

**ELECTRIC DISCHARGE MACHINING
CHARACTERISTICS OF HARDENED TOOL
STEEL USING ALUMINIUM, COPPER AND
COPPER ELECTROPLATED ALUMINIUM
ELECTRODES**

**Thilaga Vaani Nagalingam
Matrix Number: KGC 030012
Session 2004/2005**

**A Dissertation Submitted to The Faculty of Engineering
University of Malaya in Partial Fulfillment of
The Requirement for The Degree of
Master of Engineering (M.Eng.)**



**Department of Engineering Design and Manufacture
University of Malaya**

March 2005

Perpustakaan Universiti Malaya



A511898549

ABSTRACT

Electric discharge machining (EDM) is one of the modern non-conventional machining methods for manufacturing geometrically complex or hard materials parts that are extremely difficult to machine by conventional machining process. The objective of this research is to study the influence of operating parameters of EDM of hardened tool steel (SKD 11) with aluminium, copper and copper coated aluminium as electrodes. The effectiveness of the EDM process with these three different electrodes is evaluated in terms of the material removal rate (MRR), electrode wear ratio (EWR), diametral overcut and the surface finish quality of the hardened tool steel. EDM machining parameters could not achieve maximum MRR and minimum surface finish simultaneously. Higher MRR is accompanied with a worse surface finish. In contrast, if machining parameters were set to finer machining conditions, a finer surface integrity would result. However, the MRR would be relatively worse. Therefore, it is important to find the optimum machining conditions based on the target function chosen. In this study, Taguchi Parametric Robust Design is used to plan the experiments and Pareto ANOVA is used to find the optimum machining parameters for maximum MRR and minimum surface roughness. The electrode wear ratio (EWR) and diametral overcut were investigated under these optimum conditions.

This study has shown that machining performance in the EDM process can be improved effectively by using optimum combination of input variables for the objective function chosen. Aluminium electrode is a better choice of electrode for finish machining and copper electroplated aluminium electrode is a better choice of electrode for rough machining of the SKD 11 tool steel workpiece.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude and appreciation to my project supervisor, Prof. Dr. Mohammed Hameedullah for his persistent and valuable guidance, encouragement and patience throughout the completion of this project. This project would not have been completed without his provision.

I also would like to express my heartiest thanks to all the staff of Engineering Design and Manufacture Department, particularly to Mr. Murruthi Muthusamy (head of EDM lab) and Mr. Mohd. Nasrul (lab assistant of workshop) for their technical help.

My thanks also goes to all my friends, course mate and others who have helped directly and indirectly in my project.

Last but not least, my family especially to my mother Madam Saroja Nagalingam and father Mr.Nagalingam for their continuous support and trust, encouragement and understanding that gave me the inspiration to go on all these years.

CONTENTS

ABSTRACT.....	ii
ACKNOWLEDGEMENTS.....	iii
CONTENTS.....	iv
LIST OF FIGURES.....	xi
LIST OF TABLES.....	xvii
LIST OF PUBLICATIONS.....	xx

CHAPTER 1: INTRODUCTION

1.1 Preword.....	1
1.2 Objectives.....	3
1.3 Project Scope.....	3
1.4 Methodology.....	4

CHAPTER 2: LITERATURE REVIEW

PART A (EDM)

2.1 Introduction to EDM.....	10
2.2 History of EDM.....	11
2.3 Types of EDM.....	12
2.4 New Technology in EDM.....	12
2.4.1 New Electrode Materials.....	13
2.4.2 EDM without a Dielectric Fluid.....	14
2.4.3 EDM using a Dielectric with Conductive Powders.....	14
2.4.4 EDM of Non-Conductive Materials.....	15

