THERMO-MECHANICAL ANALYSIS OF MULTIPLE PARTICLE SIZE REINFORCED SILICON CARBIDE PARTICLE ALUMINIUM MATRIX COMPOSITE BRAKE ROTOR

BY

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ABSTRACT

Braking action is recognized as one of the challenges in automotive industries as a result of frictional heat generated on the interface between brake rotor and pad. This process results to high temperature which induces several undesirable conditions such as, thermal deformation and permanent distortion resulting in braking deficiency. The application of advanced materials with improved processing technique is required to tackle these challenges for brake rotor production. In this work, multiple particle size (MPS) reinforced silicon carbide particulate (SiCp) is incorporated into aluminium matrix as reinforcement phase in order to develop a light weight automotive composite brake rotor using the novel stir casting process. Finite element (FE) and actual braking analyses were performed by considering the influence of material type, particle size variation and volume fraction on mechanical and thermal performance stability. This study covers the effect of incorporating MPS-SiC in developing aluminium matrix composite (AMC) by evaluating the microstructural and mechanical properties when compared to 6061 aluminium alloy and commercial cast iron. Actual braking test was performed using a passenger car (Proton Wira 1.3) brake system rig set up and a high speed infrared (IR) camera to capture thermal distribution on the rotor surface. It was found that the microstructural and mechanical properties of MPS-SiCp AMC were influenced by varying the 20 wt% SiC particle size in the aluminium matrix. The microstructural analysis revealed a uniform distribution of the MPS-SiC reinforced particulate in the matrix which in turn improves density and tensile strength value. The tensile strength recorded an increment of 45.8 % and 10.2 % when compared to matrix alloy and cast iron material respectively. However, the ductility reduced due to particle reinforcement. The wear rate of cast MPS-SiC AMC is lower compared to the matrix alloy and cast iron used for various type of commercial brake rotor material as revealed from previous studies. Moreover, the friction coefficient is between 0.31 to 0.44, which is observed to be within the deviation band for automotive brake system application according to the industrial standard range. On the other hand, the actual braking test for 2 MPa pressure application on the rotor contact surface revealed an average temperature of 265.1 °C and 351.6 °C for the MPS-SiC AMC and cast iron rotors respectively indicating a significant thermal difference of ~25 %. It can be therefore concluded that AMC improved heat dissipation as a result of high thermal conductivity compared to cast iron thereby avoiding undesirable effects caused at high temperature. Moreover, a good agreement was achieved for thermal profile analysis between the simulation and actual braking results which did not exceed 5.5 % for the AMC brake rotor. Conclusively, the light weight MPS-SiC AMC has successfully improved the thermal and mechanical performance of the newly fabricated AMC brake rotor.

