



**Faculty of Mechanical Engineering**

**INVESTIGATION OF MODIFIED SHIELDED METAL  
ARC WELDING (MOSMAW) FOR WELD PENETRATION  
PERFORMANCE**

**Manimaran a/l Selvam**

**Master of Science in Mechanical Engineering**

**2017**

**INVESTIGATION OF MODIFIED SHIELDED METAL  
ARC WELDING (MOSMAW) FOR WELD PENETRATION PERFORMANCE**

**MANIMARAN A/L SELVAM**

**A thesis submitted  
in fulfillment of the requirements for the degree of Master of Science in  
Mechanical Engineering**

**Faculty of Mechanical Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2017**

## **DECLARATION**

I declare that this thesis entitle “Investigation of Modified Shielded Metal Arc Welding (MOSMAW) for Welding Penetration Performance” is the result of my own research except as cited in the references. This thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : .....

Name : MANIMARAN A/L SELVAM

Date : 1<sup>st</sup> October 2017

## **APPROVAL**

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Mechanical Engineering.

Signature : .....

Supervisor Name : .....

Date : .....

## **DEDICATION**

To my beloved Mother Lecthumy Monian , Father Selvam Gangan and my Wife

Thevimalar

## ABSTRACT

This study is about an investigation of modified shielded metal arc welding (MOSMAW) with tubular welding electrode. The existing shielded metal arc welding process (SMAW) was modified into MOSMAW to investigate the weld ability and performance of tubular welding electrode. In the preliminary investigation it was found that heat content and interaction of Helium (He) produced a deeper penetration depth ( $PD$ ) and penetration area ( $PA$ ) as compared with Argon gas (AR) with gas volume flow rate range (0 -2.5 L/min). Secondly from the weld microstructure investigation it was found that there were four weld phases that include ferrite ( $\alpha$ ), pearlite ( $P$ ), widmanstatten ferrite ( $\alpha_w$ ) and the acicular ferrite ( $\alpha_a$ ) on three types of flux covered electrode (E6010, E6013 and E7018). Meanwhile hardness range was evident on the weld regions within the SMAW process. Based on, the nondestructive testing, PT and RT method the impact of moisture effect was found with the usage of E7018 tubular electrode which had weld surface defects compared to the use of E6013 tubular electrode. As for the tensile tests, E7018 had higher ultimate tensile strength (UTS) compared to E6013 electrode. The fracture mode found was ductile fracture and the guided bend test found E6013 and E7018 with fed orifice gases to have uniform face bend without the initiation of any crack. As for the weld region element analysis it was found that it had the usual element composition of carbon steel and electrode flux material in weld metal, HAZ and base metal. Moreover, the weld arc temperature measurement in the MOSMAW process with E6013 with Helium fed gases produced higher arc temperature compared to the process without gas provision. The DOE results indicated that the weld variables welding current ( $I$ ), electrode travel speed ( $S$ ), electrode travel feed rate ( $F$ ) and volume flow rate ( $Q$ ) interacted significantly with the responses bead width  $W$ , penetration depth  $PD$ , penetration area  $PA$  and dilution  $\%D$ . Further investigation on the DOE samples of weld penetration depth ( $PD$ ) and penetration area ( $PA$ ) indicated that the interaction were proportional to welding current ( $I$ ) and volume flow rate ( $Q$ ). The micro hardness test result hardness rate region was found to be within the SMAW carbon steel hardness range.

