

**UNIVERSITI TEKNOLOGI MARA**

**MICROSTRUCTURAL AND WEAR  
PROPERTIES OF Fe-BASED  
HARDFACING MATERIALS  
DEPOSITED ON CARBON STEEL  
BASE METAL**

**AFZALLEH BIN JILLEH**

Thesis submitted in fulfilment  
of the requirements for the degree of  
**Doctor of Philosophy**  
(Science)

**Faculty of Applied Sciences**

**July 2018**

## ABSTRACT

The study focused on microstructural investigation and wear analysis of iron (Fe) based hardfacing fillers of Series 1 (hypereutectic white cast iron (WCI)) – alloys A, B, C and D; Series 2 (hypo-eutectic WCI) – alloys F, G and H; and Series 3 (hypereutectoid steel) – alloy E. The hardfacing alloys were deposited on carbon steel base metal using self-shielded flux cored arc welding (FCAW) technique onto the base metal which is SJR235RG2 type steel. Phase formation, microstructural and mechanical properties of hardface deposits were investigated in the as-deposited condition. In Series 1, the addition of niobium (Nb) and molybdenum (Mo) with tungsten (W) and vanadium (V) additives resulted in microstructure refinement of the proeutectic  $M_7C_3$  carbide phase as revealed by optical microscopy and field-emission scanning electron microscope (FESEM) analysis. XRD (x-ray diffraction) and energy dispersive x-ray (EDX) analysis showed the existence of  $M_7C_3$  (M=Cr, Fe), MC (M=Nb, Mo) and the matrix of  $\alpha$ -ferrite phase. Nb and Mo found to form MC carbide while W and V dispersed uniformly in matrix and carbide phase. The increasing of alloying elements in the filler further increased the microstructure refinement, increased hardness and wear resistance. The main wear mechanism observed in Series 1 hardfacing alloys are abrasive wear, indicated by surface grooves and surface fatigue, indicated by material delamination. In Series 2, the major addition of titanium (Ti) with Mo, Nb and V, resulted in fine distribution of MC carbides embedded within  $\alpha$ -dendritic structure as revealed by optical microscopy and FESEM analysis. XRD and EDX analysis showed the existence of  $M_7C_3$  (M=Cr, Fe), MC (M=Ti, V, Nb, Mo) and the matrix of  $\alpha$ -ferrite phase. Increase of hardness and wear resistance is due to the distribution of MC carbide and excess chromium (Cr) that dissolves in the  $\alpha$ -ferrite phase as solid solution. The main wear mechanism observed in Series 2 hardfacing alloys is abrasive wear, while hardface alloys with alloying addition showed surface delamination which was attributed to the presence of soft phase adjacent to the MC carbides. In Series 3, optical microscopy and FESEM-EDX analysis showed existence of MC (M=Ti, V, Mo), martensite and retained austenite. The dilution effect has resulted in the formation of martensite and retained austenite matrix. Thus, the strength of hardface deposit was contributed from MC carbide dispersion, martensite phase and the Cr solid solution that dissolved in the matrix.

## ACKNOWLEDGEMENT

Alhamdulillah, The Most Gracious, The Most Merciful, peace and blessing of Allah upon His Beloved Muhammad, for giving me the opportunity to commence on my study as well for the strength, energy and wellbeing to complete it.

Firstly, I would like to express my deepest gratitude to my honourable supervisor, Dr. Mahesh Kumar Talari who had tirelessly guided me while pursuing this study, for his best guidance, patience, motivation, immense knowledge and continuous support. He has provided me with his constructive views and full professionalism without which this study not be completed. His guidance helped me in all the time of this thesis completion as well as in other research papers. I could not have imagined having a better advisor and mentor for this study. Besides, my appreciation goes to my respectable co-supervisors, Dr. Venugopal Thota and Prof. Dr. Mohamad Kamal Harun. Without their precious support it would not be possible to conduct this research.

I place on record, my sincere thank you to my fellow comrades, Dr. Ahmad Lutfi Anis and Widyani Darham, as well as Izzul Adli Mohd Arif, for all their help and guides, the sleepless nights we were working together before deadlines, and for all the fun we have had in our memorable “home” - B433. Not to forget, thank you to Mr. Azlan Zakaria and Dr. Mohd Husairi Fadzilah Suhaimi for their contributions in the B433’s circle. I am also grateful to other postgraduate colleagues, laboratory assistants and any individual involved directly or indirectly throughout all the time of this study.