2.5 Die-Sinking EDM Machine.....	15
2.5.1 Principles of EDM Operation.....	16
2.5.2 Mechanics of EDM.....	18
2.5.3 Types of EDM Circuits.....	23
2.5.3.1 Resistance capacitance relation circuits.....	23
2.5.3.2 Rotary impulse generator.....	25
2.5.3.3 Controlled pulse circuits.....	25
2.5.4 Servo Mechanism.....	26
2.6 Dielectric Fluid.....	27
2.6.1 Criteria for Assessing Dielectric Fluid.....	27
2.6.2 Functions of Dielectric Fluid.....	29
2.7 Flushing Techniques.....	30
2.8 Influencing Parameters in EDM.....	31
2.8.1 Pulse On Time.....	31
2.8.2 Pulse Off Time.....	31
2.8.3 Discharge Current.....	32
2.8.4 Electrode/Workpiece Combination.....	33
2.8.5 Flushing.....	34
2.8.6 Dielectric.....	34
2.8.7 Polarity.....	35
2.8.8 Voltage.....	35
2.8.9 Duty Factor.....	36
2.9 EDM Machining Performance.....	37
2.9.1 Material Removal Rate.....	37
2.9.2 Overcut.....	38

2.9.3 Surface Finish.....	39
2.9.4 Electrode Wear.....	40
2.10 Surface Integrity.....	41
2.10.1 Effect of Spark Erosion on Workpiece.....	41
PART B (DESIGN OF EXPERIMENTS)	
2.11 One-Factor-At-A-Time Design.....	44
2.12 Factorial Design.....	44
2.13 Orthogonal Array Design.....	45
2.14 Parameter Design.....	48
2.14.1 Structure of Parameter Design.....	48
2.14.2 Signal-To-Noise (S/N) Ratios.....	51
2.14.3 Pareto ANOVA Analysis of Variation.....	52
2.14.4 Optimization.....	52

CHAPTER 3: EXPERIMENTAL INVESTIGATIONS

3.1 Constant Parameters.....	54
3.1.1 Workpiece.....	54
3.1.2 Electrodes.....	54
3.1.2.1 Preparation of Electrode for EDM – Electroplating of Copper on Aluminium Electrode.....	56
3.1.3 Dielectric Used in EDM.....	57
3.2 Variable Parameters.....	57
3.2.1 Factor Characteristics Relation Diagram.....	58
3.2.2 Planning of Screening Experiments.....	58
3.2.3 Final Planning of Experiments.....	59

3.3 Performance Parameters.....	62
3.4 Experimental Set-Up.....	63
3.5 Equipment Used.....	63
3.5.1 EDM Machine.....	64
3.5.2 Mahr Perthometer.....	66
3.5.3 Microscope Optiphot.....	67
3.5.4 Scanning Electron Microscope (SEM).....	67
3.5.5 Digital Vernier Caliper.....	68
3.5.6 Digital Precision Balance.....	68
3.6 Experimental Procedure.....	69
3.6.1 Preparation of the Electrodes for Experimental Runs.....	69
3.6.2 Screening Experiments.....	69
3.6.3 Experiments for Determining Optimum Machining Conditions in Finishing Conditions with Aluminium Electrodes.....	70
3.6.4 Experiments for Determining Optimum Machining Conditions in Roughing Conditions with Aluminium Electrodes.....	71
3.6.5 Experiments for Determining Optimum Machining Conditions in Finishing Conditions with Copper Electroplated Aluminium Electrodes.....	71
3.6.6 Experiments for Determining Optimum Machining Conditions in Roughing Conditions with Copper Electroplated Aluminium Electrodes.....	72
3.7 Machining Program.....	72

CHAPTER 4: RESULTS AND ANALYSIS OF DATA

4.1 Aluminium Electrode.....	74
4.1.1 Electron Probe Micro Analysis (EPMA) Results.....	74
4.1.2 Microstructure of Aluminium Electrode.....	74
4.2 Workpiece.....	74
4.3 Screening Experiments.....	75
4.3.1 Graphical Analysis.....	84
4.4 Experiments using Aluminium Electrode.....	86
4.4.1 Results of Confirmation Tests under Optimum Conditions for Maximum Metal Removal Rate in Rough Machining.....	92
4.4.2 Results of Confirmation Tests under Optimum Conditions for Minimum Surface Roughness in Finish Machining.....	93
4.4.3 Graphical Analysis.....	94
4.4.4 Graphical Analysis of Various Output Parameters using Different Electrodes under Optimum Conditions for Maximum Metal Removal Rate using Aluminium Electrode.....	96
4.4.5 Graphical Analysis of Various Output Parameters using Different Electrodes under Optimum Conditions for Minimum Surface Roughness using Aluminium Electrode.....	98
4.4.6 Scanning Electron Microscopic (SEM) Analysis.....	100
4.5 Experiments using Copper Electroplated Aluminium Electrode.....	103
4.5.1 Results of Confirmation Tests under Optimum Conditions for Maximum Metal Removal Rate in Rough Machining.....	109
4.5.2 Results of Confirmation Tests under Optimum Conditions for Minimum Surface Roughness in Finish Machining.....	109

