UNIVERSITI PUTRA MALAYSIA

MECHANICAL AND TRIBOLOGICAL ENHANCEMENT OF AA6063 ALUMINUM ALLOY USING SOLID SPHERE FLY ASH PARTICLES REINFORCEMENT

ALAA MOHAMMED RAZZAQ

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By

ALAA MOHAMMED RAZZAQ

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

May 2018

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DEDICATION

This thesis is dedicated to:

The sake of Allah, my Creator and my Master,

My great teacher and messenger, Mohammed (May Allah bless and grant him and his family),

The memory of my parents, my late father and my late mother, whose prayers, support and dream.
My humble effort I dedicate to my sweet and loving Wife **(Roieda)**
I am grateful to her support ….
To my daughter (Wseq) and sons (Mohammed and Reda), whose prayers and wishes.

All the people in my life who touch my heart,

I dedicate this research.

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

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May 2018

Chairman : Dayang Laila Abang Abdul Majid, PhD
Faculty : Engineering

Fly ash (FA) has gathered widespread attention as a potential reinforcement for metal matrix composites (MMCs) to enhance the properties and reduce the cost of production. It is the most inexpensive and low density reinforcement available in large quantities as solid waste by-product. Aluminum alloys have been used in various engineering fields, such as automotive and aerospace industries, due to their low density and good mechanical properties. There is need to improve the performance of these alloys by adding reinforcements to extend their usage in many applications under wider service conditions. In this work, efforts are directed to improve the mechanical and tribological properties of AA6063 with solid sphere FA reinforcements. Relevant works were found to focus only on cenosphere FA particulates. There are many fabrication techniques available to manufacture these composites according to matrix and reinforcement materials. The compocasting technique for the fabrication of the AA6063 matrix composite reinforced with FA particles is the focus of this research. FA content, in the range of 0 –12 wt. % in increasing increments of 2% were added to the molten AA6063 alloy until they were completely blended and cooled down just below the liquidus to keep the slurry in the semi-solid state. Afterwards, the molten AA6063-FA composites were cast into prepared cast iron molds. Several techniques were used to evaluate the microstructure properties of these composites. The bulk density, porosity percentage and thermal properties of the composites were tested. This study also investigated the effect of FA addition on the mechanical properties of AA6063-FA composites. The effect of FA addition, applied load and sliding speed on the dry sliding frictional and wear behaviour has been considered in this study. Pin on disc test were conducted at different loads (24.5, 49, and 73.5 N) as well as the various sliding speeds using in this test (150, 200, and 250 rmp.) with a constant period time (10 minutes). The microstructural results showed good distribution of FA particles in the AA6063 matrix with interfacial bonding. The AA6063-FA composites exhibited good mechanical and tribological properties than the unreinforced AA6063 aluminum

alloy. The microhardness and the strength significantly increased with increase of FA content. While the impact energy and density decreased with increase in the FA content. The tensile strength of AA6063 alloy increased by 28 % with 10 wt. % of FA, the compression strength improved by 100 % with 10 wt. % of FA. Wear rate decreased with increase of FA content but increased with increase of sliding speed and applied load. The coefficient of friction declined with increase of FA content, sliding speed, and applied load.

The findings from the statistical analysis are the order of significance of the design parameters, which revealed the FA content as having the highest influence on the wear rate and coefficient of friction, followed by applied load and sliding speed. Addition to that, the strongest interaction effects is FA content with applied load. The models produced would be a useful tool in the process of AA6063-FA composites design, and can be used as a replacement for the expensive conventional experimental tests.

