan lain. Daripada hasil yang diperoleh, diperhatikan bahawa model jangka hayat urutan kedua member lebih sedikit peratus kesilapan berbanding model jangka hayat urutan pertama. Berbanding dengan model jangka hayat urutan pertama, model jangka hayat urutan kedua member bacaan yang lebih menghampiri ketepatan kerana peratus kesilapan nya yang kecil iaitu, 0.59%. Daripada kedua-dua persamaan regresi, kaitan diantara parameter-parameter pemotongan dengan jangka hayat mata alat ialah, jangka hayat mata alat meningkat dengan penurunan nilai kelajuan pemotongan, kadar suapan, dan kedalaman jejari kecuali kedalaman berpaksi. Untuk proses “end-milling” besi AISI P20 yang telah diubah suai, keadaan optimum yang diperlukan untuk memaksimakan jangka hayat mata alat adalah seperti berikut; kelajuan pemotongan pada 140 m/s, kadar suapan 0.1 mm/rev, kedalaman berpaksi 1.5 mm, dan kedalaman jejari pada 2 mm. Mengunakan parameter-parameter tersebut jangka hayat mata alat selama 39.46 min diperoleh. Nilai ini di peroleh daripada model urutan kedua. Peningkatan jangka hayat mata alat dapat membantu mengatasi masalah kos mata alat dan masa produksi.

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LIST OF SYMBOLS/ ABBREVIATIONS

R_a	Finest surface finish
TiN	Titanium Nitride
t	Tool life
V_c	Cutting speed
f	Feedrate
a_a	Axial depth
a_r	Radial depth
y	Tool life experimental value
$\hat{y}$	Tool life predicted value
β_0, β_1, β_2, β_3 and β_4	Model parameter
ε	Experimental error
x_0	Dummy variable
x_1, x_2, x_3 and x_4	Cutting speed, feed rate, axial depth of cut and radial depth of cut substitute in tool life model.
AISI	American Iron Steel Institute
ANOVA	Analysis of Variance
3-D	Three Dimensions
2-D	Two Dimension
MQL	Minimum Quantity of Lubrication
CNC	Computer Numerical Control
FKM	Fakulti Kejuruteraan Mekanikal
CVD	Chemical Vapor Deposition
PVD	Physical Vapor Deposition
RSM	Response Surface Methodology
EDM	Electrical Discharge Machine
UMP	Universiti Malaysia Pahang
ISO	International Standardization for Organization

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Machining is very important in manufacturing process. Manufacturing companies were often facing problem in settling the machining tools. It took times when changing a tool that have lost its effectiveness to replace it with a new tool. If the company changing their tool frequently it will cost the company a lost in production time when the machine has to stop running. Companies also have to spend money for the machining tools. If the changing of the machining tools can be reduced, it can help in saving the machining tools cost and the time lost when changing the new tools. Tool life affects production costs and therefore competitiveness of the process and may as well have a considerable impact on tool supply, stability of production and last but not least delivery performance. Since tool failure is unavoidable, tool life must be properly taken into account for the calculation of tooling cost and planning of tool supply for production. In daily practice this or a similar situation would call for immediate short term actions of tool life improvement in order to stabilize production or for long term activities of tool life optimization and cost reduction. [1]. This project is going to find a solution to optimize the tool life by investigating the relationship between selected cutting parameters and develop the first and second order tool life model when machining modified AISI P20 tool steel thus helping to solve the cutting tools cost and production time problem.

1.2 PROBLEM STATEMENT

The main problem to define the major reason for tool failure is the large number of process parameters and their possible interactions affecting tool life [1]. The life of cutting tool depends upon many factors, such as the microstructure of the material being cut, metal removal rate, the rigidity of the setup and effects of cutting fluid [2].

During machining process, the cutting tool ability will degrades with time; in other word it became dull. Until a certain time, the tool can no longer cut through the material. If the condition is not suitable with the tool, it will shorten the tool life faster. Low tool life may endanger tool supply and therefore production output and tooling cost may even exceed the calculated manufacturing costs of the entire product [1].

To overcome this problem, cutting tools users need to have a prediction model to help them predict the tool life by calculation. Therefore the cutting tool users can mix and match the suitable parameters for the cutting process. In this way, the cutting tools can be prevented from being damage for a short period of time.

1.3 OBJECTIVE

1. The objective of this study is to predict tool life in end-milling operation of modified AISI P20 tool steel by developing the first and second order mathematical model for tool life.
2. To investigate the relationship between cutting parameters; cutting speed, feedrate, axial depth, radial depth with tool life.

1.4 SCOPE / LIMITATION

In this project, the developed tool life models were limited to the certain range of parameters. There are four selected cutting parameters, cutting speed, feedrate, axial depth, and radial depth. The range of cutting speed is from 100 to 180 m/min, the feedrate is from 0.1 to 0.2 mm/rev, the axial depth is from 1 to 2mm, and the radial depth is from 2 to 5mm.

1.5 THESIS OUTLINE

This thesis consists of five chapters. Chapter 1 gives the introduction of this project. In the introduction, there will be brief explanations about the background of this study, the problem statement, the objective of this study, and the scope/limitation in this project.

Chapter 2 shows the literature review of this study. The literature review will discuss on the selected points such as, the machining process, CNC milling process, cutting tools, modified AISI P20 tool steel, and response surface methodology. In the cutting tool part, there will be a more deep discussion about the tool life.

Chapter 3 presents the methodology of this project. It gives information about the equipment used, the preparation of the work piece, experiment process, and response surface methodology.

Chapter 4 discus's about the analysis of the experiments in this project. From this analysis, the mathematical models for the tool life, the first and second order will be developed. The accuracy of both mathematical models will be analyzed. Thus this chapter will achieve the objective of this project.

Chapter 5 provides the conclusion and recommendation to this project. The conclusion was made after all the experiment in this project performed and the result has been analyzed. Recommendation for further experiment was made based on the experience during running the experiment.

CHAPTER 2

LITERATURE REVIEW

2.1 MACHINING PROCESS

In machining process, there are two types of cutting, orthogonal cutting and oblique cutting. The orthogonal and oblique cutting processes have then been related to each practical operation such as turning and milling [3]. Turning process is an example of orthogonal cutting. It is recognized that deformation in orthogonal cutting is confined to a narrow shear zone when the chip starts sliding up the face of the cutting tool [4]. According to the orthogonal model, the specific cutting energy is the energy consumed per unit volume of the material removed and it is independent of the cutting speed, therefore it also equals the cutting force divided by the cross sectional area of the uncut chip [5].

Oblique cutting is a 3-D type of cutting. It can be seen in milling process. Referred to the similar definition in the orthogonal cutting model, the specific cutting energy in this oblique cutting model is obtained [6]. The traditional model for oblique cutting has two shortcomings, one being that it involves only one machining case where the tool major cutting edge angle is limited to be 90°, i.e. the undeformed chip thickness is equal to the feed of the tool; whilst the other is that it takes no account of the influence of the tool feed velocity on the resultant cutting velocity. Great attention has been paid to oblique cutting by a number of researchers all around the world, because many practical machining processes are actually examples of oblique cutting, and numerous research papers have been published Orthogonal cutting is a 2-D type of cutting [7]. Figure 2.1 shows the orthogonal and oblique cutting process [8].

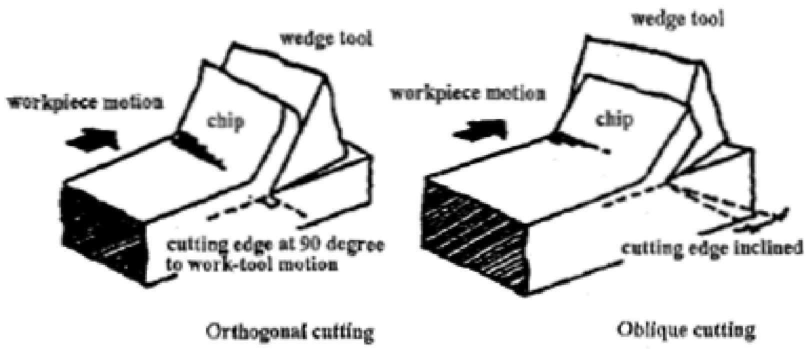


Figure 2.1: Orthogonal and oblique cutting process [8].

Source: Karri and Talhami (1995)

The machining process use coolant. Coolant emulsion rapidly affects the temperature of the chips and can sometimes favorably influence chip breaking, particularly when large cross section chips are formed [9, 10, 11]. In general, most turning and other machining applications use water based coolant emulsions. These contain a microscopic dispersion of the concentrate in water. The microscopic oil globules are homogeneously dispersed throughout the coolant. The basic ingredients of these emulsions are water, oil, and wetting agents [12].

There are many types of cutting fluid available today in the marketplace. The cutting fluid used in the underlying research was water based emulsion. It is mixed with water at a concentration of 10%. Its properties are listed in Tables 2.1 and 2.2 [13].

Table 2.1: The properties of cutting fluid [13].

The properties of cutting fluid	
Appearance-concentrate	Amber liquid
Appearance-dilution	Opaque amber-white
Odor	Bland
Residual film	Soft, fluid
pH at 20:1 (5%)	9.1 ± 0.5
Specific gravity at 60 (F)	0.93 ± 0.03
Lbs/gallon	7.7±0.1
Flash point, PMCC (F)	222

Table 2.2: Concentration and refractometer for coolant % [13].

