



UNIVERSITI PUTRA MALAYSIA

**PROPERTIES OF METAL MATRIX COMPOSITE OF ALUMINIUM -
11.8% SILICON REINFORCED WITH DIFFERENT PARTICULATES**

THOGULUVA RAGHAVAN VIJAYARAM.

FK 2006 63



**PROPERTIES OF METAL MATRIX COMPOSITE OF ALUMINIUM –
11.8% SILICON REINFORCED WITH DIFFERENT PARTICULATES**

By

THOGULUVA RAGHAVAN VIJAYARAM

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfilment of the Requirement for the Degree of Doctor of Philosophy**

May 2006



DEDICATION

Thanking THE ALMIGHTY, for giving me the knowledge to complete my doctoral research successfully.

This research work is dedicated to my family.



Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

**PROPERTIES OF METAL MATRIX COMPOSITE OF ALUMINIUM –
11.8% SILICON REINFORCED WITH DIFFERENT PARTICULATES**

By

THOGULUVA RAGHAVAN VIJAYARAM

May 2006

Chairman : Associate Professor Shamsuddin Sulaiman, PhD

Faculty : Engineering

A composite material is a materials system composed of a mixture or combination of two or more micro or macro constituents that differ in form and chemical composition and which are essentially insoluble in each other. Metal matrix composites are engineered materials composed of an elemental or alloy matrix in which an insoluble second phase reinforcer is embedded and distributed to achieve some property improvement. Particulate reinforced metal matrix composites constitute a major portion of these advanced materials. Aluminium-silicon alloys, as a matrix material, are characterized by lightweight, good strength-to-weight ratio, ease of fabrication at reasonable cost, high strength at elevated temperature, good thermal conductivity, excellent castability, good weldability, excellent corrosion resistance and wear resistance properties. Application of particulate reinforced composites in the aerospace, automotive, transportation and construction industries depends on the choice of cost affordable factor. In this research work, particulate

reinforced metal matrix composites are processed by vortex method, a melt stirring liquid metallurgy technique. Four different particulates namely, graphite, combination of tungsten carbide and aluminium silicate for hybrid composite reinforcement, quartz and titanium carbide are used as second phase reinforcers for reinforcement in the matrix. Aluminium-11.8% silicon alloy is selected as the matrix material and the particulates are mixed in different weight fraction %. Slab composite castings are made by pouring the composite mixture in grey cast, steel and copper permanent-molds. Process parameters like pouring temperature, particulate preheating temperature, impeller blade speed and shape are optimized and composite castings containing different weight fraction % of particulate are made by permanent-mold casting process. Effects on different weight fraction % addition of particulate on the particulate distribution in aluminum-11.8% silicon alloy composites are studied. The processed particulate reinforced composites are subjected to mechanical tensile testing and the properties are determined for different type of particulate reinforcements in the aluminium-11.8% silicon alloy matrix. Besides, hardness, density, impact strength-charpy, fracture toughness, electrical resistivity, electrical conductivity, thermal diffusivity, thermal conductivity, thermal expansion coefficient measurements are performed by using the appropriate equipments and machines. Metallographic studies of the processed particulate composites are conducted by optical microscopy and photomicrographs are captured at different magnifications to reveal and examine the particulate distribution in the aluminium-11.8% silicon alloy matrix. SEM observation of the fracture surfaces of tensile tested, charpy impact tested specimens are performed to study the fracture mechanics and surface characteristics with the aid of captured SEM fractographs. Interfacial bonding features of the processed composites are also analyzed with the

help of SEM. Besides, slab castings without particulate addition are made and compared with the results based on the properties and microstructural features, particularly for the uniformity of particulate distribution in the aluminum-11.8% silicon alloy base matrix. It is found that the properties of the processed particulate reinforced aluminium-11.8% silicon alloy matrix composites are superior to the cast monolithic aluminium-11.8% silicon alloy based on the above-mentioned properties studies. Photomicrographs of the processed composites based on the metallographic studies have confirmed the uniformity of particulate distribution in the aluminium-11.8% silicon alloy matrix.