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

PENAMBAHBAIKAN MEKANIKAL DAN TRIBOLOGI BAGI ALOI ALUMINUM AA6063 DIPERKUKUHKAN DENGAN ZARAH ABU TERBANG BERSFERA PADU

Oleh

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Abu terbang (FA) telah menarik minat ramai sebagai satu potensi pengukuhan terhadap komposit matriks logam (MMC) dalam meningkatkan sifat-sifat dan mengurangkan kos pengeluaran. Ia merupakan bahan pengukuhan yang murah dan berketumpatan rendah yang wujud dalam kuantiti yang banyak sebagai produk sampingan sisa pepejal. Aluminum alloys have been used in various engineering fields, such as automotive and aerospace industries, due to their low density and good mechanical properties. Aloi aluminum telah digunakan dalam pelbagai bidang kejuruteraan seperti industri automotif dan aeroangkasa, kerana ketumpatannya yang rendah dan sifat mekanikalnya yang baik. Terdapat keperluan untuk memperbaiki prestasi aloi ini melalui penambahan pengukuhan untuk meningkatkan penggunaannya dalam banyak aplikasi di bawah keadaan perkhidmatan yang lebih meluas. Dalam kajian ini, usaha ditumpukan untuk memperbaiki sifat mekanikal dan tribologikal AA6063 diperkukuhkan dengan zarah abu terbang bersfera padu. Kajian yang berkaitan menumpukan kepada zarah abu terbang senosfera sahaja. Terdapat pelbagai teknik fabrikasi yang wujud dalam menghasilkan komposit sebegini berdasarkan kepada matriks dan bahan pengukuhan. Teknik penuangan kompo untuk proses fabrikasi komposit matriks AA6063 yang dikukuhkan dengan zarah FA merupakan fokus dalam kajian ini, Kandungan FA dalam julat berat 0-12 % dengan kenaikan 2% telah digunakan. Zarah FA telah ditambahkan kepada leburan aloi AA6063 sehingga campuran betul-betul sekata dan disejukkan di bawah takat cecair untuk mengekalkan bahan dalam keadaan separa-pepejal. Kemudian, komposit AA6063 yang dileburkan ditempa di dalam acuan besi tempa yang telah disediakan, Pelbagai teknik telah digunakan dalam menilai sifat mikrostruktur bagi komposit ini. Ketumpatan pukal, peratusan rongga dan sifat termal bagi komposit ini telah dikaji. Kajian ini turut menyelidik kesan penambahan FA terhadap sifat mekanikal komposit AA6063-FA. Kesan daripada penambahan FA, beban yang dikenakan dan kelajuan gelinciran terhadap gelinciran geseran kering dan kehausan telah dipertimbangkan di

dalam kajian ini. Ujian pin atas cakera telah dijalankan pada tahap beban yang berbeza (24.5, 49, dan 73.5 N). Kelajuan gelinciran yang berbeza turut digunakan di dalam kajian ini (150, 200, dan 250 rpm) dengan tempoh masa yang tetap (10 minit). Hasil yang diperolehi menunjukkan zarah FA disebarkan secara baik dalam matriks AA6063 dengan ikatan antara muka. Komposit AA6063-FA menunjukkan sifat mekanikal dan tribologi yang baik berbanding aluminum aloi AA6063 yang tidak dikukuhkan. Kekerasan mikro telah meningkat dengan ketara bagi semua peratusan kandungan FA, peningkatan kenaikan kekuatan regangan dan mampatan adalah terhad kepada 10% pecahan berat bagi zarah FA. Sementara itu, tenaga impak dan ketumpatan berkurang dengan penambahan kandungan FA. Kekuatan regangan aloi AA6063 meningkat 28 % dengan berat 10% FA. Kekuatan mampatan tanpa FA meningkat oleh 28 % dengan berat 10% FA. Kadar kehausan berkurangan dengan peningkatan kandungan FA, namun meningkat dengan pertambahan kelajuan gelinciran dan beban yang dikenakan. Pekali geseran menurun dengan peningkatan kandungan FA, kelajuan gelinciran dan beban yang dikenakan.

Penemuan dari analisis statistik adalah susunan kepentingan bagi parameter rekabentuk yang menunjukkan bahawa kandungan FA memberikan kesan yang paling tinggi ke atas kadar haus dan pekali geseran, diikuti dengan beban yang dikenakan dan kelajuan gelinciran. Selain itu, kesan interaksi yang paling tinggi/kuat adalah kandungan FA dengan beban yang dikenakan. Model yang dihasilkan akan menjadi alat yang berguna dalam proses rekabentuk komposit AA6063-FA, dan dapat digunakan sebagai pengganti bagi ujian konvensional yang mahal.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

