



**UNIVERSITI PUTRA MALAYSIA**

**DEVELOPMENT OF FUZZY LOGIC MODEL FOR TURNING  
PROCESS OF STEEL ALLOY AND TITANIUM ALLOYS**

**TAN JIT YEAN**

**FK 2004 97**



**DEVELOPMENT OF FUZZY LOGIC MODEL FOR TURNING  
PROCESS OF STEEL ALLOY AND TITANIUM ALLOYS**

**By**

**TAN JIT YEAN**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia  
in Fulfilment of the Requirements for the Degree of Master of Science**

**November 2004**



**Dedicated with love and gratitude to**

**My dearest parent, lover, family and friends**

**as**

**my source of encouragement and support in completion of this study**

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment  
of the requirements for the degree of Master of Science

**DEVELOPMENT OF FUZZY LOGIC MODEL FOR TURNING PROCESS  
OF STEEL ALLOY AND TITANIUM ALLOYS**

**By**

**TAN JIT YEAN**

**November 2004**

**Chairman : Wong Shaw Voon, Ph.D.**

**Faculty : Engineering**

The study is about the application of fuzzy logic in representing the machinability data for the turning process. Machining is a very complex process with respect to the influences of the machining parameters such as cutting speed, feed rate, and depth of cut. In order to perform a good machining practice the proper selection of the machinability data, which includes the machining parameters and cutting tools is very important. Normally, the selection of the machinability data is done by the skilled machinist. The manufacturer may face trouble without the presence of the skilled machinists. Thus, there is a necessity to represent the knowledge of the skilled machinists into model, so that any normal machinists will be able to perform a good machining practice by retrieving the information which prescribed in the model. Consequently, fuzzy logic was chosen as a tool to describe the strategy and action of the skilled machinist.

In this study, two types of fuzzy models for different workpiece material have been developed, and they are alloy steel and titanium alloys fuzzy models. Both fuzzy models serve the purpose of predicting the appropriate cutting speed and feed rate

with respect to the corresponding input variables. Generally, the development of fuzzy model involves the design of three main elements, which are inputs membership functions, fuzzy rules (inference mechanism), and output membership functions. So far, there is no any clear procedure that can be used to develop these three elements. Thus, the strategy for generalizing the development of alloy steel fuzzy model has been suggested. This strategy is useful and less effort is required for developing a related new fuzzy models.

The design of fuzzy rules is always the difficult part in developing the fuzzy model due to the tedious way of defining fuzzy rules with the conventional method. Therefore, a new method of developing fuzzy rules, namely fuzzy rule mapping has been introduced and implemented. Through fuzzy rule mapping method, the effort and the time required in developing the fuzzy rules has been reduced. This method has been applied in the developing the fuzzy model for alloy steel.

All the predicted outputs (cutting speed and feed rate) from the alloy steel (with general strategy and fuzzy rule mapping) and titanium alloys fuzzy models were being compared with the data obtained from “Machining Data Handbook”, by Metcut Research Associate, and a good match have been obtained throughout the comparison. The average percentage errors for alloy steel fuzzy models with the implementation of general strategy and fuzzy rule mapping are about the ranges of 3.1% to 5.6% and 3.0% to 10.7%, respectively. On the other hand, the average percentage error for titanium alloys fuzzy model is about 1.8% to 5.1%. These results have showed that the machinability data information for the turning of alloy steel and

titanium alloys can be represented by fuzzy model. Besides that, it has also proved the feasibility of using the suggested strategy and fuzzy rule mapping method.