## ABSTRAK

*Kajian ini adalah mengenai penyiasatan kimpalan arka logam yang dikenali sebagai (MOSMAW) yang diubahsuai dengan menggunakan elektrod kimpalan jenis tubular. Kaedah kimpalan arka logam yang sedia ada dikenali sebagai (SMAW) telah diubahsuai ke MOSMAW untuk menyiasat keupayaan kimpalan dan prestasi elektrod kimpalan tubular. Dalam penyiasatan awal mendapati kandungan haba dan interaksi gas Helium (He) menghasilkan kedalaman penembusan yang lebih mendalam (PD) dan keluasan penembusan (PA) berbanding dengan gas Argon (AR) pada kadar isipadu gas antara (0 - 2.5 L / min). Lain daripada itu , pada penyiasatan mikrostruktur mendapati terdapat empat fasa struktur iaitu ferrite ( $\alpha$ ), pearlite (P), widmanstatten ferrite ( $\alpha_w$ ) dan acicular ferrite ( $\alpha_a$ ) pada elektrod fluks bersalut (E6010, E6013 dan E7018). Seterusnya, bagi keputusan ujian kekerasan mendapati tahap kekerasan pada fasa kimpalan memadahi dengan tahap kekerasan SMAW . Sementara itu , keputusan ujian tanpa musnah dengan kaedah PT and RT mendapati faktor kelembapan pada elektrod besalut E7018 menghasilkan kecacatan pada permukaan kimpalan berbanding dengan penggunaan elektrod besalut E6013. Seterusnya , bagi ujian tegangan mendapati electrode E7018 mempunyai kekuatan tegangan yang lebih tinggi (UTS) berbanding dengan elektrod E6013. Dalam pada itu , semasa ujian tegangan mendapati kesemua sampel ujikaji patah mengikut mod patah mulur. Manakala pada ujian kelenturan mendapati untuk elektrod bersalut E6013 dan E7018 lentur pada muka kimpalan tanpa sebarang keretakan pada permukaan kimpalan. Selain itu, bagi analisa elemen pada fasa kimpalan mendapati kesemua komposisi kimpalan memadahi komposisi elemen pada kawasan keluli kimpalan , HAZ dan karbon keluli asas .Lain daripada itu , untuk ujian pengukuran suhu pada kimpalan MOSMAW dengan elektrod E6013 dan E7018 mendapati proses MOSMAW dengan saluran gas Helium menghasilkan suhu arka tertinggi berbanding dengan kimpalan MOSMAW tanpa saluran gas. Pada ujian DOE mendapati mendapati pembolehubah kimpalan seperti arus elektrik (I) , kelajuan pergerakan elektrod (S), kadar pergerakan elektrod (F) dan kadar aliran isipadu gas (Q) berinteraksi dengan ketara dengan nilai  $R^2$  pada lebar kimpalan (W) , kedalaman penembusan kimpalan (PD), keluasan penembusan (PA) dan kesebatian kimpalan (%D).Keputusan ujian lanjutan DOE mendapati pemboleh ubah kedalaman penembusan kimpalan (PD) dan keluasan penembusan (PA)berinteraksi berkala pada pemboleh ubah arus elektrik (I) and kadar aliran isipadu gas (Q) . Akhir sekali , untuk ujian kekerasan pada permukaan kimpalan mendapati tahap kekerasan pada sampel pilihan memadahi dengan tahap kekerasan keluli karbon kimpalan SMAW.*

## ACKNOWLEDGEMENTS

All praises to GOD the Almighty for giving me the strength, guidance and patience in completing this thesis. My deepest appreciation goes to Dr.Thiru Chitrambalam for being a very helpful supervisor for this project. His valuable suggestion and encouragement have enabled me to handle this project with confidence. I would also like to express my gratitude Deputy Dean (Research and Graduate studies), Dr.Abd Rahman bin Dullah for his guidance and knowledge throughout my research progress.

I would like to extend my appreciation to all lecturers, technicians from (FKM, FTK and FKP) and administrative staffs in the department for their invaluable assistance. For the financial support, I gratefully acknowledge Universiti Teknikal Malaysia Melaka (UTeM) for the financial and infrastructure support provided throughout this research under the FRGS/2011/FKM/TK01/02/4 F00139 research fund.