Concentration	**Refractometer reading**
4% (1:25)	4.6
5% (1:20)	5.7
6% (1:17)	6.8
7% (1:14)	8.0
8% (1:12)	9.1
9% (1:11)	10.3
10% (1:10)	11.4

Source: Jaw Lin, Agrawal, and Fang (2008)

Machining with minimum quantity of lubrication (MQL) can cut down cost and improve both tool life and surface finish [14]. MQL is the name given to the process in which very small amount of oil (less than 30 ml/h) is pulverized into the flow of compressed air [15]. MQL helps in reducing cutting temperature and also averts thermal shocks, experienced by flood coolant. The air/oil aerosol mixture is then fed to the cutting area through the ducts (normally two in number) [16].

2.2 CNC MILING

This project is going to apply the oblique cutting based on the experiment that required a CNC milling process. Figure 2.2 shows the HAAS CNC machine in FKM laboratory.

Figure 2.2: HAAS CNC machine.

In a CNC (Computerized Numerical Control) machine, the tool is controlled by a computer and is programmed with a machine code system that enables it to be operated with minimal supervision and with a great deal of repeatability. The same principles used in operating a manual machine are used in programming a CNC machine. The main difference is that instead of cranking handles to position a slide to a certain point, the dimension is stored in the memory of the machine control once. The control will then move the machine to these positions each time the program is run. In order to operate and program a CNC controlled machine, a basic understanding of machining practices and a working knowledge of math is necessary. It is also important to become familiar with the control console and the placement of the keys, switches, displays, etc., that are pertinent to the operation of the machine [19]. In three-axis computer numerically controlled (CNC) machining of sculptured surface parts, the tool path pattern is crucial to surface quality and machining time [20]. Because tool path patterns determine how the cutting tool machines the surfaces, well-planned paths can both increase machining efficiency and ensure surface quality [20].

The machine illustration shows three directions of travel available on a vertical machine center. To carry the number line idea a little further, imagine such a line placed along each axis of the machine. It shows the three directions to position the coordinates around apart origin, which is where these number lines intersect on a vertical machining center with the X, Y, and Z axis lines [19]. Figure 2.4 shows the axis line in HAAS CNC machine.

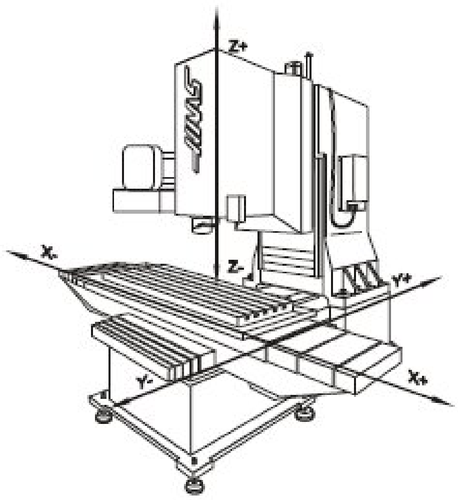


Figure 2.4: Axis lines in HAAS CNC machine [19].

Source: HAAS Automation Inc. Programming Workbook (2002)

2.3 CUTTING TOOL

The insert tool used in this experiment is TiN coated type. It was stated that in terms of the tool life coated inserts performed better than uncoated inserts [13]. Coating increases the lubricity and reduces the affinity to the work piece material. This allows the coated inserts to perform much better than the uncoated inserts, especially at higher cutting speeds

[13]. The coating provides a better thermal barrier so the temperature is reduced [21]. The speed attained after coating was double compared to that of the uncoated insert. The improvements achieved as a result of coating were extending tool life, attaining higher cutting speeds, and reducing production costs [13]. Application of coated cutting tools in the modern machining practices today is very common and extensive. A suitable coating on a cutting tool improves the machinability of a material and enhances the tool life as well [22].

Such beneficial effects of coating are achieved through remarkable improvement of wear resistance and anti-friction properties. In addition, the coating material is intended to offer chemical inertness to the work material at cutting temperature, especially for the sticky work materials. Otherwise, formation of built up edge on the rake surface is unavoidable, which leads to fluctuation of cutting force, deterioration in surface finish, drastic reduction in tool life etc. [22]. Indexable coated carbide inserts are widely used in modern manufacturing industry. These inserts have one or more thin layers of wear resistance CVD or PVD coating such as TiC, TiN, Al2O3, ZrN, CrC or diamond, which can improve machinability significantly [23].

Today, "coated carbide grades for roughing and cermets for finishing" is a well established trend [24]. For the coated carbide insert in the milling cutter, although the multiple coating layers can improve wear resistance significantly, it is still hard to bear the high load impacts and high temperature. Actually the coated layer cannot stand for long before it is worn. This will result in severe tool wear and short tool life. In the up milling operations, the cutter encounters minimum chip thickness as it enters the workpiece. This approximating rubbing at the beginning of the cut will cause an excessively work hardened layer in the workpiece, therefore higher cutting forces, higher tool wear rate and shorter tool life than those in down milling were observed. It is recommended that down milling operations be used as far as possible [23].

2.3.1 TOOL LIFE

The life of a tool is important in metal cutting since considerable time is lost whenever a tool is replaced or reset [25]. Tool life plays a critical role in an estimation of the productivity level expected for specific cutting conditions in manufacturing. It becomes extremely important both economically and for good quality that a tool insert should be chosen in such a way that it wears out in a progressive manner rather than being unpredictable for its working life due to its uncertain machining capability [13]. An ability to predict the tool life during machining is necessary not only for the design of cutting tools but also for the determination of cutting conditions, appropriate tools, etc. for a particular operation [27].

This study will predict the tool life on three-dimensional oblique process. CNC machine will be used to do the milling work. For a practical machining situation, since no machining theory is available to predict the tool life, one is compelled to rely on empirical equations such as those proposed by F.W. Taylor early in this century. A number of researchers have attempted to tackle the problem mort fundamentally by relating tool wear and hence tool life to the machining conditions in terms of machining theory [27]. For tool life, workpiece material was found as the most influential parameter followed by the rotational speed of tool. High values of tool's rotational speed proved unfavorable for tool life but favorable for surface finish. The effect of feed on tool life is much more pronounced than the effect of speed. An increased in the speed, the feed, and the axial depth of cut decreased the tool life [28]. In addition, the effects of workpiece inclination angle and radial depth of cut were analyzed upon effective cutting speed and cusp height and, subsequently, upon surface roughness.

Lot of research work has been and is being done in order to find the optimal combination of tooling, cutting, and environment parameters for enhancement of tool life, without compromising the high values of material [16]. Different observations have been reported regarding effects of workpiece's inclination angle upon performance measures. It has been reported that tool life in the case in which workpiece surface was inclined at 30◦ was about three times more than that obtained when workpiece surface was kept normal to axis of cutter [29]. Moreover, the tool failure in the first case was caused by chipping on the rake face while it was caused in the second case because of generation of extremely rough surface. In other paper, the authors reported the contrary observation, i.e., longer tool life values could be achieved when operating with cutter axis oriented normal to the workpiece surface rather than oblique one [30]. By the end of this project, there will be two mathematical models developed, the 1st order and the 2nd order. The 1st order model or the linear model is for the relationship between the machining responses and machining independent variables. The 2nd order model or the quadratic model is for the interaction between the variables [25].

2.4 MODIFIED AISI P20 TOOL STEEL

In this project, the material that is going to be machined is modified AISI P20 tool steel. Generally, AISI P20 is a chromium-molybdenum alloyed steel which is considered as a high speed steel used to build moulds for plastic injection and zinc die-casting, extrusion dies, blow moulds, forming tools and other structural components. The modified form of AISI P20 is distinguished from normal P20 steel by the balanced sulphur content (0.015%) which gives the steel better machinability and more uniform hardness in all dimensions. Modified AISI P20 possesses a tensile strength of 1044MPa at room temperature and a hardness ranging from 280 to 320 HB. The workpiece used in this study was prehardened and tempered to a minimum hardness of 300HB and was provided by ASSAB (Sweden). Some of the product made from this type of material is plastic injection mold using end-milling process.

2.5 RESPONSE SURFACE METODOLOGY (RSM)

Design of experiment technique, response surface methodology (RSM); have been used to accomplish the objective of the experimental study. RSM is a combination of mathematical and statistical techniques used in an empirical study of relationships and optimization, where several independent variables influence a dependent variable or response. In RSM, the relationship between the responses and the variables investigated is commonly approximated by polynomial functions, whilst the model parameters are obtained by a small number of experiments utilizing a design of experiment. In this study, primary machining variables such as cutting speed, feed rate and axial depth of cut, which are easily controllable, are considered in building the models [28].

In order to reduce the total number of cutting tests and allows simultaneous variation of the three independent factors, a well-designed experimental procedure has to be followed. In machining research, the Box-Behnken design has found a broad application compared to other experiment designs used for RSM. The Box-Behnken design is based on the combination of the factorial with incomplete block designs. It does not require a large number of tests as it considers only three levels (-1, 0, 1) of each independent parameter (Box and Behnken, 1960) [49]. The Box-Behnken design is normally used for non-sequential experimentation, when a test is conducted only once. It allows an efficient evaluation of the parameters in the first and second order models. Using statistical software the cutting conditions of 15 experiments are generated and the experiments are conducted randomly to minimise errors. Minitab has employed as the statistical software. In order to calculate the experimental error, the 15 experiments consider five times repeating of central point of the cutting conditions [25].

CHAPTER 3

METHODOLOGY

3.1 EQUIPMENT USED

For this project, the equipments used are, Wire EDM to cut the workpiece, CNC machine to do the milling process, and 2-D Microscope to observe the cutting tools.

3.1.1 WIRE ELECTRICAL DISCHARGE MACHINE (Wire EDM).

Before operating the milling process, the workpiece must be cut first to get the desired dimension. To do the cutting process, wire EDM is going to be use. In UMP's lab Sodick AQ 535 L CNC Wire-cut Machine is available. Figure 3.1 shows the wire EDM in FKM laboratory.