Abstrak thesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

**PEMBANGUNAN MODEL FUZZY LOGIK BAGI PROSES MELARIK  
KELULI ALOI DAN ALOI TITANIUM**

Oleh

**TAN JIT YEAN**

**November 2004**

**Pengerusi : Wong Shaw Voon, Ph.D.**

**Fakulti : Kejuruteraan**

Kajian ini adalah mengenai penggunaan logik fuzzy bagi mewakili pemilihan data kebolehmesinan bagi proses melarik. Pemesinan ialah satu proses yang sangat kompleks dengan adanya parameter pemesinan seperti kelajuan pemotongan, kadar suapan, dan kedalaman pemotongan. Untuk menjalankan proses pemotongan yang memuaskan, pemilihan data kebolehmesinan yang sesuai adalah sangat penting. Biasanya pemilihan data kebolehmesinan dilakukan oleh jurumesin mahir. Pihak pengilang mungkin menghadapi masalah untuk menjalankan praktis pemotongan yang bagus sekiranya kekurangan jurumesin mahir. Dengan itu, adalah penting dan perlu untuk mewakilkan pengetahuan jurumesin mahir dalam bentuk model, dan diharapkan jurumesin biasa mampu menjalankan praktis pemesinan yang bagus melalui maklumat yang diperolehi daripada model. Malangnya, pemilihan data kebolehmesinan tidak boleh diformula ke sebarang model matematik dengan mudah. Oleh yang demikian, logik fuzzy telah dipilih sebagai alat untuk menerangkan strategi dan tindakan jurumesin mahir.

Dalam kajian ini, dua jenis model fuzzy dengan bahan yang berlainan telah dibina, iaitu, model fuzzy keluli aloi dan aloi titanium. Kedua-dua model fuzzy ini mempunyai tujuan untuk menganggarkan kelajuan pemotongan dan kadar suapan yang optima dengan adanya input yang berkenaan. Secara umumnya, pembinaan model fuzzy melibatkan perekaan bagi 3 elemen, iaitu input fungsi keahlian, penggaris fuzzy, dan output fungsi keahlian. Kini, tiada sebarang prosedur yang jelas untuk membina model fuzzy. Dengan itu, suatu strategi simpulan keseluruhan telah dicadangkan dan dilaksanakan bagi pembinaan model fuzzy keluli aloi. Strategi tersebut adalah berguna dan dapat memudahkan kerja pembangunan sebarang model fuzzy baru yang berhubungan.

Pembinaan penggaris fungsi adalah suatu tugas yang sukar disebabkan oleh cara pembinaan penggaris fuzzy yang meletihkan. Oleh itu, cara baru bagi pembinaan set penggaris fuzzy, dan ia dinamakan “Pemetaan Penggaris Fuzzy” (Fuzzy rule mapping) telah dikemukakan bagi memudahkan kerja pembinaan penggaris fungsi. Dengan adanya cara tersebut, usaha dan juga masa yang diperlukan bagi pembinaan penggaris fuzzy dapat dikurangkan. Pemetaan Penggaris Fuzzy ini telah digunakan dalam pembentukan model fuzzy keluli aloi.

Kesemua output anggaran daripada model fuzzy keluli aloi (dengan menggunakan strategi simpulan keseluruhan dan Pemetaan Penggaris Fuzzy) dan aloi titanium akan dibanding dengan data yang diperolehi daripada “Buku Panduan Data Pemotongan”, oleh Metcut Research Associate, dan korelasi yang baik telah dipaparkan di seluruh perbandingan. Di mana, peratus kesilapan untuk model fuzzy alloy steel dengan penggunaan strategi simpulan keseluruhan dan Pemetaan Penggaris Fuzzy adalah di



antara 3.1% hingga 5.6% dan 3.0% hingga 10.7%, masing-masing. Di samping itu, peratusan kesilapan untuk model fuzzy titanium alloys adalah di antara 1.8% hingga 5.1%. Keputusan ini menunjukkan bahawa, pemilihan data keupayaan proses pemutaran bagi keluli aloi dan aloi titanium dapat diwakili oleh model fuzzy. Selain daripada itu, ia juga membuktikan kepenggunaan strategi simpulam keseluruhan dan juga Pemetaan Penggaris Fuzzy.

## ACKNOWLEDGEMENTS

First of all, I would like to express my heartiest gratitude and appreciation to my supervising committee chairman, Associate Professor Dr. Wong Shaw Voon, Faculty of Engineering, University Putra Malaysia (UPM) for invaluable advice and untiring assistance in this master research. His constant guidance, support and encouragement were the motivations that enabled me to accomplish my study.

Great thanks to committee members Associate Professor Dr. Napsiah Ismail, head of Mechanical and Manufacturing Engineering Department, UPM, and Associate Professor Dr. Abdel Magid Salem Hamouda for their constructive suggestion, proper guidance and encouragement throughout my study period.

This multidisciplinary study could not have been accomplished without the financial support from Intensification of Research in Priority Area (IRPA) programme, provided by the Ministry of Science Technology and Innovation (MOSTI).