Abstrak tesis dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**KAJIAN SIFAT BAGI ZARAHAN YANG DIPERKUAT ALUMINIUM-11.8%
SILIKON ALOI BERASASKAN KOMPOSIT MATRIK**

Oleh

THOGULUVA RAGHAVAN VIJAYARAM

Mei 2006

Pengerusi : Profesor Madya Shamsuddin Sulaiman, PhD

Fakulti : Kejuruteraan

Bahan komposit merupakan sistem bahan yang terdiri dari campuran atau kombinasi dua atau lebih mikro atau makro kandungan yang berbeza dari segi bentuk dan komposisi kimia dan kebiasaanya tidak bercampur antara satu sama lain. Besi matrik komposit adalah kejuruteraan bahan komposit yang mengandungi elemen atau aloi matrik dimana satu bahan penguat yang tidak bercampur pada fasa kedua dimasukkan bagi meningkatkan sifat bahan tersebut. Sebahagian besar kandungan bahan penguat komposit besi matrik mengandungi bahan termaju. Alloy Aluminium – Silikon sebagai bahan matrik adalah diklasifikasikan sebagai ringan, nisbah kekuatan kepada berat yang baik, senang difabrikasikan pada kos yang berpatutan, kekuatan yang tinggi pada suhu tinggi, pengalir termal yang baik, sangat mudah ditempa, mudah di kimpal, penghalang hakisan karat yang baik dan kandungan tahan hakis permukaan yang tinggi. Penggunaan komposit bahan penguat di dalam industri

aeroangkasa, automotif, pengangkutan dan pembinaan bergantung kepada faktor pilihan kos yang mampu ditanggung oleh industri berkenaan. Di dalam kajian ini, bahan penguat komposit besi matrik di proses dengan menggunakan kaedah 'vortex' iaitu satu teknik metallurgi di mana pencairan cecair melalui pengaluan dilakukan. Empat bahan berbeza yang digunakan dalam fasa kedua penguatan matrik adalah terdiri dari graphite, kombinasi tungsten karbida dan aluminium silikat bagi campuran komposisi penguat, quartz dan titanium karbida. Sebanyak 11.8% alloy silikon telah dipilih sebagai bahan matrik dan kandungan bahan ini dicampur dalam nisbah peratusan berat yang berbeza. Komposit ketulan acuan dihasilkan dengan kaedah menuang campuran komposit ke dalam acuan kelabu, keluli dan kuprum yang tetap. Parameter proses seperti suhu penuangan, suhu prapemanasan bahan, kekuatan kelajuan mata pisau dan bentuk dilaraskan pada keadaan terbaik dan acuan komposit yang mengandungi nisbah peratusan berat bahan yang berbeza dibuat menggunakan proses acuan yang tetap. Kesan pada nisbah peratusan berat tambahan pada setiap bahan dalam aluminium 11.8% silikon alloy dikaji. Komposit penguat yang telah diproses, kemudian diuji dengan ujian tegangan mekanikal dan kandungan kekuatan bahan tersebut ditentukan bagi bahan penguat yang berbeza di dalam matrik aluminium 11.8% silikon aloi. Selain itu, ujian kekerasan, ketumpatan, kesan kekuatan-charpy, ketahanan keretakan, ketahanan pengaliran elektrik, konduktor elektrik, diffusiti termal, pengukuran konduktor termal telah dijalankan menggunakan peralatan dan mesin yang bersesuaian. Akhirnya metallograf dijalankan keatas zarahhan bahan komposit yang telah diproses dan fotomikrograf diambil pada skala pembesaran yang berbeza bagi menunjukkan dan menguji pengagihan zarahhan bahan dalam matrik aluminium-11.8% silikon aloi. Melalui pemerhatian SEM pada permukaan retak dari ujian kekuatan, satu ujian kekuatan-