4.5.3 Graphical Analysis.....	110
4.5.4 Graphical Analysis of Various Output Parameters using Different Electrodes under Optimum Conditions for Maximum Metal Removal Rate using Copper Electroplated Aluminium Electrode.....	112
4.5.5 Graphical Analysis of Various Output Parameters using Different Electrodes under Optimum Conditions for Minimum Surface Roughness using Copper Electroplated Aluminium Electrode.....	114
4.5.6 Scanning Electron Microscopic (SEM) Analysis.....	116
CHAPTER 5: DISCUSSION	
5.1 Electrodes and Workpiece.....	118
5.2 First Phase of Investigations.....	119
5.3 Second Phase of Investigations.....	121
5.3.1 Machining with Aluminium Electrode.....	123
5.3.1.1 Graphical Analysis.....	129
5.3.2 Machining with Copper Electroplated Aluminium Electrode.....	132
5.3.2.1 Graphical Analysis.....	138
5.3.3 SEM Analysis.....	139
CHAPTER 6: CONCLUSION	142
CHAPTER 7: RECOMMENDATION	145
REFERENCES	146

APPENDIX A:

SCREENING EXPERIMENTS DATA.....152

APPENDIX B:

ROUGH MACHINING DATA WITH ALUMINIUM ELECTRODE.....160

APPENDIX C:

FINISH MACHINING DATA WITH ALUMINIUM ELECTRODE.....179

APPENDIX D:ROUGH MACHINING DATA WITH COPPER ELECTROPLATED
ALUMINIUM ELECTRODE.....192**APPENDIX E:**FINISH MACHINING DATA WITH COPPER ELECTROPLATED
ALUMINIUM ELECTRODE.....202**APPENDIX F:**

S/N RATIOS.....212

APPENDIX G:

AVERAGE MRR AND AVERAGE SURFACE ROUGHNESS.....216

APPENDIX H:

EDM SPECIFICATIONS.....221

APPENDIX I:

EPMA ANALYSIS PRINT OUT.....231

LIST OF FIGURES

	Page Number
Figure 1.1 Flow Chart.....	9
Figure 2.1 Basic Die-Sinking EDM System.....	16
Figure 2.2 Details of Electrode Surface Characteristics.....	18
Figure 2.3 Variation of Melting Temperature Depth Z and Crater Volume v_c with Discharge Time t_d	20
Figure 2.4 Variation of Melting Temperature Depth Z and Crater Volume v_c with Discharge Time t_d	21
Figure 2.5 Role of Cavitation in Material Removal.....	21
Figure 2.6 Effect of Forced Circulation of Dielectric Fluid.....	22
Figure 2.7 Relaxation Circuit.....	24
Figure 2.8 Variation of Gap Voltage.....	24
Figure 2.9 Rotary Impulse Generator for EDM.....	25
Figure 2.10 EDM with Controlled Pulse Circuit.....	25
Figure 2.11 EDM with Controlled Pulse Circuit without Capacitor.....	26
Figure 2.12 Surface Roughness, Electrode Wear and Metal Removal in Relation to the Firing Period.....	41
Figure 2.13 Section of a Surface that has been Subjected to Spark Erosion.....	42
Figure 2.14 Cracks in the Melted Zone.....	43
Figure 2.15 Factor Characteristics Relation Diagram.....	49
Figure 3.1 Work Material SKD 11 Tool Steel (Hardness 64 HRC).....	54
Figure 3.2 Aluminium Electrodes.....	55
Figure 3.3 Copper Electrodes.....	55
Figure 3.4 Copper Electroplated Aluminium Electrodes.....	55