ملخص البحث

تعتبرإجراءات كبح الفرامل من التحديات التي تواجه مصنع السيارات بسبب الحرارة الناجمة عن التفاعل بين دوار الفرامل والوسادة. وهذه العملية تؤدي إلى إرتفاع درجة الحرارة الذي ينتج منه ظروف غير مرغوب فيها، مثل تشوه الحرارية تشويها دائما مما يؤدي إلىالعجز في الكبح.إن تطبيق المواد المتقدمة مع تحسين تقنية المعالجةاًمطلوب لمواجهة هذه التحديات التي تواجه إنتاج الفرامل. في هذا البحث، قد تم تعزيزعدة حجم الجسيمات (MPS) وكربيد السيليكون جسيم (SiCp) وتم دمجها في مصفوفة من الألمنيوم من أجل تطوير صناعة السيارات الخفيفة الوزن والفرامل باستخدام رواية إثارة عملية الصب و عنصر (FE) لتحليل الكبح من خلال النظر في تأثير نوع المادة والجسيمات واختلاف الحجم ونسبة الحجم على استقرار أداء السيارات الميكانيكية والحرارية .وتتناول هذه الدراسة أثر دمج-MPS كربيد الألومنيوم في تطوير مصفوفة مركب (AMC) من خلال تقييم الخصائص المجهرية والميكانيكية بالمقارنة مع سبائك الالومنيوم 6061 و الحديد التجارية.وقد تمت التجربة الحقيقية لكبح الفرامل باستخدام سيارة بروتون ويرا (1.3) وتلاعب بنظام إعداد عالية السرعة (IR) وآلة التصوير(الكاميرا) لإلتقاط التوزيع الحراري على سطح الدوار. وتبين ان تأثر خصائص المجهرية والميكانيكية من MPS-SiCp AMC من خلال تغييرالعشرين بالمائة من وزن كربيد حجم الجسيمات في المصفوفة الألومنيوم. وكشف تحليل المجهرية توزيع موحد للجسيمات-MPS كربيد المسلحة في المصفوفة وهذا بدوره يحسن قوة كثافة وقيمة الشد. وسجلت قوة الشد زيادة قدرها45.8 ٪ و10.2 ٪ بالمقارنة مع سبيكة مصفوفة و مادة الحديد على التوالي. ومع ذلك،وقد انخفضت ليونة بسبب تعزيز الجسيمات. وكان معدل البلى من الزهر-MPS كربيد AMC أقل بالمقارنة مع سبيكة مصفوفة والحديد الزهر المستخدمة لنوع مختلف من مواد الفرامل التجارية كما كشفت في الدراسات السابقة .وعلاوة على ذلك، فإن معامل الاحتكاك بين0 ،0-31،44، الذي يتم الاحتفال به ليكون ضمن فرقة الانحراف عن فرامل السيارات تتطلب تطبيق النظام وفقا لمجموعة من المعايير الصناعية النموذجية. ومن جهة أخرى، كشف الاختبار الكبح لمدة 2 ميغاباسكال تطبيق الضغط على السطح الاتصال الدوار يبلغ متوسط درجة الحرارة من265 ، 1درجة مئوية و351 ، 6 درجة مئوية ل-AMC MPSكربيد الحديد الزهر والدوارات على التوالي مشيرا إلى اختلاف كبير الحرارية من ~ 25 ٪ .ويمكن أن نستنتج من ذلك أن AMC تبديد الحرارة تحسن نتيجة لموصلية الحرارية العالية مقارنة مع الحديد الزهر وبالتالي تجنب ظروف غير مرغوب فيها في درجة حرارة عالية. وعلاوة على ذلك، تم التوصل إلى اتفاق جيد لتحليل الشخصية الحرارية بين المحاكاة والنتائج الفعلية للكبح التي لم تتجاوز5.5 ٪ لفرامل الدوار. وأخيرا - MPS فإن AMC خفيفة الوزن كربيد AMC قد نجحت في تحسين الأداء الحراري و الميكانيكي لدوار فراملAMC حديثة الصنع.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion; it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Masters of Science (Materials Engineering).

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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Signature.................................. Date....................................

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Affirmed by Adebisi Adetayo Abdulmumin

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Signature Date

To my beloved parents

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LIST OF ABBREVIATIONS

Al	Aluminium
Al_2O_3	Aluminium oxide
AMC	Aluminium matrix composite
ASTM	American society for testing and materials
BF	Brake factor
BP	Brake power
CAE	Computer aided engineering
CFD	Computational fluid dynamics
CGI	Compact graphite iron
CPU	Central processing unit
CTE	Coefficient of thermal expansion
DENS	Density
DOF	Degree of freedom
DPS	Dual particle size
EDS	Energy-dispersive X-ray spectroscopy
EX	Young`s modulus
FEA	Finite element analysis
FESEM	Field emission scanning electron microscope
FeC	Iron carbide
Fe_2O_3	Iron oxide
FEM	Finite element method
GFN	Grain fineness number
GUI	Graphical user interface
ICDD	International centre for diffraction data
IIUM	International Islamic University Malaysia
IR	Infra red
MMC	Metal matrix composite
MPS	Multiple particle size
NUXY	Poisson’s ratio
SiCp	Silicon carbide particle
SPS	Single particle size
TEI	Thermo elastic instability
TPS	Triple particle size
XRD	X-ray diffraction