charpy dilakukan ke atas spesimen bagi mengkaji keretakan mekanik dan sifat – sifatnya dengan bantuan dari fraktograf SEM yang telah diambil. Ciri-ciri struktur persamaan di antara permukaan bagi komposit yang telah diproses juga dianalisis dengan bantuan SEM. Selain itu, ketulan proses acuan tanpa zarahhan bahan tambahan dihasilkan dan dibandingkan dengan hasil keputusan dari properti dan ciri-ciri struktur mikro khasnya pembentukan zarahhan bahan dalam matrik aluminium-11.8% silikon aloi. Hasil dari kajian ini menunjukkan properti bagi hasil proses dari komposit bahan penguat matrik aluminium-18% silikon aloi adalah lebih baik dari acuan monolithic aluminium-11.8% silikon alloy. Fotomikrograf keatas komposit yang telah diproses berdasarkan kajian mettalograf membuktikan pembentukan zarah-zarah di dalam aluminium-11.8% silikon aloi matrik.

ACKNOWLEDGEMENTS

I would like to express my gratitude, appreciation and thanks to my research supervisor and the chairman of my supervisory committee Associate Professor Dr. Shamsuddin Sulaiman and thankful to the members of the supervisory committee Professor Dr. AMS Hamouda and Associate Professor Dr Megat Hamdan Mohamad Ahmad Megat for their support in this research work and entire preparation of this doctoral dissertation.

I would like to convey my thanks to Mr. Ahmad Saifuddin Ismail, Foundry lab Technician for his assistance during the entire period of my research project

I am thankful to Mr.Wilden, Strength of Materials laboratory for his assistance in performing the mechanical testing.

I would like to appreciate and express my thanks to Mr.Saiful, Technician, Aerospace engineering materials laboratory, who provided me the facility to capture the photomicrographs by optical microscopy.

I would like to express my sincere thanks to Mr.Raffiuz Zaman Haroun, UPMN, Institute of Biosciences for his assistance in taking SEM micrographs and fractographs.

I would like to convey my thanks to Ms.Yusmavati, Makmal Bahan, Thermal Physics laboratory, and especially to Mr.Ishkander, Master's student, Biophysics

laboratory of Physics department who has assisted me in performing the CTE measurements.

I would like to express my sincere thanks and gratitude to my beloved wife Mrs. Vaishnavi Thoguluva Vijayaram who have helped me a lot in editing my thesis and for her consistent encouragement to work on this PhD research project.

Among the people to whom I am indebted, I would like to express my sincere thanks to my friend and colleague, Mr. Karmegam Karuppaih, Master's students of our department for his kind assistance on translating my PhD abstract to Bahasa Melayu.

TABLE OF CONTENTS

DEDICATION	ii
ABSTRACT	iii
ABSTRAK	vi
ACKNOWLEDGEMENTS	ix
APPROVAL	xi
DECLARATION	xiii
LIST OF TABLES	xvii
LIST OF FIGURES	xxi
LIST OF ABBREVIATIONS	xxxix
CHAPTER	
1 INTRODUCTION	1
1.1 Background	1
1.2 Problem statement	4
1.3 Objectives of the research	6
1.4 Scope and limitation	7
1.5 Overview and layout of thesis	8
2 LITERATURE REVIEW	9
2.1 General	9
2.2 Metal matrix composites (MMCs)	17
2.3 Classification of Composites	19
2.4 Significance of composites	26
2.5 Matrix / Matrices	27
2.6 Reinforcing phase / materials	29
2.6.1 Factors affecting reinforcement	34
2.6.2 Particulate reinforcement	40
2.7 Application of metal matrix composites	39
2.8 Properties of composites relevant to aluminium-based MMCs	43
2.9 Material selected for processing composites	47
2.9.1 Aluminum – 11.8 % silicon eutectic alloy	48
2.9.2 Tungsten carbide	50
2.9.3 Titanium carbide	51
2.9.4 Quartz	51
2.9.5 Graphite	52
2.9.6 Aluminium silicate	53
2.10 Permanent metal mold casting process	65
2.11 Metallograpy (Optical metallurgical microscopy)	69
2.12 SEM (Scanning Electron Microscopy)	74
2.13 Conclusion	78
3 RESEARCH METHODOLOGY	80
3.1 Introduction	80
3.2 Material description for processing particulate reinforced aluminium-11.8% silicon alloy based metal matrix composites	84
3.3 Analysis procedure	88