Figure 3.5 Factor Characteristics Relation Diagram.....	58
Figure 3.6 Cavity Formed in the Workpiece.....	63
Figure 3.7 Diameter of the Cavity Formed.....	63
Figure 3.8 EDM Die Sinking Machine A30R.....	64
Figure 3.9 Filter System in EDM A30R.....	65
Figure 3.10 NC Power Supply Unit.....	65
Figure 3.11 Electrode Holder and Table.....	65
Figure 3.12 Schematic Diagram of the EDM Process.....	66
Figure 3.13 Mahr Perthometer (Model: Mahr Perthometer M1).....	66
Figure 3.14 Microscope Optiphot (Model: Nikon HFX-II).....	67
Figure 3.15 Scanning Electron Microscope (Model: Philip XL40).....	68
Figure 3.16 Digital Precision Balance (Model: AND, HF-3000).....	68
Figure 4.1 Microstructure of Aluminium Electrodes.....	74
Figure 4.2 Metal Removal Rate (MRR) versus Experimental Numbers in Screening Experiments.....	84
Figure 4.3 Surface Roughness versus Experimental Numbers in Screening Experiments.....	84
Figure 4.4 Contribution Ratio (%) of Factors for Metal Removal Rate (MRR) in Screening Experiments.....	85
Figure 4.5 Contribution Ratio (%) of Factors on Surface Roughness in Screening Experiments.....	85
Figure 4.6 Metal Removal Rate (MRR) versus Experimental Numbers in Rough Machining with Aluminium Electrode.....	94
Figure 4.7 Surface Roughness versus Experimental Numbers in Finish Machining with Aluminium Electrode.....	94

Figure 4.8 Contribution Ratio (%) of Factors for Metal Removal Rate (MRR) in Rough Machining with Aluminium Electrode.....	95
Figure 4.9 Contribution Ratio (%) of Factors on Surface Roughness in Finish Machining with Aluminium Electrode.....	95
Figure 4.10 Metal Removal Rate (MRR) versus Electrode Material Under Optimum Rough Machining Conditions for Maximum MRR.....	96
Figure 4.11 Surface Roughness versus Electrode Material Under Optimum Rough Machining Conditions for Maximum MRR.....	96
Figure 4.12 Electrode Wear Ratio (EWR) versus Electrode Material Under Optimum Rough Machining Conditions for Maximum MRR.....	97
Figure 4.13 Diametral Overcut versus Electrode Material Under Optimum Rough Machining Conditions for Maximum MRR.....	97
Figure 4.14 Metal Removal Rate (MRR) versus Electrode Material Under Optimum Finish Machining Conditions for Minimum Surface Roughness.....	98
Figure 4.15 Surface Roughness versus Electrode Material Under Optimum Finish Machining Conditions for Minimum Surface Roughness.....	98
Figure 4.16 Electrode Wear Ratio (EWR) versus Electrode Material Under Optimum Finish Machining Conditions for Minimum Surface Roughness.....	99
Figure 4.17 Diametral Overcut versus Electrode Material Under Optimum Finish Machining Conditions for Minimum Surface Roughness.....	99
Figure 4.18 SEM Picture of Workpiece Surface after EDM under Optimum Conditions of Section 4.4.1 with Aluminum Electrodes.....	100

Figure 4.19 SEM Picture of Workpiece Surface after EDM under Optimum Conditions of Section 4.4.1 with Copper Electrodes.....	100
Figure 4.20 SEM Picture of Workpiece Surface after EDM under Optimum Conditions of Section 4.4.1 with Copper Electroplated Aluminum Electrodes.....	101
Figure 4.21 SEM Picture of Workpiece Surface after EDM under Optimum Conditions of Section 4.4.2 with Aluminum Electrodes.....	101
Figure 4.22 SEM Picture of Workpiece Surface after EDM under Optimum Conditions of Section 4.4.2 with Copper Electrodes.....	102
Figure 4.23 SEM Picture of Workpiece Surface after EDM under Optimum Conditions of Section 4.4.2 with Copper Electroplated Aluminum Electrodes.....	102
Figure 4.24 Metal Removal Rate (MRR) versus Experimental Numbers in Rough Machining with Copper Electroplated Aluminium Electrode.....	110
Figure 4.25 Surface Roughness versus Experimental Numbers in Finish Machining with Copper Electroplated Aluminium Electrode.....	110
Figure 4.26 Contribution Ratio (%) of Factors For Metal Removal Rate (MRR) in Rough Machining with Copper Electroplated Aluminium Electrode.....	111
Figure 4.27 Contribution Ratio (%) on Surface Roughness in Finish Machining with Copper Electroplated Aluminium Electrode.....	111
Figure 4.28 Metal Removal Rate (MRR) versus Electrode Material Under Optimum Rough Machining Conditions for Maximum MRR.....	112
Figure 4.29 Surface Roughness versus Electrode Material Under Optimum Rough Machining Conditions for Maximum MRR.....	112