I would like to thank the Ministry of Higher Education and the Malaysia Government for funding my Master's fees under the MYBRAIN 15 program. I would also like to thank the Faculty of Technology Engineering (FTK-UTeM), Faculty of Manufacturing Engineering (FKP-UTeM) , Megasteel Sdn Bhd and Sirim Sdn Bhd (NDT division and Welding testing laboratory) for providing me the research facilities. I would like to take this opportunity to thank my FKM (UTeM) research colleagues Sadiq Aziz, Tan Beng Hong, Sivanganam and Sean John Mathew for their outstanding support and knowledge sharing throughout my research. Last but not least, my deepest appreciation goes to my father; Selvam Gangan , my mother; Letchumy Moonian, my siblings ;S.Pubalan, S.Saraswathy , S.Sandran , S.Selvi , S.Suresh , S.Priya and my wife Thevimalar Manogaran. Their love and support have given me the strength and spirit to the completion of this thesis. Thank you so much.



## TABLE OF CONTENTS

	<b>PAGE</b>
<b>DECLARATION</b>	
<b>APPROVAL</b>	
<b>DEDICATION</b>	
<b>ABSTRACT</b>	<b>i</b>
<b>ABSTRAK</b>	<b>ii</b>
<b>ACKNOWLEDGEMENTS</b>	<b>iii</b>
<b>TABLE OF CONTENTS</b>	<b>iv</b>
<b>LIST OF TABLES</b>	<b>vii</b>
<b>LIST OF FIGURES</b>	<b>xi</b>
<b>LIST OF APPENDICES</b>	<b>xix</b>
<b>LIST OF ABBREVIATIONS &amp; SYMBOLS</b>	<b>xx</b>
<b>LIST OF PUBLICATION</b>	<b>xxvii</b>
<b>CHAPTER</b>	
<b>1. INTRODUCTION</b>	<b>1</b>
1.1 Background of study	1
1.2 Problem statement	3
1.3 Research objectives	4
1.4 Scope of research	4
1.5 Structure and layout of thesis	5
<b>2. LITERATURE REVIEW</b>	<b>7</b>
2.1 Shielded metal arc welding (SMAW)	7
2.2 Welding electrode	9
2.3 Type of flux coating	12
2.4 Nature of cellulose material and in welding applications	16
2.4.1 Background of cellulose material	16
2.4.2 Characteristic of coated Cellulose welding electrode	18
2.5 The problem of cellulose coated electrode in fusion welding process	20
2.5.1 Hydrogen induced cold cracking (HICC)	20
2.6 Summary	28
<b>3. EXPERIMENT SETUP</b>	<b>30</b>
3.1 Introduction	30
3.2 MOSMAW universal electrode holder	32
3.3 Prototype of modified electrode holder	32
3.4 Actual / workable tool electrode holder	34
3.5 Consumable tubular coated flux electrode	37
3.6 Experimental setup	39
3.7 The arc initiation of MOSMAW process in the machine automation	41
3.8 Sample preparation for the experimental work	44
3.9 Metallographic sample preparation	46