min	Minute
rpm	Revolution per minute
ASTM	American Society For Testing and Materials
FA	Fly ash
Al	Aluminum
AA6063	AA6063 aluminum alloy
AA6063-FA	AA6063 aluminum alloy-fly ash composites
MMCs	Metal matrix composites
AMCs	Aluminum matrix composites
AMMCs	Aluminum metal matrix composites
Al-FA	Aluminum – fly ash
CTE	Coefficient of thermal expansion
Al_2O_3	Aluminum Oxide
SiC	Silicon Carbide
SiO_2	Silicon dioxide
B_4C	Boron carbide
Graphite	Gr
Cubic boron nitride	CBN
Hexagonal boron nitride	HBN
Titanium diboride	TiB_2
Carbon nanotubes	CNT
XRD	X-ray Diffraction
XRF	X-ray fluorescence

VPSEM	Variable Pressure Scanning Electron Microscope
EDX	Energy-dispersive X-ray
FESEM	Field-Emission Scanning Electron Microscopy
RSM	Response surface method
DRAMCs	Discontinuously reinforced aluminum matrix composites
CFA	Fly ash cenosphere
PFA	Fly ash precipitator
TGA	Thermogravimetric Analysis
UTM	Universal Testing Machine
MTS	Material testing system
LVDT	Linear variable differential transformer
YS	Yield tensile strength (MPa)
UTS	Ultimate tensile strength (MPa)
UCS	Ultimate compression strength (MPa)
SS	Semisolid-semisolid
SL	Semisolid-liquid

LIST OF SYMBOLS

θ	The contact angle measurement of the liquid-solid (Wettability)
γ_{sg}	Interfacial energies between solid and gas phase
γ_{sl}	Interfacial energies between solid and liquid phase
γ_{lg}	Interfacial energies between liquid, and gas phase
W_{ad}	Energy required to separate a unit area (J/m^2)
BHN	Brinell Hardness Number
F_n	The normal force
V_r	Relative velocity
T_o	The initial temperature
T_p	Thermal properties
M_p	Mechanical properties
Ch_p	Chemical properties
HRD	Rockwell Hardness
V_f	Volume fraction
A_n	Nominal contact area of the wearing source (mm^2)
H_o	Room-temperature hardness of the softer sliding member
A	Thermal diffusivity ($mm^2\ S^{-1}$)
r_o	The radius of the circular nominal contact area (mm)
W	Volume lost per unit area of surface per unit slide distance slide (mm^3)
P_n	Normal pressure applied between the surface (N/mm^2)
H	The hardness (MPa)

K	The Archard's wear coefficient is dimensionless, always less than unity
W_r	Wear rate (mm^3/m)
F_r	Coefficient of friction
D_m	Dry mass
S_m	The mass of the test specimen after soaking
M_s	Saturated mass
Ve	Exterior volume
B	Bulk density
ρ	Apparent porosity
ρ_{FA}	Al-fly ash composites density ($gram/cm^3$)
M	Composite sample mass in air (gram)
m_1	Composite sample mass in distilled water (gram)
ρ_{H2O}	Distilled water density
Δl	Change in length (mm)
L_0	Original test piece length (mm)
α	Mean linear thermal expansion coefficient (K^{-1})
W_i	Wear rate function
T_1	Reference temperature (°C or °K)
T_2	Test temperature (°K)
σ_t	Tensile strength (MPa)
F_t	Tensile force N
A	Cross sectional area (mm^2)
ε	Strain
σ_c	Compression strength (MPa)

F_c	Compression force N
H_v	Vickers microhardness (MPa)
Wp	Weight of pendulum (Kgf)
g	Gravitational acceleration (m/s^2)
r	Distance from axis of rotation to center of gravity of pendulum (m)
α_1	Angle of fall of pendulum
β	Angle of rise of pendulum in its swing after breaking test sample
μ	The coefficient of friction
F_T	Tangential force (N)
F_N	Normal force (N)
V	Volume loss (mm^3)
S	Sliding speed (rpm)
L	Applied load (N)
W_{rp}	Predicted wear rate
F_{rp}	Predicted coefficient of friction
W_{re}	Experimental wear rate
F_{re}	Experimental coefficient of friction
W_{ra}	Average of experimental wear rate
F_{ra}	Average of experimental coefficient of friction
Vol.%	Percentage of volume fraction
Wt. %	Percentage of weight fraction