Figure 4.30 Electrode Wear Ratio (EWR) versus Electrode Material Under Optimum Rough Machining Conditions for Maximum MRR.....	113
Figure 4.31 Diametral Overcut versus Electrode Material Under Optimum Rough Machining Conditions for Maximum MRR.....	113
Figure 4.32 Metal Removal Rate (MRR) versus Electrode Material Under Optimum Finish Machining Conditions for Minimum Surface Roughness.....	114
Figure 4.33 Surface Roughness versus Electrode Material Under Optimum Finish Machining Conditions for Minimum Surface Roughness.....	114
Figure 4.34 Electrode Wear Ratio (EWR) versus Electrode Material Under Optimum Finish Machining Conditions for Minimum Surface Roughness.....	115
Figure 4.35 Diametral Overcut versus Electrode Material Under Optimum Finish Machining Conditions for Minimum Surface Roughness.....	115
Figure 4.36 SEM Picture of Workpiece Surface after EDM under Optimum Conditions of Section 4.5.1 with Copper Electroplated Aluminium Electrodes.....	116
Figure 4.37 SEM Picture of Workpiece Surface after EDM under Optimum Conditions of Section 4.5.1 with Copper Electrodes.....	116
Figure 4.38 SEM Picture of Workpiece Surface after EDM under Optimum Conditions of Section 4.5.2 with Copper Electroplated Aluminium Electrodes.....	117
Figure 4.39 SEM Picture of Workpiece Surface after EDM under Optimum Conditions of Section 4.5.2 with Copper Electrodes.....	117

Figure 5.1 Effect of Discharge Current on the Average Metal Removal Rate (MRR) with Aluminium Electrodes.....	126
Figure 5.2 Effect of Discharge Voltage on the Average Metal Removal Rate (MRR) with Aluminium Electrodes.....	126
Figure 5.3 Effect of Pulse On Time on the Average Metal Removal Rate (MRR) with Aluminium Electrodes.....	127
Figure 5.4 Effect of Discharge Current on the Average Surface Roughness with Aluminium Electrodes.....	127
Figure 5.5 Effect of Discharge Voltage on the Average Surface Roughness with Aluminium Electrodes.....	128
Figure 5.6 Effect of Pulse On Time on the Average Surface Roughness with Aluminium Electrodes.....	128
Figure 5.7 Effect of Discharge Current on the Average Metal Removal Rate (MRR) with Copper Electroplated Aluminium Electrodes.....	135
Figure 5.8 Effect of Discharge Voltage on the Average Metal Removal Rate (MRR) with Copper Electroplated Aluminium Electrodes.....	135
Figure 5.9 Effect of Pulse On Time on the Average Metal Removal Rate (MRR) with Copper Electroplated Aluminium Electrodes.....	136
Figure 5.10 Effect of Discharge Current on the Average Surface Roughness with Copper Electroplated Aluminium Electrodes.....	136
Figure 5.11 Effect of Discharge Voltage on the Average Surface Roughness with Copper Electroplated Aluminium Electrodes.....	137
Figure 5.12 Effect of Pulse On Time on the Average Surface Roughness with Copper Electroplated Aluminium Electrodes.....	137