Special thanks also goes to my colleagues and friends, who in one way or another have support, assistance and gave me courage to proceed to completion. Last but not least, my deepest thanks to my family members, especially my parent for their continued support.

I certify that an Examination Committee met on 29<sup>th</sup> November 2004 to conduct the final examination of Tan Jit Yean on his Master of Science thesis entitled “Development of Fuzzy Logic Model for Turning Process of Steel Alloy and Titanium Alloys” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

**Mohd Sapuan Salit, Ph.D**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Megat Mohamad Hamdan Megat Ahmad, Ph.D.**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**Mohd. Rashid Osman**

Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**Noordin Mohd. Yusof, Ph.D.**

Associate Professor  
Faculty of Mechanical Engineering  
Universiti Teknologi Malaysia  
(Independent Examiner)

---

**ZAKARIAH ABD. RASHID, Ph.D.**

Professor/Deputy Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date:

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee are as follows:

**Wong Shaw Voon, Ph.D.**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Napsiah Ismail, Ph.D.**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**Abdel Magid Salem Hamouda, Ph.D.**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

---

**AINI IDERIS, Ph.D.**

Professor/Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date:

## **DECLARATION**

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

---

**TAN JIT YEAN**

Date:

## TABLE OF CONTENTS

	<b>Page</b>
DEDICATION	ii
ABSTRACT	iii
ABSTRAK	v
ACKNOWLEDGEMENTS	viii
APPORVAL SHEETS	x
DECLARATION	xii
LIST OF TABLES	xvi
LIST OF FIGURES	xviii
LIST OF ABBREVIATIONS/NOTATIONS/GLOSSARY OF TERMS	xx

### CHAPTER

<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Problem Statements	4
	1.2 Objectives	6
	1.3 Scope of Research	7
	1.4 Organization of Thesis	8
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>9</b>
	2.1 Fuzzy Logic	9
	2.1.1 Fuzzy Model	10
	2.1.2 Fuzzy Membership Functions	10
	2.1.3 Fuzzy Rules	12
	2.1.4 Fuzzy System	13
	2.1.5 Example of Fuzzy Logic Operation	15
	2.1.6 Development of Fuzzy Rules	21
	2.2 Machining Process	22
	2.3 Turning Process	24
	2.3.1 Cutting Tool Materials	28
	2.3.2 Tool Life	30
	2.4 Machinability and Artificial Intelligence System	32
	2.5 Titanium Alloys	35
	2.5.1 Classification of Titanium Alloys	35
	2.5.2 Commercially Pure Titanium Alloys	36
	2.5.3 Alpha Alloys	37
	2.5.4 Alpha-Beta Alloys	37
	2.5.5 Beta Alloys	38
	2.5.6 Influence of Alloying Elements	38



2.6	Machining of Titanium Alloys	40
2.7	Issues From the Literature	41
<b>3</b>	<b>METHODOLOGY AND THE DEVELOPMENT OF FUZZY MODEL</b>	<b>42</b>
3.1	Research Methodology	43
3.2	General Strategies in Fuzzy Models Development	45
3.2.1	Implementation of General Strategies	47
3.2.2	Fuzzy Rules	55
3.2.3	Fuzzy Membership Function	60
3.3	Fuzzy Rules Mapping	64
3.3.1	Fuzzy Rule Representation	65
3.3.2	Linear Fuzzy Rules Mapping	69
3.3.3	Non-Linear Fuzzy Rules Mapping	73
3.3.4	The Multiple-Variable Averaging Method and Influential Factor	78
3.3.5	Implementation of linear fuzzy rule mapping	81
3.3.6	Implementation of Non-Linear Fuzzy Rule Mapping	87
3.4	Development of Titanium Alloys Fuzzy Model	95
3.4.1	Input and Output Membership Functions of Titanium Alloys Fuzzy Rules	101
3.4.2	Fuzzy Rules of Titanium Alloys Fuzzy Model	107
<b>4</b>	<b>RESULTS AND DISCUSSION</b>	<b>114</b>
4.1	General Strategies in Fuzzy Model Development	114
4.1.1	Comparison Amongst the General Strategies	116
4.2	Fuzzy Rules Mapping	119
4.2.1	Implementation of Linear Fuzzy Rule Mapping	119
4.2.2	Implementation of Non-Linear Fuzzy Rule Mapping	121
4.2.3	Comparison Between Linear and Non-Linear Fuzzy Rule Mapping in Terms of 3-D Graphical Form	124
4.2.4	General Discussion of Fuzzy Rule Mapping	124
4.3	Titanium Alloys Fuzzy Model	125
4.3.1	Recommended Cutting Speed for Titanium Alloys	128
4.3.2	General Discussion	129
<b>5</b>	<b>CONCLUSIONS AND RECOMMENDATION</b>	<b>132</b>
5.1	Conclusions	132
5.2	Future Recommendation	135
	<b>REFERENCES</b>	<b>136</b>
	<b>APPENDICES</b>	<b>140</b>