3.3.3	Procedure to fabricate the designed permanent metallic mold for pouring composite slurry mixture	92
3.4	Production methods of metal matrix composite materials	92
3.4.1	Particulate reinforced metal matrix composite casting fabrication by vortex liquid slurry mixing process	93
3.4.2	Characterization of particulates selected for this research work	94
3.4.3	Melting and casting of particulate reinforced metal matrix composites	99
3.5	Vortex mixing equipment and accessories	110
3.6	Composite casting process in action	115
3.7	Test description	122
3.8	Tensile testing of the prepared test samples	123
3.9	Testing procedure	125
3.10	Hardness measurement	126
3.11	Impact strength	127
3.12	Determination of electrical resistivity and electrical conductivity	128
3.13	Thermal diffusivity and thermal conductivity measurement	128
3.14	Thermal expansion (CTE) determination	130
3.15	Fracture mechanics studies	135
3.16	Metallography and microstructural research studies	140
3.17	Fracture surface analysis and interfacial bonding characterization by SEM	140
4	RESULTS AND DISCUSSION	142
4.1	Introduction	142
4.2	Properties and metallurgical aspects of LM6 alloy without grain refiner addition	144
4.3	Properties and metallurgical aspects of LM6 alloy with grain refiner addition	148
4.4	Comparison of properties and metallurgical aspects of graphite-particulate reinforced LM6 alloy composites against grain refiner added LM6 alloy	152
4.4.1	Metallography of graphite particulate reinforced aluminium-11.8% silicon alloy composite samples studied by a metallurgical microscope at different magnifications	166
4.5	Comparison of properties and metallurgical aspects of tungsten carbide and aluminium silicate particulate reinforced LM6 alloy hybrid composites against grain refiner added LM6 alloy	180
4.6	Comparison of properties and metallurgical aspects of quartz-particulate reinforced LM6 alloy composites against grain refiner added LM6 alloy	211
4.6.1	Metallography of quartz particulate reinforced aluminium-11.8% silicon alloy composite samples studied by a metallurgical microscope at different magnifications	227
4.7	Comparison of titanium carbide-particulate reinforced LM6 alloy matrix composites with LM6 alloy castings based on its properties and metallurgical aspects	248



4.7.1	Metallography of 12% titanium carbide particulate reinforced LM6 alloy composites	255
4.8	Interpretation and comparison of properties of different type of particulate reinforced LM6 alloy matrix composites	264
4.9	Conclusions	267
5	CONCLUSION	269
	REFERENCES	275
	APPENDICES	284
	BIODATA OF THE AUTHOR	368
	PUBLICATIONS	378