3.9.1	Weld bead and geometry measurement	47
3.10	Micro hardness testing	48
3.11	Microstructure analysis	50
3.11.1	Sample preparation of microstructure analysis	50
3.11.2	Macro etching and microstructure image viewing	52
3.12	Destructive testing	54
3.12.1	Tensile test and bending test	54
3.13	Non-destructive Testing	63
3.13.1	Liquid penetration (PT)	63
3.13.2	Radiographic testing (RT)	65
3.14	Scanning electron microscopy (SEM) , Electron diffraction and (EDX) X-ray diffraction (XRD)	69
3.15	Welding temperature measurement	70
3.16	Computational fluid dynamic analysis for internal flow in the tubular welding electrode	71
3.16.1	Plan of investigation	73
3.16.2	Meshing analysis on the simulation model	74
3.16.3	Determination of input data for simulation	75
3.17	Design of experiment for MOSMAW process	78
3.17.1	Weld parameter selection using screening test	79
3.17.2	Response Surface Methodology	82
3.17.3	Development of Design matrix and Mathematical model	83
3.18	Summary	87
<b>4.</b>	<b>RESULTS AND DISCUSSION OF FLUID FLOW ANALYSIS IN THE TUBULAR WELDING ELECTRODE</b>	<b>89</b>
4.1	Introduction	89
4.2	2D Asymmetrical model of fluid flow simulation	89
4.3	Summary	100
<b>5.</b>	<b>RESULTS AND DISCUSSION OF THE MOSMAW PROCESS</b>	<b>101</b>
5.1	Preliminary investigation	101
5.1.1	Investigation of weld bead geometry and relationship	101
5.2	Microhardness	108
5.3	Microstructure analysis	110
5.4	Non-destructive testing	115
5.5	Mechanical testing on the welded joints in the MOSMAW process	120
5.5.1	Tensile test	120
5.5.2	Bend test	125
5.5.3	Fracture surface and behavior of weld	127
5.6	Weld element analysis of MOSMAW process	129
5.7	Weld arc temperature measurement	133
5.8	Design of experiment (DOE)	134
5.8.1	Weld bead width ( <i>W</i> )	134
5.8.2	Penetration depth ( <i>PD</i> )	140
5.8.3	Penetration Area ( <i>PA</i> )	146
5.8.4	Percentage of dilution ( <i>%D</i> )	151
5.9	The effect of secondary heat from feed gas supply	158

5.10 Summary	162
<b>6. CONCLUSION AND RECOMMENDATION</b>	<b>166</b>
6.1 Conclusion	166
6.2 Recommendation	169
<b>REFERENCE</b>	<b>170</b>
<b>APPENDICES</b>	<b>199</b>

## LIST OF TABLES

<b>TABLE</b>	<b>TITLE</b>	<b>PAGE</b>
2.1	Main flux coating ingredients and their function	12
2.2	Estimated composition of Lingnocellulosic Feed stock	17
2.3	Chemical composition of some typical of some typical cellulose containing material	18
2.4	The welding electrode classification based on AWS	18
2.5	The moisture content in the raw material of consumable electrodes	24
3.1	Chemical composition, weight (%) of high cellulose flux coating (E6010)	38
3.2	Chemical composition, weight (%) of tubular electrode rutile flux coating (E6013)	38
3.3	Chemical composition, weight (%) of tubular electrode low hydrogen coating (E7018)	38
3.4	Chemical composition, weight (%) of mild solid rod (E6010)	38
3.5	Chemical composition, weight (%) of tubular mild solid rod E6013 and E7018	38

3.6	Chemical composition of base metal	45
3.7	Consumable SMAW electrode storage and drying temperature	58
3.8	The calculated input control variables and the resulted flow characteristics for Argon gas (Ar)	77
3.9	The calculated input control variables and the resulted flow characteristics for Helium gas (He)	78
3.10	The calculated input control variables and the resulted flow characteristics for Carbon dioxide gas(CO <sub>2</sub> )	79
3.11	Process control parameters and limits	78
3.12	The measurement of Speed and Feed rate	80
3.13	The factorial test result on the selected factors and the obtained response	81
3.14	The experimental parameter for Response surface method	82
3.15	Experimental Design matrix	85
4.1	The simulation result for Argon	90
4.2	The simulation result for Helium	91
4.3	The simulation result for Carbon dioxide	91
5.1	The input parameter and variables for bead geometry relationship investigation	101
5.2	Result of weld bead geometry measurement by applying Rutile covering (E6013) tubular electrode	102
5.3	Result of weld bead geometry measurement by applying low hydrogen (E7018) covering tubular electrode	103
5.4	Result of penetration testing on MOSMAW process with	