**BIODATA OF THE AUTHOR**  
**LIST OF PUBLICATIONS**

171  
172





## LIST OF TABLES

Table		Page
1.1	Involved cutting tools and variables in the development of fuzzy models	7
2.1	Typical example of fuzzy rules in matrix form	11
3.1	List of possible strategies	46
3.2	Expression for the inputs parameters	50
3.3	Cutting Speed fuzzy rules of cast alloy fuzzy model	51
3.4	Feed rate fuzzy rules of cast alloy fuzzy model	51
3.5	Expression of output parameters	52
3.6	Cutting speed fuzzy rules of high speed steel fuzzy model	57
3.7	Cutting speed fuzzy rules of uncoated carbide (brazed and throw-away) fuzzy model	57
3.8	The parameters of Equations 4.3 and 4.4	62
3.9	Interaction of multiple-input and multiple-output variables	66
3.10	Incorporation of all sets of rules with multiple-input averaging method	69
3.11	Interaction between multiple-input and multiple-output variables with incorporation of all sets of fuzzy rules	72
3.12	Rule matrix with the application of Equation 3.9	72
3.13	Rule matrix with the application of Equation 3.10	72
3.14	Rule matrix with the application of Equation 3.14	77
3.15	Rule matrix with the application of Equation 3.15	77
3.16	The application of MVA method for linear fuzzy rule mapping	79
3.17	Cutting speed rule matrix with the application of Equation 3.17	82
3.18	Cutting speed rule matrix with the application of Equation 3.18	84
3.19	Implementation of MVA method for linear fuzzy rule mapping	87
3.20	Cutting speed rule matrix for cast alloy model using Equation 3.19	88

3.21	Cutting speed rule matrix for cast alloy model using Equation 3.20	90
3.22	Application of MVA method for non-linear fuzzy rule mapping	92
3.23	Cutting speed rule matrix with simplified non-linear fuzzy rule mapping	93
3.24	Input 1 fuzzy expression of titanium alloys fuzzy model	102
3.25	Input 2 fuzzy expression of titanium alloys fuzzy model	105
3.26	Output fuzzy expression for titanium alloys fuzzy model	106
3.27	Fuzzy rules of cutting speed of commercially pure fuzzy model	107
3.28	Fuzzy rules of cutting speed of alpha and alpha-beta fuzzy model (annealed)	107
3.29	Cutting speed fuzzy rules of alpha & alpha-beta alloys fuzzy model (solution treated & aged)	108
3.30	Cutting speed fuzzy rules of beta alloys fuzzy model	108
3.31	Feed rate fuzzy rules for all types of titanium fuzzy models	110
4.1	Results summary of alloy steel fuzzy model (referred to 1st strategy)	115
4.2	Results summary of alloy fuzzy model (referred to 2nd strategy)	115
4.3	Results summary of alloys fuzzy model (referred to 3rd strategy)	116
4.4	Summary of results using linear fuzzy rule mapping	120
4.5	Summary of results using non-linear fuzzy rule mapping	122
4.6	Summary of results for commercially pure fuzzy model	125
4.7	Summary of results for alpha & alpha-beta alloys fuzzy model (annealed)	126
4.8	Summary of results for alpha & alpha-beta alloys fuzzy model (solution treated & aged)	126
4.9	Summary of results for beta alloys fuzzy model	127