LIST OF TABLES

Table		Page
2.1	List of common matrix materials used in composites application	20
2.2	Some potential composite-reinforcement phase/materials and their applications	31
2.3	Features and application of metal matrix composites	39
2.4	Composition of Aluminium-11.8 percentage silicon alloy expressed in percentage	48
2.5	Mechanical, thermal and electrical properties of Aluminium-11.8% silicon alloy	49
2.6.	Properties of quartz	51
3.1	The weight ratio of graphite in Aluminium-11.8% silicon alloy	95
3.2	The weight ratio of combined tungsten carbide and aluminum silicate in Aluminium-11.8% silicon alloy	97
3.3	The weight ratio of Quartz in Aluminium-11.8% silicon alloy	98
3.4	The weight ratio of Titanium carbide in Aluminium-11.8% silicon alloy	99
3.5	Fracture behavior and fracture type	138
4.1	Mechanical properties of LM6 alloy without grain refiner addition	145
4.2	Mechanical properties of LM6 alloy without grain refiner addition	145
4.3	Hardness value of LM6 alloy without grain refiner addition	145
4.4	Density of LM6 alloy without grain refiner addition	145
4.5	Average Impact strength of LM6 alloy without grain refiner addition	146
4.6	Electrical resistivity and electrical conductivity of LM6 alloy without grain refiner addition	146
4.7	Average Electrical resistivity and electrical conductivity of LM6 alloy without grain refiner addition	146
4.8	Thermal diffusivity and conductivity of LM6 alloy without grain refiner addition	146



4.9	Mechanical properties of LM6 alloy with grain refiner addition	148
4.10	Mechanical properties of LM6 alloy with grain refiner addition	148
4.11	Hardness of LM6 alloy with grain refiner addition	149
4.12	Density of LM6 alloy with grain refiner addition	149
4.13	Impact strength of LM6 alloy with grain refiner addition	149
4.14	Electrical resistivity and conductivity of LM6 alloy with grain refiner addition	149
4.15	Average electrical resistivity and conductivity of LM6 alloy with grain refiner addition	150
4.16	Thermal diffusivity and conductivity of LM6 alloy with grain refiner addition	150
4.17	Mechanical properties of graphite particulate reinforced LM6 alloy composites	152
4.18	Mechanical properties of graphite particulate reinforced LM6	154
4.19	Hardness Vs weight fraction % addition of graphite	155
4.20	Density of graphite composites Vs Weight fraction % of graphite	156
4.21	Impact strength Vs Weight fraction % of graphite	157
4.22	Electrical resistivity and electrical conductivity Vs Weight	158
4.23	Average Electrical resistivity and electrical conductivity Vs Weight fraction % of graphite	158
4.24	Thermal diffusivity and thermal conductivity Vs Weight fraction % of graphite	159
4.24 A	Linear thermal expansion coefficient (CTE) Vs Weight fraction addition of graphite	164
4.24 B	Determination of fracture toughness value for graphite particulate reinforced LM6 alloy composites made in GCI mold	165
4.25	Mechanical properties of the processed hybrid composite	181
4.26	Mechanical properties of the processed hybrid composite	182
4.27	Hardness Vs weight fraction % of combined tungsten carbide and aluminium silicate	183

4.28	Density Vs Weight fraction % of combined tungsten carbide and aluminium silicate	184
4.29	Impact strength Vs Weight fraction % of combined tungsten carbide and aluminium silicate	185
4.30	Electrical resistivity and conductivity of combined tungsten carbide and aluminium silicate	186
4.31	Average Electrical resistivity and electrical conductivity of combined tungsten carbide and aluminium silicate	186
4.32	Thermal diffusivity and conductivity of combined tungsten carbide and aluminium silicate	187
4.32 A	Weight fraction percentage addition of combined tungsten carbide and aluminium silicate particulate Vs Linear thermal expansion coefficient (CTE)	191
4.32 B	Determination of fracture toughness value for the hybrid (aluminium silicate and tungsten carbide particulate reinforced) LM6 alloy composites made in GCI mold	192
4.33	Mechanical properties of quartz particulate composites	212
4.34	Mechanical properties of quartz particulate composites	214
4.35	Hardness Vs Weight fraction % of quartz	215
4.36	Impact strength Vs Weight fraction % of quartz	217
4.37	Thermal diffusivity and conductivity Vs Weight fraction % of quartz	219
4.37 A	Linear thermal expansion coefficient (CTE) Vs Weight fraction addition of quartz particulate	224
4.37 B	Determination of fracture toughness value for quartz particulate reinforced LM6 alloy composites made in GCI mold	225
4.38	Mechanical properties of titanium carbide composites	249
4.39	Mechanical properties of titanium carbide composites	249
4.40	Hardness Vs Weight fraction % of titanium carbide	250
4.41	Density Vs Weight fraction % of titanium carbide	250
4.42	Impact strength Vs Weight fraction % of titanium carbide	251