CHAPTER 1

INTRODUCTION

1.1 Introduction

Over the past decades, the demand for light weight structural materials has increased rapidly, especially in the automotive and aerospace industries. In recent times, aluminum alloys have gained wide acceptance in such applications owing to its properties and comparative advantages such as lightweight, good machinability, and energy efficiency-low power consumption. Aluminum AA6063 alloy is widely employed for construction and transportation applications [1]. As a base line material, it possesses good formability, weldability, machinability, and corrosion resistance, as well as a medium strength relative to other grades of aluminum alloys [2, 3]. However, with a view to implementing them as high performance materials for use in the aerospace, automobile, chemical and transportation industries it is essential to improve the strength, elastic modulus and wear resistance of the AA6063 alloy over the conventional base [4].

In spite of their attractive properties, AA6063 alloy has not been able to completely satisfy the overall requirements in applications such as automotive industry. For instance brake discs drums and rotors, pistons, automobile drive shafts, brake discs for railway applications, fan exit guide vanes, and blade sleeves for aerospace applications, are required to withstand high mechanical, thermal stresses during their service lives and also under tribological conditions. In order to overcome these drawbacks and to meet the ever increasing demand of modern day technology, composite materials have been proposed as the most promising candidate. With the inclusion of high strength and high modulus refractory particles such as SiC, TiC, B4C, Al2O3, MgO, TiO2, etc.to a ductile metal matrix, a material whose mechanical property lies between that of the matrix alloy and the ceramic reinforcement is generated [5-8].

Among the liquid phase processing methods, the stir casting is an attractive processing method to produce aluminum matrix composites (AMCs). It has salient features, a cost-effective manufacturing processes (relatively inexpensive) and offers a wide selection of materials, and processing conditions and fit for mass production without damaging the reinforcement particles [9]. Compocasting technique is adopted over the stirring process as this eliminates wettability problem of particles and results in better properties of AMCs [10].

1.2 Background

Specific material property requirements for application have highly increased, making several conventional alloy systems inappropriate. Metal matrix composites (MMCs) are new generation materials with a strong ceramic reinforcement incorporated into the metal matrix to improve its properties. MMCs combine metallic properties of matrix alloys (ductility and toughness) with ceramic properties of reinforcements (high strength and high modulus), leading to greater strength in shear and compression and higher service-temperature capabilities [11, 12]. In contrast to monolithic alloys, MMCs possess significantly improved properties such as high specific strength, high stability at elevated temperatures, lower coefficients of thermal expansion and good wear resistance [13]. Moreover, the remarkable physical and mechanical properties of the aluminum metal matrix composites (AMMCs) have made these materials attractive for applications in the aerospace and automotive industries, thermal management areas and industrial products etc. [13-15].

Meanwhile, out of the various types of MMCs, particulate reinforced composites in particular, the particulate reinforced aluminum matrix composite have aroused the interest of experts in the field owing to their low cost with advantages like isotropic properties and the possibility of secondary processing facilitating fabrication of secondary components [16]. Ceramic materials such as Al_2O_3, SiC, SiO_2, and B_4C have been reported as suitable reinforcement particles. Then seen from recent research endeavors and increasing awareness towards nurturing a green environment, fly ash (FA) has aroused the interest of researchers as promising reinforcement candidate due to its low density, economic viability and availability in commercial quantity.

In their work, Ramachandra, M. and Radhakrishna [17] observed an increase in the wear resistance of AMCs with increasing FA content, but decreases with increase in normal load and sliding velocity. More so, they observed that the corrosion resistance decreased with increasing FA content. FA as a filler has proven suitable for mechanical, physical and tribological properties enhancement including hardness, stiffness, wear and abrasion resistance as well as decrease density. Furthermore, it also improves the maintainability, damping capacity, and coefficient of friction which are most desirable in automotive and industrial applications [16, 18-23].

Notably, the mechanical properties of composites can be controlled by the properties of the constituent phases, relative amount and dispersed phase geometry including particle size, shape and orientation in the matrix [14, 24, 25]. Meanwhile, it has been observed thus far, that the particle size and weight fraction of the reinforcement phase in metal matrix composites influences the formation of dislocations due to thermal mismatch and the concurrent development of residual and internal stresses. Also worthy of note is that the metal matrix composites have remarkable benefits owing to the combined metallic and ceramic properties, thereby yielding improved physical and mechanical properties [26-28].