## LIST OF FIGURES

<b>Figure</b>	<b>Page</b>
2.1 Typical example of fuzzy membership functions	9
2.2 Basic configuration of fuzzy system	12
2.3 Membership functions of input $X_1$	14
2.4 Membership functions of input $X_2$	14
2.5 Output $Z$ membership functions	15
2.6 Graphically presentation of the aggregation of fuzzy rules	17
2.7 The three main principles of machining processes: (a) turning, (b) drilling, and two common forms of milling: (c) peripheral milling, and (d) face milling (extracted from Ref. [21])	21
2.8 Turning process (extracted from Ref. [21])	23
3.1 Methodology flow chart	43
3.2 Flow chart for the implementation of general strategies	47
3.3 Material hardness membership functions (cast alloy fuzzy model)	49
3.4 Depth of cut membership functions (cast alloy fuzzy model)	50
3.5 Cutting speed membership functions cast alloy fuzzy model (1st Strategy)	53
3.6 Feed rate membership functions cast alloy fuzzy model (1st Strategy)	53
3.7 3-D graphical representation of fuzzy rule (Refer to cast alloy fuzzy rules in Table 3.3)	59
3.8 Cutting Speed membership functions of high speed steel fuzzy model (with second strategy)	63
3.9 Feed rate membership functions of high speed steel fuzzy model (With second strategy)	63
3.10 Cutting speed membership functions of high speed steel fuzzy model (with third strategy)	64
3.11 2-D relationship chart between input and output	81
3.12 3-D graphical representation of cutting speed rules with Table 3.17	84
3.13 3-D graphical representation of cutting speed rules of Table 3.18	86
3.14 3-D graphical representation of Table 3.19 (with MVA method)	87

3.15	3-D graphical representation of the fuzzy rules in Table 3.20	89
3.16	3-D graphical representations of fuzzy rules in Table 3.21	91
3.17	3-D graphical form of cutting speed rule with MVA method	92
3.18	3-D graphical presentation of fuzzy rules in Table 3.23	93
3.19	Implementation of MVA method with incorporation of influential factor	95
3.20	Commercially pure fuzzy models	98
3.21	Alpha & alpha-beta alloys fuzzy models	98
3.22	Beta alloys fuzzy models	99
3.23	Titanium alloys fuzzy system	100
3.24	Input membership functions of impurity percentage (commercially pure fuzzy model)	101
3.25	Input membership functions of weight percentage of vanadium (alpha & alpha-beta alloys fuzzy model)	102
3.26	Input membership functions of material hardness (beta alloys fuzzy model)	104
3.27	Input membership functions of depth of cut (for all types of titanium alloys fuzzy model)	104
3.28	Output membership functions of cutting speed (for all types of titanium alloys fuzzy model)	105
3.29	Output membership functions of feed rate (for all types of titanium alloys fuzzy model)	106
3.30	The 3-D graph of high speed steel fuzzy rules of commercially pure alloys fuzzy model	111
3.31	The 3-D graph of fuzzy rules of alpha and alpha-beta alloys (annealed) fuzzy model	111
3.32	The 3-D graph of fuzzy rules of alpha and alpha-beta alloys (solution treated & aged) fuzzy model	112
3.33	The 3-D graph of fuzzy rules of beta alloys fuzzy model	112
4.1	Graph of cutting speed vs material hardness for high speed steel fuzzy model when using 1 mm depth of cut	118
4.2	Graph of feed rate vs material hardness for high speed steel fuzzy model when using 1 mm and 3.8 mm depth of cut	119

## LIST OF ABBREVIATIONS

CNC	Computer Numerical Control
AI	Artificial Intelligent
GOL	Genetic Optimization Library
EXCATS	Expert Computer Aided Cutting Tool Selection
CAD	Computer Aided Design
IGES	Initial Graphic Exchange Specification
CAPP	Computer Aided Process Planning
MIA	Multiple-Input Averaging
MAPE	Mean Absolute Percentage Error

# CHAPTER 1

## INTRODUCTION

Machining is one of the important processes in a manufacturing system. It serves the purpose of generating a desired shape of the workpiece from a solid body, and it can also be performed to improve the tolerances and surface finish of a previously form of workpiece. This process involves the removal of the excessive material from the workpiece in the form of chips. Generally, machining is capable of producing geometric configurations, tolerances, and surface finishes, which are normally difficult to obtain by any other technique. However, machining removes the material which has already been paid, and the chips produced are relatively small, thereby causing difficulties in recycling. Thus, the manufacturers try to reduce the process of machining, especially in mass production. Because of this, machining has lost some of the important application areas. Meanwhile, as the development of machining technology has kept growing, the new technology, called computer numerical control (CNC) has been introduced, and this enables machining to capture the new application areas.