4.43	Electrical resistivity and conductivity Vs Weight fraction % of titanium carbide	251
4.44	Average value of electrical resistivity and conductivity Vs Weight fraction % of titanium carbide	251
4.45	Thermal diffusivity and conductivity Vs Weight fraction % of titanium carbide	252
4.45 A	Linear thermal expansion coefficient (CTE) Vs 12% addition of Titanium carbide particulate reinforced aluminium alloy composites (Ticalium)	254
4.45 B	Determination of fracture toughness for 12% titanium carbide particulate reinforced LM6 alloy composites	254

LIST OF FIGURES

Figure		Page
2.1	A sessile drop to the left is an example of poor wetting ($\theta > 90^\circ$) and the sessile drop to the right is an example of good wetting ($\theta < 90^\circ$)	36
2.2	Inverted trinocular metallurgical microscope	70
3.1	Flow chart describes the research plan to carry out this thesis work	82
3.2	Flow chart describes the particulate reinforced metal matrix composite casting fabricate on process	83
3.3	Aluminium-11.8% silicon alloy ingot	85
3.4	Grain refiner Aluminium-Titanium-Boron master alloy	85
3.5	Procured particulates in the containers	86
3.6	Samples of graphite, tungsten carbide, aluminum silicate, quartz and titanium carbide particulates	86
3.7	Leica inverted trinocular microscope	87
3.8	Composite slab product pattern	89
3.9	Permanent metallic molds	90
3.10	Steel mold	90
3.11	Copper mold (Vertically positioned)	91
3.12	Copper mold (Horizontally positioned)	91
3.13	Electronic balance	94
3.14	Induction melting furnace	100
3.15	Control panel of induction melting furnace	100
3.16	Complete induction furnace melting unit	101
3.17	Graphite crucible	111
3.18	Vortex mixing machine	111
3.19	Particulate preheating muffle furnace	112
3.20	Impeller blades used in this research project	112

3.21	Vortex machine impeller blade speed controlling unit	113
3.22	Particulate reinforced Aluminium-11.8 % silicon alloy matrix composite castings processed by vortex mixing method	113
3.23	View of composite castings processed in three different metallic molds	114
3.24	Preheated particulate is ready to disperse in the crucible containing liquid alloy matrix	115
3.25	Ready to start the composite casting process	116
3.26	Top view of the vortex machine set-up	116
3.27	Melting of aluminium-11.8% silicon alloy is starting	117
3.28	Full view of the composite casting process before starting	117
3.29	Permanent metallic molds are numbered as 1, 2 and 3 for identification	118
3.30	Checking the speed of the impeller blade	118
3.31	Mixing of the particulate in the melting furnace	119
3.32	Mixing of particulate in the metal well crucible of the induction-melting furnace	119
3.33	Vortex mixing in action	120
3.34	Mixing in action by the vortex machine impeller blade	120
3.35	Pouring the composite slurry mixture in grey cast iron mold	121
3.36	Pouring composite slurry mixture in steel mold	121
3.37	Pouring the composite slurry mixture in copper mold	122
3.38	Tensile Specimen BS specifications	123
3.39 (a)	Instron Universal testing machine	125
3.40	Mitutoyo Hardness testing machine	126
3.41	Mitutoyo hardness tester	127
3.42	Gunt Impact tester	127
3.43	Schematic sketch of a pushrod dilatometer to determine the linear	132