From the existing literature, the casting technique has been showcased as the most preferred choice for aluminum MMCs fabrication. In particular, the stir casting technique is economically viable and also promotes the distribution of the particulate reinforcement along the grain boundaries of aluminum melt. With a view to homogenizing the matrix material with the reinforcement particles, mechanical stirring of the composite is performed by a stirring bars, and then poured in a mould for solidification. By investigating the effect of the three different stir casting methods on the properties of FA reinforced Al-7Si-0.35Mg alloy, Rajan et al. [29] reported that the dispersion of FA particles were more effective in compocasting method than in liquid metal stir casting due to the shearing of FA particles by the solid primary phases existing in semisolid slurry. Using the stir casting method, Shirvanimoghaddam et al. [30] investigated the influence of processing temperature on the mechanical properties of aluminum composites reinforced with micron-sized particles. They observed significant improvement 125% increase in the hardness and 52% in tensile strength.

Anilkumar et al. [20] prepared Al6061 reinforced with FA through the utilization of the stir casting technique and concluded that the tensile strength increased with increasing weight percentage of FA. Their finding was attributed to the role played by the hard FA particles during sample failure as barriers to the advancing dislocation front, thus strengthening the matrix. Similarly, the good bonding of smaller size FA particles with the matrix was also reported as an additional factor for this behaviour. However, the authors observed a decrease in the tensile strength beyond the 15 wt% mark of FA reinforcement due to the poor wettability of the reinforcement with the matrix in this sample formulations. Meanwhile, the particle size increase of the FA has been reported to promote mechanical property deterioration in AMCs [31]. By employing the compocasting technique, Ervina et al. [13] successfully incorporated FA into the semi-solid state of LM6 melt to fabricate FA reinforced aluminum composites. Selvam et al. [32] observed that the addition of FA particles enhanced the microhardness and tensile strength of the AMCs. Moreover, FA ash particles are thermodynamically stable at the applied casting temperature. Hence, the interface between the aluminum matrix and FA particle was clear and the bonding was proper. More so, no interfacial reaction was observed between FA particles and aluminum matrix during the casting process. The processing temperature for the compocasting method is considerably low as compared to the stir casting method which is insufficient to initiate interfacial reactions. In addition the incorporation of FA particles into semi-solid aluminum alloy was observed to have improved the wettability.

Recently, most of the existing literature in this field of study have focused more on the aluminum alloy based composites, such as A357, A359, 2618, 2214, 6061 and 7075 [33-35]. However, the use of AA6063 as a base material for the development of Al matrix composites is rarely reported [36, 37]. Relative to other aluminum alloys, the AA6063 alloy is often available in commercial quantity in the metal markets of most developing countries [38]. However, one of the major drawbacks of these materials is their low strength and wear resistance. This limitation is due to the fact that AA6063 alloy undergo extensive plastic deformation and material removal under sliding wear conditions[39]. The FA particles collected by electrostatic precipitators from the exhaust gases in thermal power stations[40]. Solid FA particles can be used as reinforcement material. Relevant works [41, 42]were found to focus only on cenosphere FA particulates. Hence, this research investigates the physical, thermal, mechanical, and tribological properties of AA6063-FA composite after fabrication with the compocasting method.

1.3 Problem Statement

The AA6063 alloy doesn't always provide the required properties under all service conditions which is overcome by reinforcing this alloy with ceramic particles. Meanwhile, the high cost and limited supply of conventional ceramic materials are the major setbacks encountered especially in most developing countries where the development of discontinuously reinforced aluminum matrix composites [43] is yet to be fully explored. Despite their potential benefits in weight reduction, increased composites life and improved recyclability, the high cost of the present day MMCs compared to aluminum alloys has inhibited the large scale production of these composite materials in areas such as the automotive industry and specialized applications [26, 42, 44]. Hence, it becomes imperative to promote the economic viability of these group of materials by utilizing cheaper reinforcements. With a view to overcoming this limitation, several research and development programs have focused on the improvement of aluminum-based MMCs using low cost industrial wastes as the reinforcement particulate [45, 46].