Machining process is very complex with respect to the influences of the machining parameters, such as the cutting speed, feed rate, and depth of cut. It is closely related to the machinability data which includes the proper selection of cutting tools and machining parameters. The selection of machinability data has played an important role in the effectiveness of machine tool utilization, which directly influences the overall manufacturing cost. The influences of the machining parameters on machine



tools are not always precisely known and hence, it becomes difficult to recommend the optimum machinability data for machining process. Consequently, the selection of the machinability data is normally done by a skilled machinist, who will make the decision based on their experience and intuition. Through the experience gained over the years, skilled machinist possesses certain empirical rules and guiding principles for choosing the optimum machinability data. Another method which is the most widely used source of obtaining machinability data is the “Machining Data Handbook” [1]. The handbook recommends the cutting speed and feed rate given a particular depth of cut, material hardness, and cutting tool.

Artificial intelligence (AI) is concerning with a system that is capable of exhibiting the characteristics of a human behaviour, such as the ability of learning, reasoning, problem solving. The aim of artificial intelligence is to simulate the human behaviour on the computer, and it can be experimental knowledge (expertise) or basic description of fact [2]. Nowadays, the term AI has gain popularity due to the successful application of its concept in many common commercial products.

Expert system is one of the elements of artificial intelligence, and it is also known as knowledge-based system. The expert system or knowledge-based system can be defined as an intelligent computer program that possess the ability to capture the specific knowledge of a particular domain, and imitate the problem solving strategies of human experts to provide the recommendations [3]. In other words, an expert system is capable of performing an intellectually demanding task as well as a human expert. They represent a new problem solving paradigm that utilizes many techniques developed from AI research. An expert system possesses the capacity for

a heuristic approach, which is, making a good judgement and good guess just like the an expert [2].

Another common element of artificial intelligence is fuzzy logic. Generally, the word “fuzzy” can be defined as blurred; imprecisely defined; confuse or vague. Hence, fuzzy logic is defined as the mathematical means of representing vagueness and imprecise information. Fuzzy logic has today become one of the widely used technologies due to its successful application in many controlling systems. It is so widely used because of its ability in representing the vagueness and imprecise information. It is very suitable in defining the relationship between a system inputs and desired system outputs [4]. It is also popular for its ability to develop rule-based expert system. Fuzzy controllers and fuzzy reasoning have found particular applications in very complex industrial systems that cannot be modelled precisely even under various assumptions and approximations [5]. The control of such systems by experienced human operators was proven in many cases to be more successful and efficient compared to the classical automatic controllers. The human controllers employ experiential rules that can be cast in the fuzzy logic model. These observations inspired many investigation and research works in this area, thus, fuzzy logic and fuzzy rule-based control system have been developed [4].

Fuzzy logic was introduced by Zadeh [6] in his pioneering work in the middle of 1960s. The exploration of fuzzy logic was then followed by Mandani [7] who has applied the concept of fuzzy logic in modelling and controlling the pressure for a small boiler. Recently, the concept of fuzzy logic has also been applied to prescribe the machining process, where, El Baradie [8] has developed the first fuzzy model for





machinability data selection of carbon steel for the turning process. The works were then extended by Wong *et al.* [4], where a new fuzzy model for machinability data selection of carbon steel has been developed. Later, similar types of fuzzy models have been developed for representing the turning process of alloy steel [9].

## **1.1 Problem Statement**

The optimum performance and the effectiveness of the machining process always depend on the proper selection of machinability data. In fact, the selection of machinability data is not an easy task and not always precisely known due to the complexity of the machining process. Therefore, it becomes very difficult to achieve the optimum performance when machining. Even though there is a good source for obtaining machinability data, which is through the “Machining Data Handbook” [1], but the recommended data can only be considered as a good starting point. This is because of the influence from other variable such as part configuration, machine condition, type of fixture, dimensional tolerance and surface roughness. In this case, the selection of the machinability data can be carried out by a skilled machinist who will decide the appropriate turning parameters based on the knowledge and experience gained over the years. Therefore, there is a necessity to cast the knowledge of the skilled machinists into a model. Hence, fuzzy model has been developed to describe the machinability data selection due to its ability in representing vague and imprecise information.

Generally, the development of fuzzy model involves the design of 3 elements, and they are the input membership function, fuzzy rule, and output membership function.