4.1	LM6 alloy without grain refiner poured in GCI mold - 50x	147
4.2	LM6 alloy without grain refiner poured in GCI mold - 100x	147
4.3	LM6 alloy without grain refiner poured in GCI mold - 200x	147
4.4	LM6 alloy with grain refiner poured in GCI mold - 50x	151
4.5	LM6 alloy with grain refiner poured in GCI mold - 100x	151
4.6	LM6 alloy with grain refiner poured in GCI mold - 200x	151
4.7	Tensile strength Vs Weight fraction % of graphite (GCI mold)	153
4.8	Yield stress Vs Weight fraction % of graphite (GCI mold)	153
4.9	Fracture stress Vs Weight fraction % of graphite (GCI mold)	154
4.10	Specific strength Vs Weight fraction % of graphite (GCI mold)	154
4.11	Specific stiffness Vs Weight fraction % of graphite (GCI mold)	155
4.12	Hardness Vs Weight fraction % of graphite (GCI mold)	156
4.13	Density Vs Weight fraction % of graphite (GCI mold)	156
4.14	Impact strength Vs Weight fraction % of graphite (GCI mold)	157
4.15	Electrical resistivity Vs Weight fraction % of graphite (GCI mold)	158
4.16	Electrical conductivity Vs Weight fraction % of graphite (GCI mold)	159
4.17	Thermal diffusivity Vs Weight fraction % of graphite (GCI mold)	159
4.18	Thermal conductivity Vs Weight fraction % of graphite (GCI mold)	160
Graph A	Weight fraction % of graphite addition Vs Linear thermal expansion coefficient (CTE)	163
Graph B	Weight fraction % addition of graphite Vs Fracture toughness, K _{1C}	165
4.19 A	1% Graphite particulate composite magnified at 50x (GCI mold)	167
4.19 B	1% Graphite particulate composite magnified at 50x (GCI mold)	167
4.20 A	1% Graphite particulate composite magnified at 100x (GCI mold)	168
4.20 B	1% Graphite particulate composite magnified at 100x (GCI mold)	168

4.21	2% Graphite particulate composite magnified at 50x (GCI mold)	169
4.22 A	3% Graphite particulate composite magnified at 50x (GCI mold)	169
4.22 B	3% Graphite particulate composite magnified at 50x (GCI mold)	170
4.22 C	3% Graphite particulate composite magnified at 50x (GCI mold)	170
4.22 D	3% Graphite particulate composite magnified at 50x (GCI mold)	171
4.22 E	3% Graphite particulate composite magnified at 50x (GCI mold)	171
4.23 A	% Graphite particulate composite magnified at 50x (GCI mold)	172
4.23 B	4 % Graphite particulate composite magnified at 50x (GCI mold)	172
Sample 1	Tensile fracture surface of 1% weight fraction of graphite composite made in grey cast iron mold magnified at 2000-x by SEM	174
Sample 2	Tensile fracture surface of 2% weight fraction of graphite composite made in grey cast iron mold magnified at 2000-x by SEM	175
Sample 3	Tensile fracture surface of 3% weight fraction of graphite composite made in grey cast iron mold magnified at 2000-x by SEM	176
Sample 4	Tensile fracture surface of 4% weight fraction of graphite composite made in grey cast iron mold magnified at 2000-x by SEM	176
Sample 5	Interface and bonding in 1% weight fraction of graphite composite made in grey cast iron mold magnified at 1500-x by SEM	177
Sample 6	Interface and bonding in 2% weight fraction of graphite composite made in grey cast iron mold magnified at 1200-x by SEM	178
Sample 7	Interface and bonding in 3% weight fraction of graphite composite made in grey cast iron mold magnified at 1500-x by SEM	179
Sample 8	Interface and bonding in 4% weight fraction of graphite composite made in grey cast iron mold magnified at 1200-x by SEM	180
4.24	Tensile strength Vs Weight fraction % of combined tungsten carbide and aluminium silicate (GCI mold)	181
4.25	Specific strength Vs Weight fraction % of combined tungsten carbide and aluminium silicate (GCI mold)	182
4.26	Specific stiffness Vs Weight fraction % of combined tungsten carbide and aluminium silicate (GCI mold)	183