LIST OF TABLES

	Page Number
Table 1.1 L ₈ (2 ⁷) Orthogonal Array for Screening Experiments.....	6
Table 1.2 Basic Structure of Parameter Design for Screening Experiments.....	6
Table 1.3 L ₈ (2 ⁷) Orthogonal Array for Final Planning.....	7
Table 1.4 Basic Structure of Parameter Design for Final Planning.....	7
Table 2.1 L ₈ (2 ⁷) Orthogonal Array.....	45
Table 2.2 L ₈ Orthogonal Array Design with Seven Factors.....	46
Table 2.3 One-Factor-At-A-Time Design with Seven Factors.....	47
Table 2.4 Basic Structure of Parameter Design.....	50
Table 3.1 Chemical Composition of SKD 11 (wt%)......	54
Table 3.2 Detail of Each Electrode.....	55
Table 3.3 Physical Properties of the Copper and Aluminium Materials.....	55
Table 3.4 Levels of Input Variables for Screening Experiments.....	59
Table 3.5 Actual Experimental Conditions in Screening Experiments.....	59
Table 3.6 Levels of Input variables for Finishing Condition.....	60
Table 3.7 Actual Experimental Conditions in Final Finish Machining Experiments.....	60
Table 3.8 Levels of Input Variables for Roughing Condition.....	61
Table 3.9 Actual Experimental Conditions in Final Rough Machining Experiments.....	61
Table 3.10 Constant Parameters.....	61
Table 4.1 Chemical Composition of Aluminium Electrode (wt.%).	74
Table 4.2 Chemical Composition of SKD 11 (wt%).	75
Table 4.3 S/N Ratios in Screening Experiments.....	75

Table 4.4 Pareto ANOVA for Two Level Factors for Metal Removal Rate in Screening Experiments.....	76
Table 4.5 Pareto ANOVA for Two Level Factors for Surface Roughness in Screening Experiments.....	78
Table 4.6 Pareto ANOVA for Two Level Factors for Electrode Wear Ratio in Screening Experiments.....	80
Table 4.7 Pareto ANOVA for Two Level Factors for Diametral Overcut in Screening Experiments.....	82
Table 4.8 S/N Ratio for MRR in Roughing Conditions using Aluminium Electrode.....	86
Table 4.9 Actual Experimental Conditions in Rough Machining Experiments.....	86
Table 4.10 S/N Ratio for Surface Roughness in Finishing Conditions using Aluminium Electrode.....	87
Table 4.11 Actual Experimental Conditions in Finish Machining Experiments.....	87
Table 4.12 Pareto ANOVA for Two Level Factors for Metal Removal Rate in Rough Machining using Aluminium Electrode.....	88
Table 4.13 Pareto ANOVA for Two Level Factors for Surface Roughness in Finish Machining using Aluminium Electrode.....	90
Table 4.14 Average MRR with 3 Replication.....	92
Table 4.15 Results of the Confirmation Tests for Rough Machining with Aluminium Electrodes.....	92
Table 4.16 Average Surface Roughness with 3 Replication.....	93
Table 4.17 Results of the Confirmation Tests for Finish Machining using Aluminium Electrodes.....	93

Table 4.18 S/N Ratio for MRR in Roughing Conditions using Copper Electroplated Aluminium Electrodes.....	103
Table 4.19 S/N Ratio for Surface Roughness in Finishing Conditions using Copper Electroplated Aluminium Electrodes.....	104
Table 4.20 Pareto ANOVA for Two Level Factors for Metal Removal Rate in Rough Machining using Copper Electroplated Aluminium Electrode.....	105
Table 4.21 Pareto ANOVA for Two Level Factors for Surface Roughness in Finish Machining using Copper Electroplated Aluminium Electrode.....	107
Table 4.22 Results of the Confirmation Tests for Rough Machining using Copper Electroplated Aluminium Electrodes.....	109
Table 4.23 Results of the Confirmation Tests for Finish Machining using Copper Electroplated Aluminium Electrodes.....	109

LIST OF PUBLICATIONS

Thilaga Vaani and Mohammed Hameedullah, (2005), Optimization of control parameters in electric discharge machining of hardened tool steel with aluminium electrodes, Accepted for oral presentation and publication in the Proceedings of the First National Seminar on Advanced Processes and Systems in Manufacturing (APSIM 2005), National University of Malaysia, Bangi, Malaysia, 17-18 May 2005.

Thilaga Vaani and Mohammed Hameedullah, (2005), Optimization of control parameters in electric discharge machining of hardened tool steel with copper electroplated aluminium electrodes, Accepted for oral presentation and publication in the Proceedings of the International Conference on Recent Advances in Mechanical & Materials Engineering (ICRAMME 2005), University of Malaya, Kuala Lumpur, Malaysia, 30-31 May 2005.

Thilaga Vaani and Mohammed Hameedullah, (2005), Optimization of control parameters in electric discharge machining of hardened tool steel (SKD 11) with different electrodes material through Taguchi's Robust Parametric Design, Journal Material Process Technology, submitted for publication.