	Tubular welding electrode (Rutile covering electrode) E6013	116
5.5	Result of penetration testing on MOSMAW process with Tubular welding electrode (Low hydrogen electrode) E7018	116
5.6	Result of Radiographic testing on the welded samples from MOSMAW process with solid rod electrode E6010, and flux covered tubular electrode E6013 and E7018.	118
5.7	Result of tensile test on the welded samples from MOSMAW process	120
5.8	Location of fracture in the welded samples on the MOSMAW process with and without fed gases supply	124
5.9	Results of bend test on welded samples of MOSMAW process with and without feed gas	126
5.10	Chemical composition of weld metal for conventional cellulose stick electrode	130
5.11	Chemical composition of weld metal for rutile covering (tubular electrode)	130
5.12	Chemical composition of weld metal for rutile covering feded with Argon gas (tubular electrode)	130
5.13	Chemical composition of weld metal for rutile covering feded with Helium gas (tubular electrode)	130
5.14	Temperature measurement using OPTEX Portable Thermo-Hunter	133
5.15	Temperature measurement using OPTEX Portable Thermo- Hunter on multiple weld parameters	134
5.16	ANOVA results for Weld bead width ( $W$ )	135
5.17	Estimation regression coefficient for Weld bead width ( $W$ )	136

5.18	ANOVA results for Penetration depth ( <i>PD</i> )	141
5.19	Estimation regression coefficient for Penetration depth ( <i>PD</i> )	142
5.20	ANOVA results for Penetration Area ( <i>PA</i> )	146
5.21	Estimation regression coefficient for Penetration Area ( <i>PA</i> )	147
5.22	ANOVA results for Percentage of dilution ( <i>%D</i> )	152
5.23	Estimation regression coefficient for Percentage of dilution ( <i>%D</i> )	153
5.24	Selection of DOE samples for further investigation	158

## LIST OF FIGURES

<b>FIGURE</b>	<b>TITLE</b>	<b>PAGE</b>
1.1	The propagation of crack at weld region due to HICC	2
2.1	Shielded metal arc welding process , SMAW	7
2.2	Flux coated electrode of SMAW process	10
2.3	Types of flux covering of SMAW consumable electrode	14
2.4	Scheme of hierarchical levels of the structure organization of wood cellulose	16
2.5	The three condition influencing formation of HICC in weld	21
2.6	The interaction of of stress and hydrogen content with cooling temperature after welding process	22
2.7	The formation of hydrogen from the consumable electrode on SMAW and FCAW	23
2.8	The chronology of hydrogen diffusion in weld region	23
2.9	Illustration of hydrogen in the weldment during welding process	26
2.10	The hydrogen concentration of diffusion in weld metal and HAZ region	27
3.1	Flow chart of experimental work on MOSMAW process	31
3.2	The prototype fabrication work	33
3.3	The complete assemble of all components and also fitted with the newly developed tubular electrode	33



3.4	Fabrication of actual workable model of modified electrode holder MOSMAW	34
3.5	The fabricated components (a) and the pre-assembly of components (b)	35
3.6	Full view of modified electrode holder and tubular welding electrode for machine automation MOSMAW process	36
3.7	The developed tubular welding electrode for the experimental work	37
3.8	The setup of fabricated electrode holder with milling machine spindle connector (a) into conventional milling machine (b)	39
3.9	Work piece jig holder (a) installed with square plywood underneath (b)	39
3.10	Rubber insulation installation on connecting nut and bolt	40
3.11	The schematic diagram of arc initiation by using graphite rod	41
3.12	Schematic diagram for MOSMAW experimental setup	42
3.13	Conventional Milling machine variable speed motors	43
3.14	Overview of experimental setup in conventional milling machine	44
3.15	Work piece cutting (a) on band saw machine (b)	45
3.16	Metallographic sample preparation	46
3.17	Hot press mounting (a) hot mounted press sample (b)	46
3.18	Dino –lite digital macrographs capture device for weld bead geometry measurement	47
3.19	Captured macrograph image from Dinocapture 2.0	48
3.20	Vickers hardness press (a) mounted sample positioning (b)	49
3.21	Microhardness indentation region on test sample	50
3.22	Grinding process on mounted sample	51