LIST OF SYMBOLS

a	Deceleration of vehicle
A_{mcp}	Area of master cylinder
A_s	Surface area
A_{wc}	Wheel cylinder area
d	Distance travelled
d_c	Minimum stopping distance
D	Diameter of brake rotor
ε	Emissivity
E	Kinetic energy
F_{bf}	Brake factor for front wheel
F_{br}	Brake factor for rear wheel
F_{bt}	Total brake factor
F_p	Pedal force
g	Deceleration due to gravity
h_t	Convective heat transfer
k	Thermal conductivity
k_a	Thermal conductivity of air
m	Vehicle weight
n	Revolution per minute
η_c	Wheel cylinder efficiency
η_L	Pedal lever efficiency
σ	Stephan-Boltzmann

ρ_a	Density of air
p	Pedal actuation
p_o	Push out pressure
q_{cond}	Heat transfer conduction
q_{conv}	Heat dissipation convection
q_{rad}	Heat dissipation by radiation
r	Radius of pin
r_d	Radius of disc
r_L	Pedal lever ratio
R_e	Reynolds number
R_T	Radius of tyre
t_s	Solidification time
t	Time
t_b	Time to stop vehicle
T_i	Inside temperature
T_o	Outside temperature/ambient temperature
T_s	Temperature of brake rotor surface
μ_a	Viscosity of air
μ_r	Adherence coefficient
v	Speed of vehicle
V	Velocity of air
V_o	Initial velocity
W_r	Wear rate
Δw	Weight loss

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The demand for efficient use of energy and materials is being considered strongly because of diminishing resources in the present times. There has been an important role of materials in the development of advanced technology. In the transportation industry, automobile parts made from steel and iron are known to be very bulky compared with today's light weight vehicles. Iron, copper and their alloys have been utilized for thousands of years for structural applications until last century when the bauxite ore known as the main provider of aluminium was discovered as the second most abundant ore in the earth crust. Its properties make it to become an economic competitor to steel and cast iron for structural applications because of its excellent combination of lower density, lightweight, high thermal conductivity, high coefficient of thermal expansion (CTE), good corrosion resistance and higher ductility etc. However, the poor mechanical and tribological properties of aluminum limit its wider range of usage.

Realizing the potential as well as availability of aluminum, considerable efforts are being made to explore the possibilities of improving the mechanical strength and wear resistance so as to meet the requirements of various applications. More aluminum is being consumed recently (Miller, Zhuang, Bottema, Wittebrood, De Smet, Haszler and Vieregge, 2000) than all other non ferrous metals and alloys. The transformation of the automobiles requiring more fuel, frequent maintenance and also endangers the environment to the energy efficient automobiles requiring lesser maintenance and which is also environment friendly has resulted from better advanced engineering materials (Telang, Rehman, Dixit and Das, 2010). With the advent of lighter weight efficient material technology, the automobiles industry undertook a shift towards aluminum alloy cars; in order to improve the mechanical strength and modulus properties of aluminum. This can be achieved by alloying various elements such as Cu, Zn, Mg, Si, Mn etc. (Polmear, 1995).

Amidst the various aluminum alloys, the following are found to show tremendous improvement and find application in automobile structural components; Al-Zn-Mg alloys exhibit improvement in mechanical strength, Al-Mg cast alloys show excellent corrosion resistance, good machinability and attractive appearance when anodized. In automotive parts, Al-Si alloys are used extensively because of their properties like low CTE, bearing properties, good corrosion resistance in association with the strength and stiffness and significant weight reduction.