Figure 3.1: CNC Wire-cut Machine.

Each wire EDM available in the market has its own specifications. For this Sodick AQ 535 L CNC Wire-cut Machine, its specifications were shown in Table 3.1 and 3.2.

Table 3.1: Specification of Sodick AQ 535 L

Scope	
Max. work piece dimensions	1000x650x290 (mm)
Max. work piece weight	800 kg
Working range	550x250 (mm)
Processing accuracy	±2,5 mkm
Finest surface finish (R_a)	0.17

Table 3.2: Specification of Sodick AQ 535 L

Other specifications
Auto Wire Threader
Submersed cutting
X and Y Linear motors
EF4 Anti-Electrolysis/ Fine Finish circuitry
LCD Touch screen

Source: Advanced EDM Supply and Microny [41]

3.1.2 CNC MACHINE

The experiment is going to operate a milling process. So, this project is going to use the CNC machine that is available in FKM laboratory in Universiti Malaysia Pahang (UMP). The brand of machine that UMP use HAAS CNC machine. The experiments in this project are going to use the VF6 machine. Figure 3.2 shows the HAAS CNC machine in FKM laboratory.

Figure 3.2: VF6 HAAS CNC machine.

Table 3.3 until 3.10 shows the specifications of the VF6 machine:

Table 3.3: VF-6/40 Travels specification.

Travels	S.A.E	Metric
X Axis	64 "	1626 mm
Y Axis	32 "	813 mm
Z Axis	30 "	762 mm
Spindle Nose to Table (~ min)	4 "	102 mm

Table 3.4: VF-6/40 Table specification.

Table	S.A.E.	Metric
Length	64 "	1626 mm
Width	28 "	711 mm
T-Slot Width	5/8 "	16 mm
T-Slot Center Distance	4.92 "	125.0 mm
Number of Std T-Slots	5	
Max Weight on Table (evenly distributed)	4000 lb	1814 kg

Table 3.5: VF-6/40 Spindle specification.

Spindle	S.A.E.	Metric
Max Rating	20 hp	14.9 kW
Max Speed	7500 rpm	7500 rpm
Max Torque	75 ft-lb @ 1400 rpm	102 Nm @ 1400 rpm
Drive System	Direct Speed Belt Drive	Direct Speed Belt Drive
Max Torque w/opt Gearbox	250 ft-lb @ 450 rpm	339 Nm @ 450 rpm
Taper	CT/40	CT/40
Bearing Lubrication	Air/Oil Injection	
Cooling	Liquid Cooled	

Table 3.6: VF-6/40 Feedrate specification.

Feedrates	S.A.E.	Metric
Rapids on X	540 in/min	13.7 m/min
Rapids on Y	600 in/min	15.2 m/min
Rapids on Z	600 in/min	15.2 m/min
Max Cutting	500 in/min	12.7 m/min

Table 3.7: VF-6/40 Axis motors specification.

Axis motors	S.A.E.	Metric
Max Thrust X	3400 lb	15124 N
Max Thrust Y	3400 lb	15124 N
Max Thrust Z	5600 lb	24910 N

Table 3.8: VF-6/40 Tool changer specification.

Tool changer	S.A.E.	Metric
Max Tool Diameter (adjacent empty)	6 “	152 mm
Max Tool Diameter (full)	3 “	76 mm
Max Tool Length (from gage line)	16 “	406 mm
Max Tool Weight	12 lb	5.4 kg
Tool-to-Tool (avg)	2.8 sec	2.8 sec
Chip-to-Chip (avg)	3.6 sec	3.6 sec

Table 3.9: VF-6/40 Accuracy (1 axis) specification.

Accuracy (1 axis)	**S.A.E.**	**Metric**
Positioning (±)	0.0003 " (with linear scales)	0.008 mm (with linear scales)
Repeatability (±)	0.0002 " (with linear scales)	0.005 mm (with linear scales)

Table 3.10: VF-6/40 General specification.

General	**S.A.E.**	**Metric**
Air Required	4 scfm, 100 psi	113 L/min, 6.9 bar
Coolant Capacity	95 gal	360 L
Power (options may increase requirement)	195-260 VAC/50 A	195-260 VAC/50 A
Machine Weight	21000 lb	9526 kg

Source: HAASCNC [42].

3.2.3 2-D MICROSCOPE.

To observe the wear that occurs on the cutting tools, 2-D microscope will be use. 2-D microscope is available in FKM Mechanical Preparation Laboratory. Figure 3.3 shows the 2-D microscope in FKM Mechanical Preparation Laboratory.

Figure 3.3: 2-D microscope.

3.2 WORKPIECE PREPARATION.

In this project, the workpiece material is modified AISI P20 tool steel. Table 3.11 shows the chemical analysis of modified AISI P20 tool steel.

Table 3.11: Chemical analysis of modified AISI P20 tool steel [48].

Composition	Percentage
C	0.38
Si	0.3
Mn	1.5
Cr	1.9
Mo	0.15
S	0.015
Fe	Balance

Source: Abou-El-Hossein, Kadirgama, Hamdi, and Benyounis (2007)

Table 3.12 shows the physical properties for modified AISI P20 tool steel.

Table 3.12: Physical properties of modified AISI tool steel [47].

	Temperature		
	20°C	200°C	400°C
Density (kg/m^3)	7800	7750	7700
Coefficient of thermal expansion (Per °C From 20°C)	-	12.7 x 10^{-6}	13.6 x 10^{-6}
Thermal conductivity (J/m.s °C)	29.0	29.5	31.0
Modulus of elasticity (N/mm^2)	205 000	200 000	185 000
Specific heat (J/kg° C)	460	-	-

Source: West Yorkshire Steel Company Ltd.

The cutting tool used in this study is a 0◦ lead-positive end milling cutter of 31.75mm diameter. The end mill can be equipped with two square inserts whose all four edges can be used for cutting. The tool inserts were made by Kennametal and had an ISO catalogue number of SPCB120308 (KC735M). In this study, only one inserts per one experiment was mounted on the cutter. The insert had a square shape, back rake angle of 0◦, clearance angle of 11◦, and nose radius of 0.794mm and had no chip breaker. KC735M inserts are coated with a single layer of TiN. The coating is accomplished using PVD techniques to a maximum of 0.004mm thickness.

The 27 experiments were performed in a random manner on HAAS CNC milling machine and using a standard coolant. Each experiment was stopped after 85mm cutting length. Meanwhile, the data about tool life component *t*, was acquired with the aid of a 2-D microscope. After each run, the cutting tool will be observed under the 2-D microscope. A cutting pass was conducted in such a way that a shoulder, of depth ranging from 1 to 2 mm, and width of 2 to 5 mm, was produced. Figure 3.4 shows the experimental setup of this study.

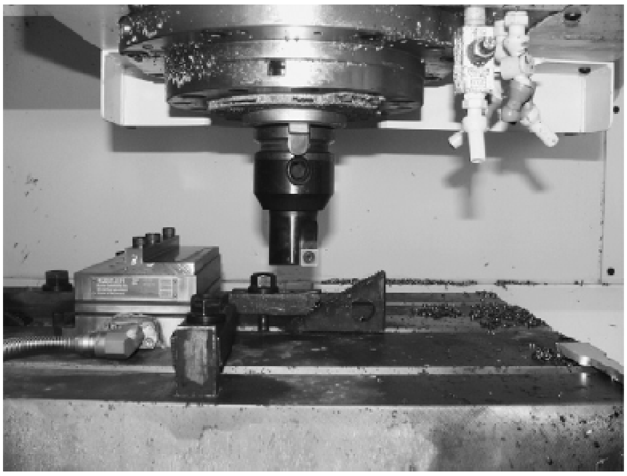


Figure 3.4: Experimental setup [48].

Source: Abou-El-Hossein, Kadirgama, Hamdi, and Benyounis (2007)

3.3 RESPONSE SURFACE METHODOLOGY (RSM)

In this study, primary machining variables such as cutting speed, feed rate, radial depth and axial depth of cut, which are easily controllable, are considered in building the models. By using statistical software (Minitab) the cutting conditions of 27 experiments are generated and the experiments are conducted randomly to minimize errors. Based on the range of parameters that has been decided, the design of experiment can be build. Table 3.13 shows the range of parameters in this project.

Table 3.13: Range of parameters [48].

Factors	Coding of levels		
	-1	0	1
Cutting speed (m/s)	100	140	180
Feed rate (mm/rev)	0.1	0.2	0.3
Axial depth (mm)	1	1.5	2
Radial depth (mm)	2	3.5	5

Source: Abou-El-Hossein, Kadirgama, Hamdi, and Benyounis (2007)

In order to reduce the total number of cutting tests and allow simultaneous variation of the four independent factors, a well-designed experimental procedure has to be followed. In machining research, the Box–Behnken design has found a broad application compared to other experiment designs used for RSM. The Box–Behnken design is based on the combination of the factorial with incomplete block designs. It does not require a large number of tests as it considers only three levels (−1, 0, 1) of each independent parameter [12].

The levels of the four input independent variables are given in Table 1. The Box–Behnken design is normally used for non-sequential experimentation, when a test is conducted only once. It allows an efficient evaluation of the parameters in the first and second order models. Using Minitab the cutting conditions of 27 experiments are generated and the experiments are conducted randomly to minimize the chance errors. In order to calculate the experimental error, the 27 experiments consider five times repeating of the central point of the cutting conditions. After a series of preliminary trial tests had been conducted and based on the recommendations given by the tool and workpiece manufacturers, the cutting conditions of the main experiments were established. Table 6 shows the Conditions of cutting experiments according to Box–Behnken design.