3.23	Polishing process with text, nap and micro cloth pad on polishing machine	52
3.24	Zeiss upright microscopy with image characterization software	54
3.25	Schematic diagram of manual MOSMAW process	55
3.26	Butt joint with Single V-groove chamfering	56
3.27	V-groove angle chamfering milled machining work with inclination jig	56
3.28	Welding passes on the single V-groove butt joint	57
3.29	Sample cutting process with high pressure abrasive water jet machine	58
3.30	Tensile test, sample dimension (mm) and specification	59
3.31	Bending test, sample dimension (mm) and specification	59
3.32	Tensile test final sample	60
3.33	Bending test final sample	60
3.34	Electrical furnace	61
3.35	Universal tensile test machine (UTM)	62
3.36	Guided face bend test	63
3.37	PT testing procedure	64
3.38	The testing procedure of Penetration test	64
3.39	Radiation room (a) , Radiation generator (b) and sample placement on radiographic film (c)	66
3.40	Fluorescence light was used inside dark room for radiation film development.	67
3.41	Films developing process in the dark room	67
3.42	Radiographic viewer for imaging the defect	68

3.43	SEM, EDX (a) and XRD test machine (b)	69
3.44	Weld element spotted on three spectrum	70
3.45	The schematic diagram instrument setup for weld arc measurement	70
3.46	Tubular welding technique and (b) internal flow characteristic in the tube	71
3.47	The theory of gas flow in the tubular welding electrode	72
3.48	The manufactured tubular welding electrode and Schematic diagram of tubular welding electrode with boundary region/condition in axisymmetric geometry for 2D	74
4.1	The simulation contour (a) and vector (b) illustration of fluid flow in the 1.8 mm tubular welding electrode in axisymmetric orientation	92
4.2	The entrance length development on the axisymmetric model at $Q = 2.0$ l/min of Helium gas	93
4.3	The velocity flow contour image of Helium gas at volume flow rate 2.0 l/min	94
4.4	Pressure variation at the wall boundary on the axial distance (340 mm) of the simulation model in the Laminar flow.	95
4.5	Velocity profile of maximum velocity of Helium gas at outlet boundary region with varies range of volume flow rate, $Q$ (L/min)	96
4.6	Velocity profile of maximum velocity of Argon gas at outlet boundary region with varies range of volume flowrate, $Q$ (L/min)	97
4.7	Velocity profile of maximum velocity of Carbon dioxide gas at outlet boundary region with varies range of volume flow rate, $Q$ (L/min)	98

4.8	Validation of CFD Simulation with analytical result of velocity outlet (Vout) fluid flow analysis on the 1.8 mm diameter of axisymmetrical model	99
5.1	Macrograph images of weld bead geometry on welded samples of rutile coated (E6013) and Low hydrogen coated tubular welding electrode (image scale :1mm)	102
5.2	Weld penetration depth for E6013 tubular rutile covered electrode	104
5.3	Weld penetration depth for E7018 tubular low hydrogen covered electrode	104
5.4	Penetration area for E6013 tubular rutile covered e electrode	105
5.5	Penetration area for E7018 tubular low hydrogen covered electrode	106
5.6	The result of XRD on E7018 low hydrogen powder of tubular covered electrode	107
5.7	The microhardness profile of on conventional electrode (E6010) and tubular flux coating electrodes (E6013 and E7018) without feed gas	109
5.8	The hardness HV of on tubular electrode type rutile covering and feded gases such Argon and Helium gas	110
5.9	Weld region at (a) Base metal, (b) HAZ and (c) Weld metal of welded sample using conventional stick E6010 high cellulose electrode	111
5.10	The micrographs of heat affected zone (HAZ) on rutile (E6013) and low hydrogen (E7018) in tubular welding electrode with and without gas supply	112
5.11	The weld metal on rutile (E6013) and low hydrogen (E7018)	