In particular, I wish to express my special thanks from the bottom of my heart to my family for their great understanding, patience, abundance of love and great deal of encouragement morally, spiritually and materially in this long and challenging journey. I also would like to thanks to Wan Mimi Suziana Wan Omran for her advices, moral support and understanding during crucial moment in my study. I also would like to thanks to all my friends, especially to my fellow runners and hikers for their good wishes

Finally, this thesis is dedicated to my late brother, Azman Jilleh, for his enormous influence in my life.

Thank you.

# TABLE OF CONTENTS

	<b>Page</b>
<b>CONFIRMATION BY PANEL OF EXAMINERS</b>	<b>ii</b>
<b>AUTHOR'S DECLARATION</b>	<b>iii</b>
<b>ABSTRACT</b>	<b>iv</b>
<b>ACKNOWLEDGEMENTS</b>	<b>v</b>
<b>TABLE OF CONTENTS</b>	<b>vi</b>
<b>LIST OF TABLES</b>	<b>x</b>
<b>LIST OF FIGURES</b>	<b>xii</b>
<b>LIST OF SYMBOLS</b>	<b>xx</b>
<b>LIST OF ABBREVIATIONS</b>	<b>xxi</b>
<b>CHAPTER ONE: INTRODUCTION</b>	<b>1</b>
1.1 Background of Study	1
1.2 Problem Statement	4
1.3 Objectives of Study	6
1.4 Scope and Limitations	6
1.5 Significance of the Study	8
<b>CHAPTER TWO: LITERATURE REVIEW</b>	<b>10</b>
2.1 Overview	10
2.2 Materials Selection	10
2.2.1 The Application of Fe-Based Hardfacing Alloys to Minimize Wear	11
2.2.2 Fe-Fe <sub>3</sub> C Binary System	12
2.2.3 Fe-Cr and Cr-C Binary System	19
2.3 Iron-Chromium-Carbon Ternary System	21
2.3.1 White Cast Iron	21
2.3.2 Effects of Alloying Elements Addition on Microstructure	23
2.3.2.1 Titanium addition	25
2.3.2.2 Molybdenum addition	30
2.3.2.3 Niobium addition	33

2.3.2.4	<i>Tungsten addition</i>	36
2.3.2.5	<i>Vanadium addition</i>	38
2.3.3	Hardness and Wear Properties Above 4 wt.% Carbon	39
2.3.4	Hardness and Wear Properties In Between 2 to 4 wt.% Carbon	46
2.3.5	Hardness and Wear Properties Below 2 wt.% Carbon	48
2.4	Wear on the Surface of Machine Component	52
2.4.1	Wear Mode	53
2.4.1.1	<i>Abrasive Wear</i>	53
2.4.1.2	<i>Adhesive Wear</i>	57
2.4.1.3	<i>Surface Fatigue</i>	59
2.5	Hardfacing Methods to Minimize Wear	62
2.5.1	Powder Cored Welding Wire	64
2.5.2	Welding Technique Used for Hardfacing	65
2.5.3	Hardfacing Using Self-Shielded FCAW	68
2.5.4	Weld Dilution and Multipass Welding	69
2.6	Summary on the Literature Review	71
 <b>CHAPTER THREE: PREPARATION AND CHARACTERIZATION</b>		<b>75</b>
3.1	Preparation of Hardfacing Alloys	75
3.1.1	Hardfacing Process	77
3.2	Sample Characterization and Analysis	78
3.2.1	XRD Characterization of Bulk Sample	80
3.2.1.1	<i>X-ray Beam Interaction with Sample</i>	81
3.2.2	Microstructure Evaluation by Optical Microscope/Stereomicroscope	83
3.2.2.1	<i>Principle of Stereomicroscope and Optical Microscope</i>	84
3.2.3	Microstructure Evaluation by FESEM-BSE and EDX Mapping	86
3.2.3.1	<i>Sample Interaction in FESEM-BSE and EDX mapping</i>	87
3.2.4	Rockwell Hardness Test	89
3.2.4.1	<i>Working Principle of Rockwell Hardness Test</i>	90
3.2.5	Wear Test	93
3.2.5.1	<i>Wear Test by Dry Sand/Rubber Wheel Wear Test Machine</i>	93
3.2.5.2	<i>Principle of Dry Sand/Rubber Wheel Abrasion Test</i>	95
3.2.5.3	<i>Wear Test by Pin-On-Disk Wear Test Machine</i>	95
3.2.5.4	<i>Principle of Pin-On-Disk Wear Test</i>	97