The experiment of this project will be conducted base on the generated table. And the experiments orders are according to the axial depth, from the smallest number to the biggest number. Table 3.14 shows the design of experiment table that will be applied in this project.

Table 3.14: Design of experiment.

Cutting speed (m/s)	**Feed rate (mm/rev)**	**Axial depth (mm)**	**Radial depth (mm)**	**Exp. Tool life (min)**
140	0.15	1	2	
140	0.2	1	3.5	
100	0.15	1	3.5	
180	0.15	1	3.5	
140	0.1	1	3.5	
140	0.15	1	5	
100	0.15	1.5	2	
140	0.1	1.5	2	
100	0.2	1.5	3.5	
140	0.15	1.5	3.5	
180	0.2	1.5	3.5	
180	0.15	1.5	2	
140	0.2	1.5	2	
140	0.2	1.5	5	
140	0.15	1.5	3.5	
180	0.1	1.5	3.5	
100	0.1	1.5	3.5	
100	0.15	1.5	5	
140	0.1	1.5	5	
180	0.15	1.5	5	
140	0.15	1.5	3.5	

140	0.15	2	5
140	0.2	2	3.5
140	0.1	2	3.5
140	0.15	2	2
100	0.15	2	3.5

To fill the tool life column, Tool life formula will be used. The experimental value of tool life will be expressed as in Eq. (3.1).

$$\text{Tool life} = TL/FM \qquad \textbf{(3.1)}$$

After conducting the experiment, we fill up the design of experiment table. When the table was completed, the data can be process in Minitab software thus developing the first and second order tool life model when milling modified AISI P20 tool steel.

CHAPTER 4

ANALYSIS

4.1 MODEL FOR TOOL LIFE

With reference to the response surface method, where the response variable is the tool life in this study, the relationship between the investigated four cutting conditions and the response can be represented by the following linear equation:

$$\ln t = A\ln V_c + B \ln f + C \ln a_a + D\ln a_r + E$$

where t is the tool life (response), A, B, C, D and E are constants, while V_c, f, a_a and a_r the cutting speed (mm/min), feedrate (mm/rev), axial depth of cut (mm) and radial depth of cut (mm), respectively. Equation (4.1) can be written as follows:

$$y = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \varepsilon \text{ or}$$

$$\hat{y} = y - \varepsilon = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x3 + \beta_4 x_4 \qquad \textbf{(4.1)}$$

where y is the tool life experimental value and ŷ is the predicted value, while x_0, x_1, x_2, x_3, x_4 and ε are dummy variable (x_0 = 1), cutting speed, feed rate, axial depth of cut, radial depth of cut, and experimental error, respectively. β_0, β_1, β_2, β_3 and β_4 are the model parameters.

In most cases, the response surface variables demonstrate some curvature in most ranges of the cutting parameters. Therefore, it would be useful to consider also the second order model in this study. The second order model helps understand the second order effect of each factor separately and the two-way interaction amongst these factors combined. This model can be represented by the following equation:

$$\hat{y}'' = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_{11} x_2^{1} + \beta_{22} x_2^{2} + \beta_{33} x_2^{3} + \beta_{44} x_2^{4} + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{14} x_1 x_4 + \beta_{23} x_2 x_3 + \beta_{24} x_2 x_4 + \beta_{34} x_3 x_4 \quad \textbf{(4.2)}$$

4.2 RESULTS AND DISCUSSION

4.2.1 Development of first order tool life model

After conducting the first passes (one pass is equal to 85mm length) of the 27 cutting experiments, the tool life values are used to find the parameters appearing in the postulated first order model Equation (4.3). To do the calculation of these parameters, the method of least squares is used with the aid of MINITAB. The first order linear equation for predicting the tool life is expressed as:

$$\hat{y} = 60.7101 - 0.146229 x_1 - 136.917 x_2 + 3.54333 x_3 - 3.64222 x_4 \quad \textbf{(4.3)}$$

From this linear equation, one can easily notice that the response $\hat{y}$ (tool life) is affected significantly by the feed rate followed by the axial depth of cut and then by the radial depth of cut, and lastly, by the cutting speed. Generally, the increase in the axial depths of cut will cause the tool life to become smaller. On the other hand, the decrease in cutting speed, federate, and radial depth will increase the tool life. This can be proved by the sign in the developed linear equation. The proposed linear equation is valid only for cutting modified AISI P20 with a 0◦ lead end mill equipped with TiN coated KC735M carbide inserts and within the cutting conditions ranges used in the experimentation. Table 4.1 shows the tool life values received by experimentation and the values predicted by the first order model.

Table 4.1: Tool life values received by experimentation and the values predicted by the first order model

Number of experiment	Cutting speed (m/s)	Feedrate (mm/rev)	Axial depth (mm)	Radial depth (mm)	Exp. tool life (min)	Predicted tool life (min)
2	140	0.15	1.0	2.0	8.23	15.9594
7	140	0.20	1.0	3.5	2.43	3.6503
11	100	0.15	1.0	3.5	17.00	16.3453
14	180	0.15	1.0	3.5	3.94	4.6469
19	140	0.10	1.0	3.5	16.39	17.3419
21	140	0.15	1.0	5.0	4.33	5.0328
4	100	0.15	1.5	2.0	25.10	23.5803
5	140	0.10	1.5	2.0	39.46	24.5769
6	100	0.20	1.5	3.5	11.48	11.2711
9	140	0.15	1.5	3.5	10.93	12.2678
10	180	0.20	1.5	3.5	1.30	-0.4272
12	180	0.15	1.5	2.0	7.51	11.8819
15	140	0.20	1.5	2.0	15.79	10.8853
22	140	0.20	1.5	5.0	2.02	-0.0414
24	140	0.15	1.5	3.5	11.33	12.2678
25	180	0.10	1.5	3.5	14.17	13.2644
26	100	0.10	1.5	3.5	16.15	24.9628
8	100	0.15	1.5	5.0	18.70	12.6536
17	140	0.10	1.5	5.0	19.43	13.6503
18	180	0.15	1.5	5.0	3.46	0.9553
22	140	0.15	1.5	3.5	8.50	12.2678
1	140	0.15	2.0	5.0	6.88	8.5761
3	140	0.20	2.0	3.5	3.79	7.1936
13	140	0.10	2.0	3.5	13.36	20.8853
16	140	0.15	2.0	2.0	24.29	19.5028
20	100	0.15	2.0	3.5	18.70	19.8886
27	180	0.15	2.0	3.5	6.56	8.1903

It is clear that the predicted values are very close to the experimental readings. This indicates that the obtained linear model is able to provide, to a great extent, accurate values of cutting forces. Figure 4.1 below shows the normal probability plot of the residual generated from MINITAB based on first order linear equation.

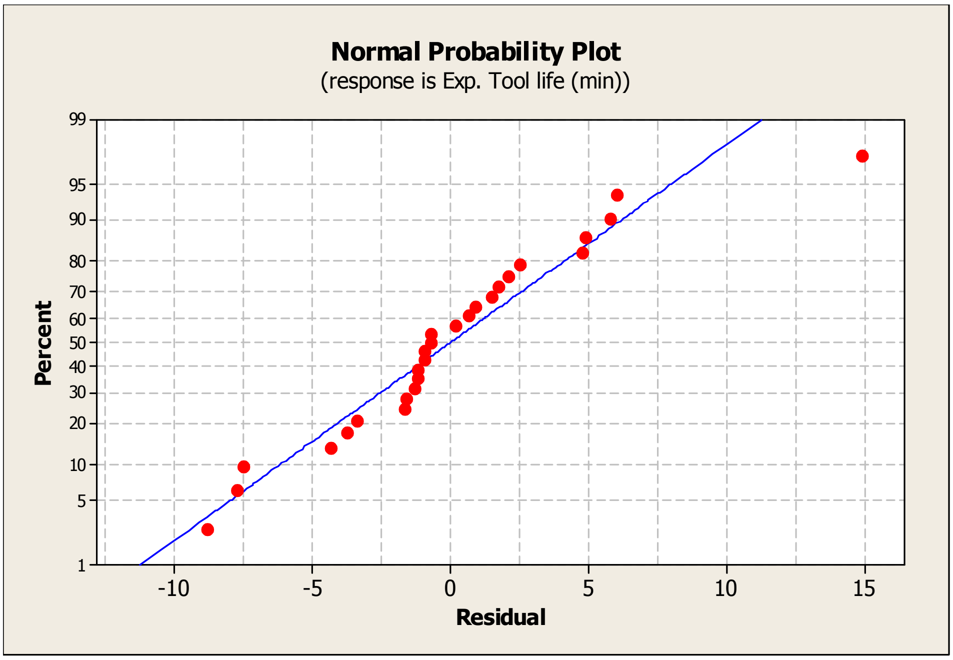


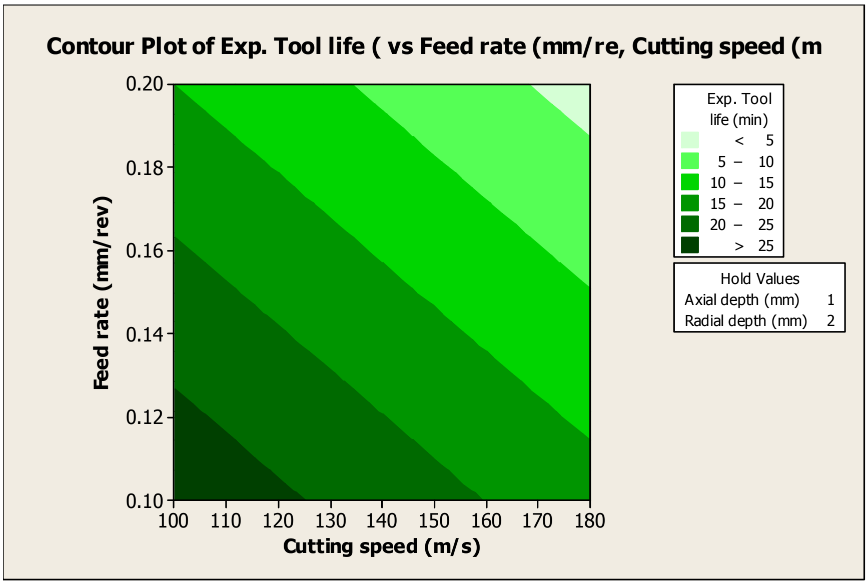
Figure 4.1: Normal probability plot for 1st order model.