Currently, waste materials from rice husk ash, red mud, FA has attracted the interest of several researchers as inexpensive reinforcement particles for the fabrication of AMCs [13, 43, 47]. Meanwhile, FA a solid waste byproduct during the combustion of coal has been considered as one of the most inexpensive and low density reinforcement available in commercial quantity [13, 16, 48]. So far, many studies have reported that the Al-FA composites can adequately increase the hardness, strength, and stiffness while decreasing the density of an unreinforced alloy [13, 32, 49-51]. More so, they are also capable of improving the wear resistance and coefficient of friction which are desirable parameters in automotive and industrial applications [52]. This also solves the storage problems of FA as well as brings down the production cost, giving an economical and eco-friendly solution. Thus far, studies on aluminum–FA composites have shown great prospects in various applications.

Literature reveals that most of the researchers are using AA6063 alloy matrix reinforced with several types of reinforcement for high properties whereas, insufficient information is available on reinforcement of FA particles in AA6063 alloy matrix. Hence, it becomes imperative to study the effect of FA addition on the physical, thermal, mechanical, tribological properties of AA6063 alloy and also to develop a benchmark of property data which can be employed in evaluating these materials for future use.

1.4 Objectives

The main objective of this experimental research work is to develop AA6063-FA composite and investigate the effect of FA as a particulate reinforced AA6063 alloy matrix composites produced by compocasting technique. The specific objectives are as follows:

- To analyze the microstructural features and particulate distribution uniformity of FA particles in the AA6063-FA composite using VPSEM.
- To investigate the physical, thermal, and mechanical properties such as bulk density, apparent porosity, thermal expansion, tensile strength, compressive strength, hardness, and impact, for AA6063 alloy and AA6063-FA composite with different percentage of FA.
- To evaluate the FA addition, applied load and sliding speed on tribological behaviour of AA6063 alloy and AA6063-FA composite.
- To perform fracture mechanics studies and hence analyze the metallurgical and fracture surface as well as to characterize interfacial bonding.
- To develop mathematical models (wear rate, and coefficient of friction) and predict the relationship between the FA content, applied load, sliding speed and wear behavior.

1.5 Scope and Limitation

In this research, AA6063 alloy is used as a matrix material due its better fluidity and castability with good mechanical properties. AA6063 belongs to aluminium 6000 series which contains Silicon as a major alloying element in the aluminium metal matrix and therefore, this study is limited within these range of aluminium alloy only. With regard to FA particulate types, this work only focus on fly ash with solid sphere as the major component. The present investigation has been focused on utilization of different weight fraction of waste FA as reinforcement material. The range of weight fraction of 2% up to 12% were considered due to research findings that suggested higher percentages will pose agglomeration problems, reduction in toughness and impact performance.

The compocasting is employed without agents to manufacture the composite material by addition of FA after preheated at 900°C and the casting process temperature reduced to 600°C a stirring speed of 300 rpm were found to be best in order to produce uniform distributions of FA.

This research is interested in the measurement of physical properties, thermal properties, mechanical properties and tribological behaviour of AA6063 the as well as microstructure of the raw and composite materials.

1.6 Thesis layout

This thesis is divided into five chapters that cover systematically the whole work as follows:

- Chapter 1; provides a general overview of current research efforts to produce inexpensive aluminum composites with short background of the AL-FA composites with possibly, the motivation of the research, the statement of problem, the objectives of the research, and the layout of this thesis.
- Chapter 2; presents a scientific literature review and previous work focused on the researches dealing with the issue of Al-FA composites and its production. It also discusses FA effect on physical, mechanical and tribological properties of aluminum metal matrix composites (MMCs).
- Chapter 3; presents materials, experimental procedures and statistical methods.
- Chapter 4; this chapter is divided into two main sections. The first, discusses the experimental results obtained from this work, and second, describes the development of the mathematical models with ANOVA of wear rate and coefficient of friction.
- Chapter 5; summarizes the conclusions emanating from the results presented in Chapter 4, looking back at the various topics touched upon this thesis, attempting to objectively evaluate the results obtained. The recommendations for future work in terms of both possible improvements and new research directions are described.

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