Composite materials consist of at least two chemically and physically distinct phases suitably distributed to provide properties not obtainable with either of the two individual phases. It signifies that two or more constituents are combined on microscopic scales to synthesize a useful material. A variety of materials can be combined on a microscopic scale. The advantage of the composite materials is that their individual constituents retain their characteristic unlike alloys. As a result, various combinations of useful properties, usually not attainable by alloys, can be obtained through composite materials by suitable tailoring the matrix and reinforcement. The reinforcement phase particles may be either harder or softer than the matrix alloy and affect the properties of the composites accordingly. The softer dispersoids like graphite, talc, mica shell etc. impart solid lubricating properties wherein the total wear resistance of the material improves (Das and Prasad, 1993). In this case, other properties such as strength, hardness etc. of the composites is less than that of the matrix alloy. However, they have been found to be within acceptable limits as confirmed through some experiments (Prasad, 1991). The reinforcement of hard ceramic particles like silicon carbide, alumina, silica, zircon etc. in aluminium alloys has been found to improve the wear resistance as well as high temperature strength and stiffness properties (Gupta, Dan and Rohatgi, 1986).

Metal matrix composites (MMC) compared to other composite is a material in which continuous metallic phase (the matrix) is combined with another phase (the reinforcements) to strengthen the metal and increase high-temperature stability. The reinforcements are typically ceramic in the form of particles, fibers or whiskers. The metals are typically, aluminium alloys, magnesium alloys, zinc alloys, copper alloys or titanium alloys. They have become attractive for engineering structural applications due to their excellent specific strength property and their properties can be determined by varying the nature of constituents and their volume fraction.

The utilization of MMC has increased in various areas of science and technology due to their special mechanical and physical properties. MMC, particularly aluminium based composites have a high strength to weight ratio, high stiffness, lower CTE, high thermal conductivity, as well as corrosion and wear resistance. Therefore MMC have the potential to replace conventional materials in various fields of application such as automotive, as well as in others advanced industries because of its properties.

MMC is accepted as an alternative candidate material because of its enhanced stiffness, strength, and weight reduction. The addition of strong ceramic reinforcement is incorporated into the metal matrix to improve its properties including specific strength, specific stiffness, wear resistance, corrosion resistance and elastic modulus

(Humphreys, Miller and Djazeb, 1990). MMC combine metallic properties of matrix alloys (ductility and toughness) with ceramic properties of reinforcements (high strength and high modulus), which translate to greater strength in shear and compression and higher service-temperature capabilities (Ajayan, Schadler, Braun and Picu, 2003). Thus, it provides significant technology and commercial importance to various institutions and industries. Other important characteristics include the immense value of wear resistance achieved for structural applications e.g., in WC/Co composites used in cutting tools or oil drilling inserts and SiC_p Al rotor in brakes.

Aluminium matrix composite (AMC) is a broad family of composite materials aimed at achieving an enhanced combination of properties and this can be attained by selecting different reinforcing phases. In addition to the matrix microstructure, reinforcing phase also controls the characteristics attainable by the MMCs (Terry and Jones, 1990). Matrices reinforced with high modules short fibres, whiskers or particulates have improved strength and stiffness and are isotropic in nature. This variety of the composites is less expensive to produce. In the case of continuous fibre or whiskers with high aspect ratio (length /diameter), to align fibres in the desired stress direction and to transfer the applied load to the fibres the matrix serves to hold them together. The mechanical properties of the composites are dependent upon the efficiency of the matrix in transferring the load to the reinforcement fibres and are therefore related to the quality of the fibre/matrix interfacial bonding. This type of composites exhibits significantly higher strength and stiffness. But they are non-isotropic in nature and are expensive. Aluminium and its alloys form the most widely investigated matrix for use in MMC. This popularity of Al-alloy as a matrix material can be attributed to its low cost relative to other light structural metals such as Mg, Ti, etc. its current dominance is on automotive component and other structural application and so on. There are two types of reinforced metal matrix composite:

i. Discontinuously reinforced (short fibre, whisker and particulate)
ii. Continuously reinforced (long continuous fibre reinforced).

Particle or discontinuously reinforced MMCs (the term discontinuously reinforced MMCs is commonly used to indicate metal matrix composites having reinforcements in the form of short fibers, whiskers, or particles) have assumed special importance for the following reasons (Chawla and Chawla, 2006):

i. Particle reinforced composites are inexpensive vis-a-vis continuous fiber reinforced composites. Cost is an important and essential parameter, particularly in applications where large volumes are required (e.g. automotive applications).
ii. Conventional metallurgical processing techniques such as casting or powder metallurgy, followed by conventional secondary processing by rolling, forging, and extrusion can be used.
iii. Enhanced modulus and strength.
iv. Increased thermal stability.
v. Higher wear resistance.
vi. Relatively isotropic properties compared to fiber reinforced composites.