The adequacy of the first order model was verified using the analysis of variance (ANOVA). At a level of confidence of 95%, the model was checked for its adequacy. As shown in Table 4.2 below, the lack-of-fit *P*-value of 0.075 is not significant with relative to the pure error. This implies that the model could fit and it is adequate. There is about a chance of 7.5% that the lack-of-fit *P*-value could occur due to noise.

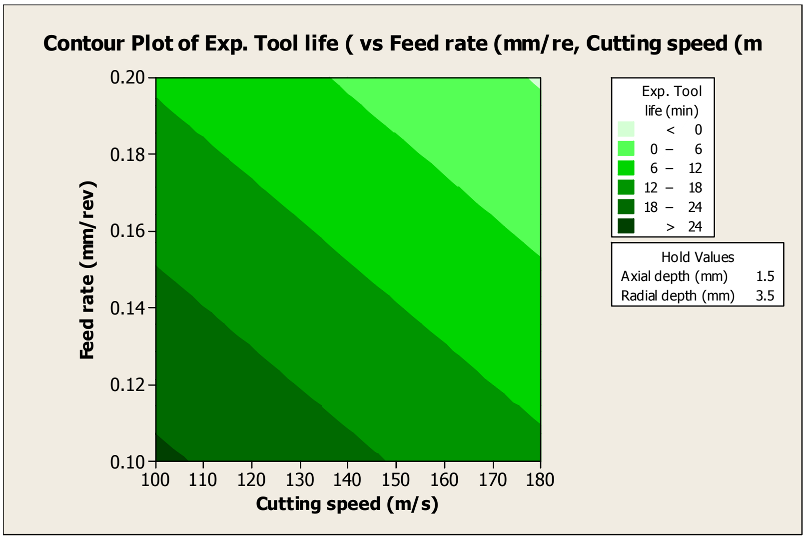
Table 4.2: Analysis of variance ANOVA for first order equation (from Minitab)

Source of variation	**Degree of freedom (d.f.)**	**Sum of squares (SS)**	**Mean squares (MS)**	***F***	***P***
Zero order term	4	1368.78	342.195	12.39	0
Residual error	22	607.49	27.613		
Lack-of-fit	20	602.80	30.140	12.85	0.075
Pure error	2	4.69	2.346		
Total	26	1976.27			

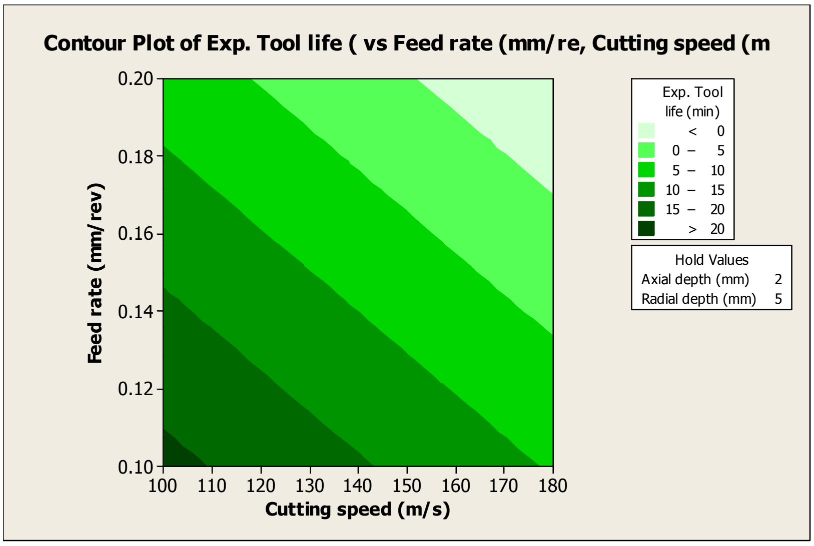
The developed linear model equation 4 was used to plot contours of the tool life at different values of the axial and radial depths of cut. Figure 4.2 below shows the tool life contours at three different combinations of the axial and radial depths (lowest "−1", middle "0", and highest values "+1"). It is clear that the reduction in cutting speed and radial depth will cause the tool life to increase dramatically. From Figure 4.2(a), the tool life reaches its highest value when all cutting conditions, except for axial depth, at their minimum values. In this case the radial depth is at its smallest value (2mm).



a) Axial depth=1mm, Radial depth=2mm



b) Axial depth=1.5mm, Radial depth=3.5mm



c) Axial depth=2mm, Radial depth=5mm

Figure 4.2: Tool life contours in cutting speed–feed plane for different combinations of axial and radial depths of cut plotted from first order model: (a) radial depth = 2mm (highest values); (b) radial depth = 3.5mm (middle values); (c) radial depth = 5mm (lowest values).

4.2.2 Development of second order tool life model

The second order equation was established to describe the effect of the four cutting conditions investigated in this study on the tool life. The model is obtained using the Box–Behnken design. The equation is given by:

$$\hat{y}'' = 68.4198 - 0.107437x_1 - 351.300x_2 + 34.0150x_3 - 14.6219x_4 + 0.000226562x_1^2 + 730.000x_2^2 - 7.63500x_3^2 + 1.89056x_4^2 - 1.02500x_1x_2 + 0.0115000x_1x_3 + 0.00979167x_1x_4 + 43.9000x_2x_3 + 20.8667x_2x_4 - 4.50333x_3x_4 \quad \textbf{(5)}$$

The model shows that the tool life increases with decreasing the axial depth but for cutting speed, federate, and axial depth, reducing the values will increase the tool life. The tool life readings obtained experimentally and predicted values by this equation are shown in Table 4.3 below.

Table 4.3: Tool life values received by experimentation and the values predicted by the second order model

Number of experiment	Cutting speed (m/s)	Feedrate (mm/rev)	Axial depth (mm)	Radial depth (mm)	Exp. tool life (min)	Predicted tool life (min)
2	140	0.15	1.0	2.0	8.23	12.9125
7	140	0.20	1.0	3.5	2.43	0.4546
11	100	0.15	1.0	3.5	17.00	13.0146
14	180	0.15	1.0	3.5	3.94	0.8562
19	140	0.10	1.0	3.5	16.39	16.3413
21	140	0.15	1.0	5.0	4.33	8.7408
4	100	0.15	1.5	2.0	25.10	26.7696
5	140	0.10	1.5	2.0	39.46	30.2063
6	100	0.20	1.5	3.5	11.48	13.4942
9	140	0.15	1.5	3.5	10.93	10.2533
10	180	0.20	1.5	3.5	1.30	-2.3042
12	180	0.15	1.5	2.0	7.51	13.8963
15	140	0.20	1.5	2.0	15.79	13.3846
22	140	0.20	1.5	5.0	2.02	5.5879
24	140	0.15	1.5	3.5	11.33	10.2533
25	180	0.10	1.5	3.5	14.17	15.4875

26	100	0.10	1.5	3.5	16.15	23.0858
8	100	0.15	1.5	5.0	18.70	14.6679
17	140	0.10	1.5	5.0	19.43	16.1496
18	180	0.15	1.5	5.0	3.46	4.1446
22	140	0.15	1.5	3.5	8.50	10.2533
1	140	0.15	2.0	5.0	6.88	5.5292
3	140	0.20	2.0	3.5	3.79	6.1929
13	140	0.10	2.0	3.5	13.36	17.6896
16	140	0.15	2.0	2.0	24.29	23.2108
20	100	0.15	2.0	3.5	18.70	16.0979
27	180	0.15	2.0	3.5	6.56	4.85958

It can be concluded from the table that the equation can produce values close to those found experimentally. Figure 4.3 below shows the normal probability plot of the residual generated from MINITAB based on 2nd order quadratic equation.