	in covered tubular welding electrode with and without gas supply	113
5.12	Image of penetration tested welded samples with developer coating for (a) E6010 -solid electrode (high cellulose electrode), (b) E6013-Rutile flux coated and (c) E7018 -Low hydrogen coated tubular electrode with Argon and Helium as orifice gases.	115
5.13	The defect formation on the weld surface on low hydrogen tubular electrode, E7018 with Argon as orifice gas indicated in (A till F)	117
5.14	Images captured from RT films from Radiographic testing on the welded samples	119
5.15	Tensile stress vs strain of welded joint.	121
5.16:	Tensile stress vs strain	122
5.17	Fracture mode on the welded sample after tensile test.	123
5.18	Lack of fusion (LOF) at the hard pass on welded joint.	125
5.19	All guided bend test samples (a) and cracked sample (b)	126
5.20	Plastic behavior region from obtained tensile test result	127
5.21	High cellulose electrode - E6010	128
5.22	Tubular rutile flux coated electrode with Argon feded gas – E6013 (Ar)	129
5.23	Tubular rutile flux coated electrode with Helium feded gas – E6013 (He)	129
5.24	Tubular low hydrogen flux coated electrode with Argon feded gas – E7018 (Ar)	129
5.25	Tubular low hydrogen flux coated electrode with Helium feded gas – E7018 (He)	129

5.26	Element composition at Weld metal using rutile flux covering of tubular electrode with Helium gas	131
5.27	Element composition at HAZ using rutile flux covering of tubular electrode with Helium gas	131
5.28	Element composition at Base metal using rutile flux covering of tubular electrode with Helium gas	132
5.29	Interaction effect of welding current ( $I$ ) and electrode travel speed ( $S$ ) on bead width	137
5.30	Interaction effect of electrode travel speed ( $S$ ) and electrode travel feedrate ( $F$ ) on bead width	138
5.31	Interaction effect of welding current ( $I$ ) and Gas volume flow rate ( $Q$ ) on bead width	139
5.32	Prediction vs observed value on width of bead geometry	140
5.33	Interaction effect of welding current ( $I$ ) and Feed rate ( $F$ ) on Penetration depth	143
5.34	Interaction effect of welding current ( $I$ ) and Gas volume flow rate ( $Q$ ) on Penetration depth	144
5.35	Prediction vs observed value on Penetration depth of bead geometry	145
5.36	Interaction effect of current ( $I$ ) and Speed ( $S$ ) on Penetration area	148
5.37	Interaction effect of current ( $I$ ) and Feed rate ( $F$ ) on Penetration area	149
5.38	Interaction effect of speed ( $S$ ) and Feed rate ( $F$ ) on Penetration area	149
5.39	Interaction effect of current ( $I$ ) and volume flow rate of helium gas ( $Q$ ) on Penetration area	150
5.40	Prediction vs observed value on Penetration area of bead geometry	151
5.41	Interaction effect of Current ( $I$ ) and Speed ( $S$ ) on Percentage	

	of Dilution (% $D$ )	153
5.42	Interaction effect of Current ( $I$ ) and Feed rate ( $F$ ) on Percentage of Dilution (% $D$ )	155
5.43	Interaction effect of Current ( $I$ ) and volume flow rate of helium gas ( $Q$ ) on Percentage of Dilution (% $D$ )	155
5.44	Prediction vs observed value on Percentage of dilution of bead geometry	157
5.45	The relationship of welding current of 100 amps and volume flow rate ( $Q$ )	159
5.46	The relationship of welding current of 125 amps and volume flow rate ( $Q$ )	159
5.47	The relationship of welding current of 150 amps and volume flow rate ( $Q$ )	160
5.48	The micro hardness profile at 100 Amps with max and min volume flow rate ( $Q$ )	161
5.49	The micro hardness profile at 125 Amps with max and min volume flow rate ( $Q$ )	161
5.50	The micro hardness profile at 150 Amps with max and min volume flowrate ( $Q$ )	162

## LIST OF APPENDICES

<b>NO.APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	RSM – Minitab result	199
B	MOSMAW Electrode holder tools drawing	211