Aluminium matrix are usually reinforced by SiC, Al_2O_3, C but TiB_2, BeO, BN, B_4C, SiB_6, Cr_3C_2, Gr, TiB, TiC, Si may also be considered (Evans, Marchi and Mortensen, 2003). Figure 1.1 and Figure 1.2 show that the usage of aluminium as matrix and SiC as particle reinforcement materials is mostly utilized for composite material application (Evans et al., 2003).

Earlier works on composites reported that the continuous fibre reinforcement composites are very expensive and hence limit their applications (Bhansali and

Mehrabian, 1982). The cost of continuous fibres, complex fabrication technique, and production volume restricted the use of composites for high performance applications. These led to the development of discontinuously reinforced composites, particularly short staple Al_2O_3 fibre, TiB_2 and SiC whiskers reinforced composites (Prasad, Dan and Rohatgi, 1993; Dhokey and Rane, 2011). Discontinuous fibre has found commercial application as selective reinforcement in the ring land area of diesel piston (Smallman and Bishop, 1999) and whisker reinforcement is under development for aerospace applications.

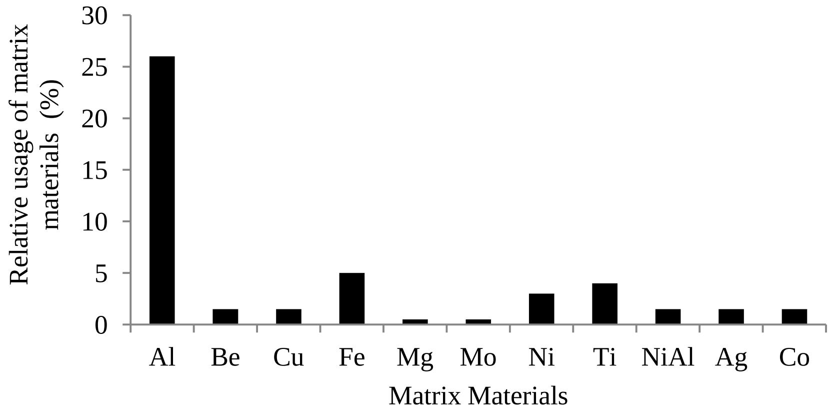

Figure 1.1: Usage of matrix materials (Evans et al., 2003)

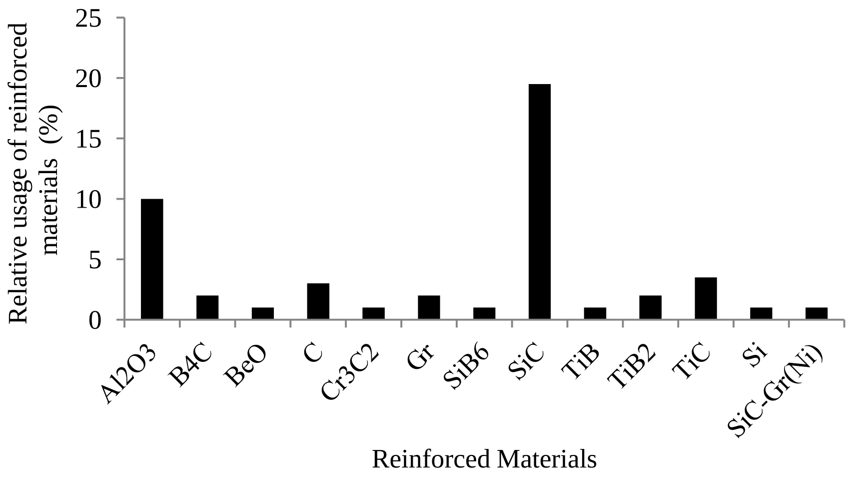

Figure 1.2: Usage of particulate reinforced materials (Evans et al., 2003)