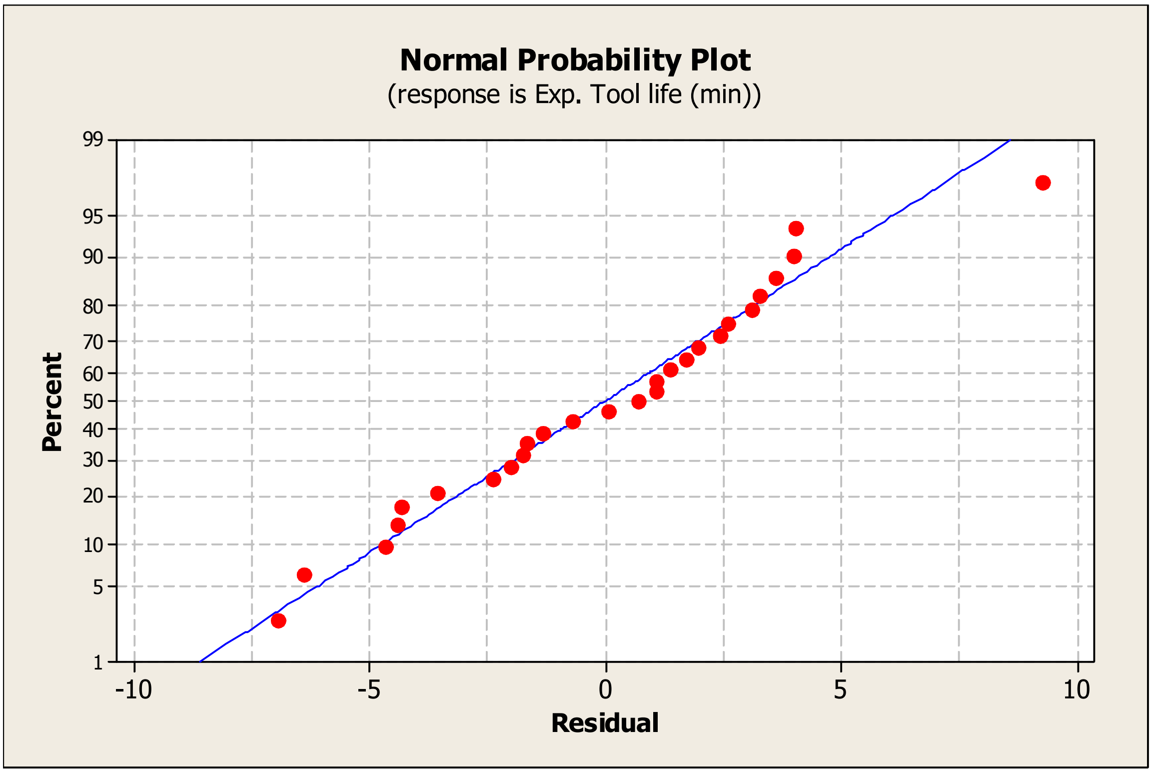


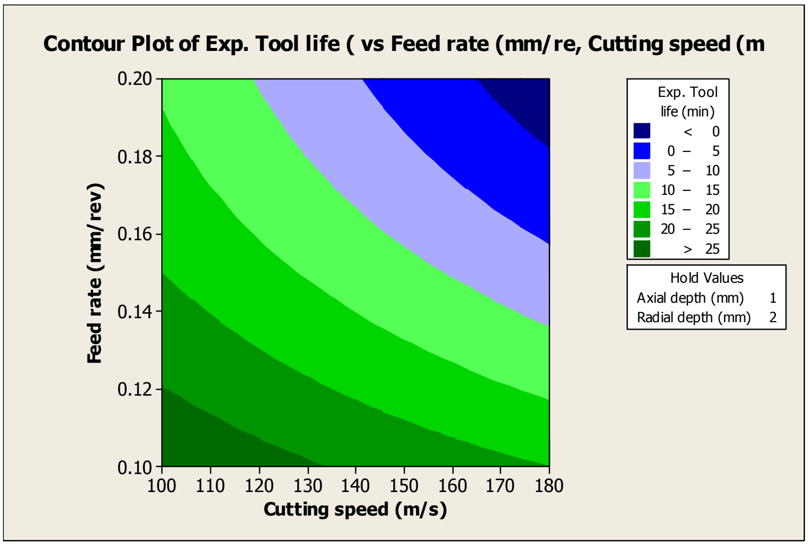
Figure 4.3: Normal probability plot for 2nd order model.

The adequacy of the second order model was verified using the analysis of variance (ANOVA). At a level of confidence of 95%, the model was checked for its adequacy. As shown in Table 4.2 below, the lack-of-fit *P*-value of 0.064 is not significant with relative to the pure error. This implies that the model could fit and it is adequate. There is about a chance of 6.4% that the lack-of-fit *P*-value could occur due to noise. The analysis of variance shown in table 4.4 indicates that the model is adequate as the *P*-values of the lack-of-fit are not significant.

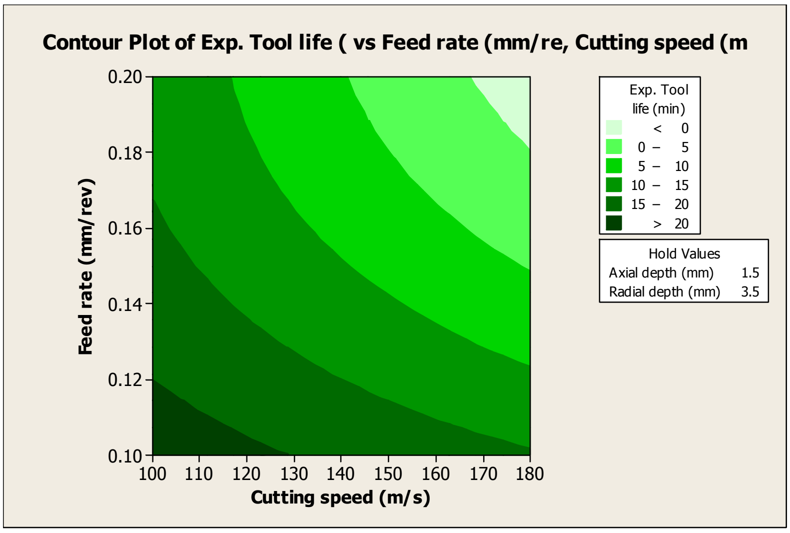
Table 4.4: Analysis of variance ANOVA for second order equation (from Minitab)

Source of variation	**Degree of freedom (d.f.)**	**Sum of squares (SS)**	**Mean squares (MS)**	***F***	***P***
Regression	14	1621.63	115.831	3.92	0.011
First order term	4	1368.78	342.195	11.58	0
Second order term	4	174.21	43.552	1.47	0.271
Interaction terms	6	78.65	13.108	0.44	0.836
Residual error	12	354.64	29.553		
Lack-of-fit	10	349.95	34.995	14.92	0.064
Pure error	2	4.69	2.346		
Total	26	1976.27			

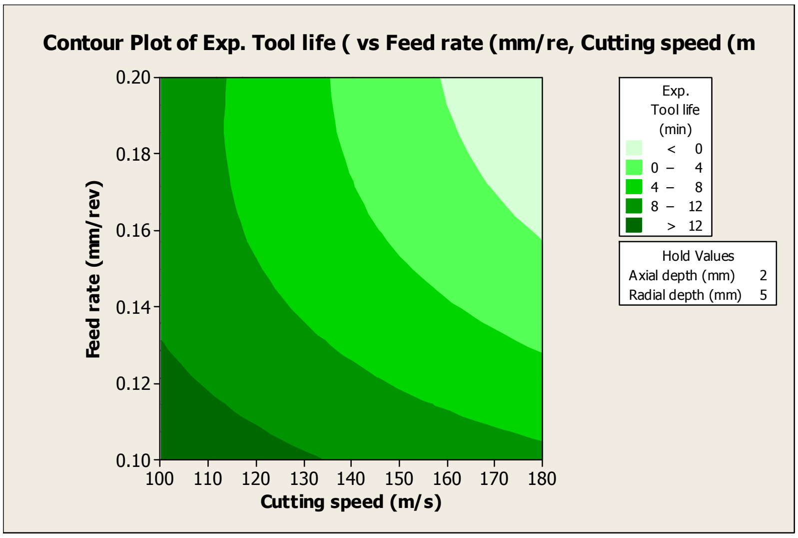
Figure 4.4 shows the contour plots of the tool life in the cutting speed and feed plane of the lowest, middle and highest values of the axial and radial depth of cut. It shows the tool life contours at three different combinations of the axial and radial depths (lowest “−1”, middle “0”, and highest values “+1”). It is clear that the reduction in cutting speed and radial depth will cause the tool life to increase dramatically. From Figure 4.2(a), the tool life reaches its highest value when all cutting conditions, except for axial depth, at their minimum values. In this case the radial depth is at its smallest value (2mm).



a) Axial depth=1mm, Radial depth=2mm



b) Axial depth=1.5mm, Radial depth=3.5mm



c) Axial depth = 2mm, Radial depth = 5mm

Figure 4.4: Tool life contours in cutting speed–feed plane for different combinations of axial and radial depths of cut plotted from first order model: (a) radial depth = 2mm (highest values); (b) radial depth = 3.5mm (middle values); (c) radial depth = 5mm (lowest values).

4.3 COMPARISON OF ERROR % BETWEEN THE 1ST ORDER AND THE 2ND ORDER TOOL LIFE MODEL

Error % of each model can be use to compare the accuracy from both developed models. The best model can be chosen from the one that has the lowest percent of error. The formula to calculate the percentage of error was shown in Equation (4.4) below.

$$\text{Error \%} = \frac{\text{Experimental tool life value} - \text{Predicted tool life value}}{\text{Experimental tool life value}} \times 100\% \qquad \textbf{(4.4)}$$

4.3.1 1st Order Tool Life Model Error Analysis.

Table 4.5 shows the comparison between the experimental tool life value and the predicted tool life value with the error percentage. By using Equation (4.4), error % was calculated.

Table 4.5: Error % for 1st order tool life model

Experimental tool life value (min)	Predicted tool life value (min)	Error %
8.23	15.9594	-93.9174
2.43	3.6503	-50.2181
17	16.3453	3.851176
3.94	4.6469	-17.9416
16.39	17.3419	-5.80781
4.33	5.0328	-16.2309
25.1	23.5803	6.054582
39.46	24.5769	37.71693
11.48	11.2711	1.819686
10.93	12.2678	-12.2397
1.3	-0.4272	132.8615
7.51	11.8819	-58.2144
15.79	10.8853	31.06206
2.02	-0.0414	102.0495
11.33	12.2678	-8.27714
14.17	13.2644	6.390967
16.15	24.9628	-54.5684
18.7	12.6536	32.33369
19.43	13.6503	29.74627
3.46	0.9553	72.39017
8.5	12.2678	-44.3271
6.88	8.5761	-24.6526
3.79	7.1936	-89.8047
13.36	20.8853	-56.3271
24.29	19.5028	19.70852
18.7	19.8886	-6.35615
6.56	8.1903	-24.8521

To help making the data analysis clearer, the error % values are shown in graph. Figure 4.5 shows the graph for 1st order model error %.

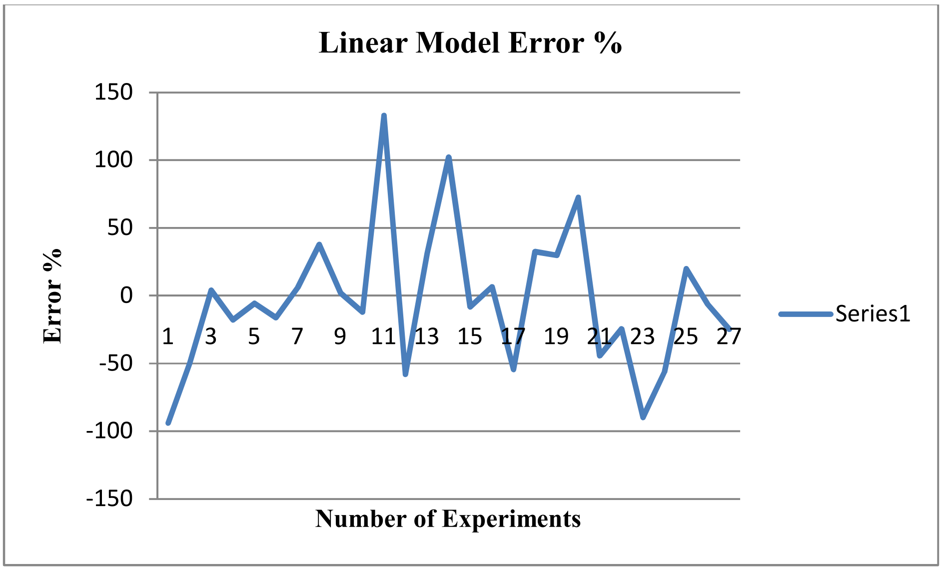


Figure 4.5: Error % for 1st order tool life model

The average value of error % for 1st order tool life model is 3.25%.

4.3.2 2nd Order Tool Life Model Error Analysis.

Table 4.6 shows the comparison between the experimental tool life value and the predicted tool life value with the error percentage. By using Equation (4.4), error % was calculated.

Table 4.6: Error % for 2nd order tool life model

Experimental tool life value (min)	Predicted tool life value (min)	Error %
8.23	12.9125	-56.8955
2.43	0.4546	81.29218
17	13.0146	23.44353
3.94	0.8562	78.26904
16.39	16.3413	0.297132
4.33	8.7408	-101.866
25.1	26.7696	-6.65179
39.46	30.2063	23.45084
11.48	13.4942	-17.5453
10.93	10.2533	6.191217
1.3	-2.3042	277.2462
7.51	13.8963	-85.0373
15.79	13.3846	15.23369

2.02	5.5879	-176.629
11.33	10.2533	9.503089
14.17	15.4875	-9.29781
16.15	23.0858	-42.9461
18.7	14.6679	21.56203
19.43	16.1496	16.88317
3.46	4.1446	-19.7861
8.5	10.2533	-20.6271
6.88	5.5292	19.63372
3.79	6.1929	-63.4011
13.36	17.6896	-32.4072
24.29	23.2108	4.442981
18.7	16.0979	13.91497
6.56	4.85958	25.92104

To help making the data analysis clearer, the error % values are shown in graph. Figure 4.6 shows the graph for 2nd order model error %.

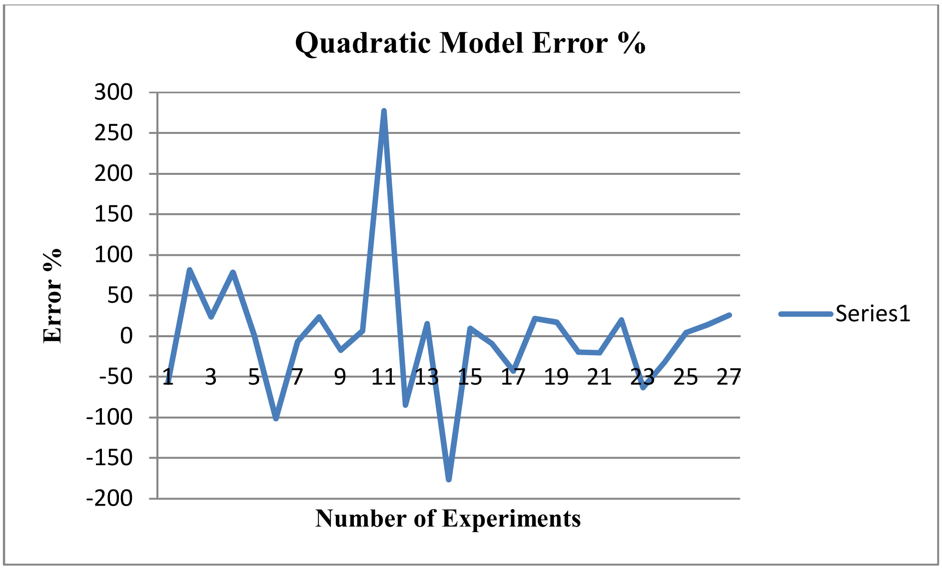


Figure 4.6: Error % for 2nd order tool life model

The average value of error % for 2nd order tool life model is 0.59%. Comparing with the 1st order model, 2nd order model gives more accurate value because the average error % shows it has smaller value.

CHAPTER 5

CONCLUSION

5.1 CONCLUSION

Response surface methodology RSM has proved to be a successful technique that can be used to predict the tool life in end milling of modified AISI P20 with TiN coated inserts mounted on 0◦ lead cutters. The first order and second order equation developed by RSM using Minitab are able to provide accurately predicted values of the tool life close to those values found in the experiments. The equations are checked for their adequacy with a confidence interval of 95%. In general, the results obtained from the prediction model are in good agreement with that obtain from experiment data. It was found that the feedrate, cutting speed, and radial depth played a major role in determining the tool life. The relationship between the four cutting parameters with tool life for 1st and 2nd order model are, the tool life increase with reduction of cutting speed, feedrate, and radial depth excluding the axial depth. This can be observed and proven from the sign of each parameter from both models.

For end-milling of P20 tool steel, the optimum conditions that is required to maximize the coated carbide tool life are as follow: cutting speed of 140 m/s, federate of 0.1 mm/rev, axial depth of 1.5 mm and radial depth of 2 mm. Using these parameters, a tool life of 39.46min was obtained. This value for tool life was obtained from the 2^{nd} order model. Comparing with the 1st order model, 2nd order model gives more accurate value because the average error % shows it has smaller value, which is 0.59%.

5.2 RECOMMENDATIONS

There are many factors that affect the tool life, not only the cutting parameters. Nowadays, there is another type of cutting that does not use lubricant. It is called dry machining process. Roughly, this type of cutting may seem shortening the tool life faster than cutting process that use lubricant or coolant. For further research, this type of machining can be studied. Looking at the advantage of dry machining that does not involve lubricant or coolant; it saves the manufacturing cost by eliminating the cost for lubricant for machining process. This type of machining also can be considered as ecological friendly since no chemical waste produced during machining process. The risk that came from the effect of the chemical reaction to human also can be prevented. Related to the dry machining process, it involves the type of coating on the cutting tool. This factor also can be include for further research, that is to investigate the effect of coating type to tool life. Other than all the factors that affect the tool life that has been mention above, the material to be use in the experiment also can be manipulate to investigate the tool life. For an example, the common materials used in industry nowadays like aluminum.

Next, the type of design of experiment can be use since there are several options available other than RSM such like, Taguchi method, and Neural Network. Each method has its own advantage according to the type of experiment that will be conducted.

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APPENDIX A

Number of experiment	Cutting speed (m/s)	Feedrate (mm/rev)	Axial depth (mm)	Radial depth (mm)	Exp. tool life (min)
2	140	0.15	1.0	2.0	8.23
7	140	0.20	1.0	3.5	2.43
11	100	0.15	1.0	3.5	17.00
14	180	0.15	1.0	3.5	3.94
19	140	0.10	1.0	3.5	16.39
21	140	0.15	1.0	5.0	4.33
4	100	0.15	1.5	2.0	25.10
5	140	0.10	1.5	2.0	39.46
6	100	0.20	1.5	3.5	11.48
9	140	0.15	1.5	3.5	10.93
10	180	0.20	1.5	3.5	1.30
12	180	0.15	1.5	2.0	7.51
15	140	0.20	1.5	2.0	15.79
22	140	0.20	1.5	5.0	2.02
24	140	0.15	1.5	3.5	11.33
25	180	0.10	1.5	3.5	14.17
26	100	0.10	1.5	3.5	16.15
8	100	0.15	1.5	5.0	18.70
17	140	0.10	1.5	5.0	19.43
18	180	0.15	1.5	5.0	3.46
22	140	0.15	1.5	3.5	8.50
1	140	0.15	2.0	5.0	6.88
3	140	0.20	2.0	3.5	3.79
13	140	0.10	2.0	3.5	13.36
16	140	0.15	2.0	2.0	24.29
20	100	0.15	2.0	3.5	18.70
27	180	0.15	2.0	3.5	6.56

Figure A: Experiment data collection table

APPENDIX B

ANOVA result from Minitab for Linear Model.

```
The analysis was done using coded units.

Estimated Regression Coefficients for Tool Life

Term             Coef  SE Coef       T      P
Constant       12.268    1.011  12.131  0.000
Cutting Speed  -5.849    1.517  -3.856  0.001
Feed Rate      -6.846    1.517  -4.513  0.000
Axial Depth     1.772    1.517   1.168  0.255
Radial Depth   -5.463    1.517  -3.602  0.002

S = 5.255   R-Sq = 69.3%   R-Sq(adj) = 63.7%


Analysis of Variance for Tool Life

Source          DF   Seq SS   Adj SS   Adj MS      F      P
Regression       4  1368.78  1368.78  342.195  12.39  0.000
  Linear         4  1368.78  1368.78  342.195  12.39  0.000
Residual Error  22   607.49   607.49   27.613
  Lack-of-Fit   20   602.80   602.80   30.140  12.85  0.075
  Pure Error     2     4.69     4.69    2.346
Total           26  1976.27


Unusual Observations for Tool Life

Obs  StdOrder  Tool Life     Fit  SE Fit  Residual  St Resid
  8         8     39.460  24.577   2.372    14.883      3.17 R

R denotes an observation with a large standardized residual.


Estimated Regression Coefficients for Tool Life using data in uncoded units

Term                Coef
Constant         60.7101
Cutting Speed  -0.146229
Feed Rate       -136.917
Axial Depth      3.54333
Radial Depth    -3.64222


Predicted Response for New Design Points Using Model for Tool Life

Point      Fit   SE Fit        95% CI               95% PI
    1  15.9594  2.37169  (11.0409, 20.8780)  (  4.0030, 27.9158)
```

2	3.6503	2.37169	(-1.2683, 8.5689)	(-8.3061, 15.6067)
3	16.3453	2.37169	(11.4267, 21.2639)	(4.3889, 28.3017)
4	4.6469	2.37169	(-0.2716, 9.5655)	(-7.3095, 16.6033)
5	17.3419	2.37169	(12.4234, 22.2605)	(5.3855, 29.2983)
6	5.0328	2.37169	(0.1142, 9.9514)	(-6.9236, 16.9892)
7	23.5803	2.37169	(18.6617, 28.4989)	(11.6239, 35.5367)
8	24.5769	2.37169	(19.6584, 29.4955)	(12.6205, 36.5333)
9	11.2711	2.37169	(6.3525, 16.1897)	(-0.6853, 23.2275)
10	12.2678	1.01129	(10.1705, 14.3651)	(1.1700, 23.3656)
11	-0.4272	2.37169	(-5.3458, 4.4914)	(-12.3836, 11.5292)
12	11.8819	2.37169	(6.9634, 16.8005)	(-0.0745, 23.8383)
13	10.8853	2.37169	(5.9667, 15.8039)	(-1.0711, 22.8417)
14	-0.0414	2.37169	(-4.9600, 4.8772)	(-11.9978, 11.9150)
15	12.2678	1.01129	(10.1705, 14.3651)	(1.1700, 23.3656)
16	13.2644	2.37169	(8.3459, 18.1830)	(1.3080, 25.2208)
17	24.9628	2.37169	(20.0442, 29.8814)	(13.0064, 36.9192)
18	12.6536	2.37169	(7.7350, 17.5722)	(0.6972, 24.6100)
19	13.6503	2.37169	(8.7317, 18.5689)	(1.6939, 25.6067)
20	0.9553	2.37169	(-3.9633, 5.8739)	(-11.0011, 12.9117)
21	12.2678	1.01129	(10.1705, 14.3651)	(1.1700, 23.3656)
22	8.5761	2.37169	(3.6575, 13.4947)	(-3.3803, 20.5325)
23	7.1936	2.37169	(2.2750, 12.1122)	(-4.7628, 19.1500)
24	20.8853	2.37169	(15.9667, 25.8039)	(8.9289, 32.8417)
25	19.5028	2.37169	(14.5842, 24.4214)	(7.5464, 31.4592)
26	19.8886	2.37169	(14.9700, 24.8072)	(7.9322, 31.8450)
27	8.1903	2.37169	(3.2717, 13.1089)	(-3.7661, 20.1467)

APPENDIX C

ANOVA result from Minitab for Quadratic Model.

```
The analysis was done using coded units.

Estimated Regression Coefficients for Tool Life

Term                            Coef  SE Coef       T      P
Constant                     10.2533    3.139   3.267  0.007
Cutting Speed                -5.8492    1.569  -3.727  0.003
Feed Rate                    -6.8458    1.569  -4.362  0.001
Axial Depth                   1.7717    1.569   1.129  0.281
Radial Depth                 -5.4633    1.569  -3.481  0.005
Cutting Speed*Cutting Speed   0.3625    2.354   0.154  0.880
Feed Rate*Feed Rate           1.8250    2.354   0.775  0.453
Axial Depth*Axial Depth      -1.9087    2.354  -0.811  0.433
Radial Depth*Radial Depth     4.2538    2.354   1.807  0.096
Cutting Speed*Feed Rate      -2.0500    2.718  -0.754  0.465
Cutting Speed*Axial Depth     0.2300    2.718   0.085  0.934
Cutting Speed*Radial Depth    0.5875    2.718   0.216  0.833
Feed Rate*Axial Depth         1.0975    2.718   0.404  0.693
Feed Rate*Radial Depth        1.5650    2.718   0.576  0.575
Axial Depth*Radial Depth     -3.3775    2.718  -1.243  0.238

S = 5.436   R-Sq = 82.1%   R-Sq(adj) = 61.1%


Analysis of Variance for Tool Life

Source          DF   Seq SS   Adj SS   Adj MS      F      P
Regression      14  1621.63  1621.63  115.831   3.92  0.011
  Linear         4  1368.78  1368.78  342.195  11.58  0.000
  Square         4   174.21   174.21   43.552   1.47  0.271
  Interaction    6    78.65    78.65   13.108   0.44  0.836
Residual Error  12   354.64   354.64   29.553
  Lack-of-Fit   10   349.95   349.95   34.995  14.92  0.064
  Pure Error     2     4.69     4.69    2.346
Total           26  1976.27


Unusual Observations for Tool Life

Obs  StdOrder  Tool Life     Fit  SE Fit  Residual  St Resid
  8         8     39.460  30.206   4.152     9.254      2.64 R

R denotes an observation with a large standardized residual.


Estimated Regression Coefficients for Tool Life using data in uncoded units

Term                                Coef
Constant                         68.4198
Cutting Speed                  -0.107438
```

Feed Rate	-351.300
Axial Depth	34.0150
Radial Depth	-14.6219
Cutting Speed*Cutting Speed	0.000226563
Feed Rate*Feed Rate	730.000
Axial Depth*Axial Depth	-7.63500
Radial Depth*Radial Depth	1.89056
Cutting Speed*Feed Rate	-1.02500
Cutting Speed*Axial Depth	0.0115000
Cutting Speed*Radial Depth	0.00979167
Feed Rate*Axial Depth	43.9000
Feed Rate*Radial Depth	20.8667
Axial Depth*Radial Depth	-4.50333

Predicted Response for New Design Points Using Model for Tool Life

Point	Fit	SE Fit	95% CI	95% PI
1	12.9125	4.15202	(3.8660, 21.9590)	(-1.9917, 27.8167)
2	0.4546	4.15202	(-8.5919, 9.5011)	(-14.4496, 15.3587)
3	13.0146	4.15202	(3.9681, 22.0611)	(-1.8896, 27.9187)
4	0.8562	4.15202	(-8.1902, 9.9027)	(-14.0479, 15.7604)
5	16.3413	4.15202	(7.2948, 25.3877)	(1.4371, 31.2454)
6	8.7408	4.15202	(-0.3056, 17.7873)	(-6.1633, 23.6450)
7	26.7696	4.15202	(17.7231, 35.8161)	(11.8654, 41.6737)
8	30.2063	4.15202	(21.1598, 39.2527)	(15.3021, 45.1104)
9	13.4942	4.15202	(4.4477, 22.5406)	(-1.4100, 28.3983)
10	10.2533	3.13863	(3.4148, 17.0918)	(-3.4237, 23.9303)
11	-2.3042	4.15202	(-11.3506, 6.7423)	(-17.2083, 12.6000)
12	13.8962	4.15202	(4.8498, 22.9427)	(-1.0079, 28.8004)
13	13.3846	4.15202	(4.3381, 22.4311)	(-1.5196, 28.2887)
14	5.5879	4.15202	(-3.4586, 14.6344)	(-9.3162, 20.4921)
15	10.2533	3.13863	(3.4148, 17.0918)	(-3.4237, 23.9303)
16	15.4875	4.15202	(6.4410, 24.5340)	(0.5833, 30.3917)
17	23.0858	4.15202	(14.0394, 32.1323)	(8.1817, 37.9900)
18	14.6679	4.15202	(5.6214, 23.7144)	(-0.2362, 29.5721)
19	16.1496	4.15202	(7.1031, 25.1961)	(1.2454, 31.0537)
20	4.1446	4.15202	(-4.9019, 13.1911)	(-10.7596, 19.0487)
21	10.2533	3.13863	(3.4148, 17.0918)	(-3.4237, 23.9303)
22	5.5292	4.15202	(-3.5173, 14.5756)	(-9.3750, 20.4333)
23	6.1929	4.15202	(-2.8536, 15.2394)	(-8.7112, 21.0971)
24	17.6896	4.15202	(8.6431, 26.7361)	(2.7854, 32.5937)
25	23.2108	4.15202	(14.1644, 32.2573)	(8.3067, 38.1150)
26	16.0979	4.15202	(7.0514, 25.1444)	(1.1938, 31.0021)
27	4.8596	4.15202	(-4.1869, 13.9061)	(-10.0446, 19.7637)