



**The Effects of Alumina on The Hybrid
Microwave Sintered Ferum-Chromium
Metal Matrix Composites**

by

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LIST OF ABBREVIATIONS

BD	Bulk Density
TP	Total Porosity
MH	Micro Hardness
KML	Komposit Matriks Logam
MMCs	Metal Matrix Composites
PM	Powder Metallurgy
NDT	Non-Destructive Testing
IR	Infra-Red
MW	Microwave
EF	Conventional Electric Furnace
BCC	Body-Centered Cubic
FCC	Face-Centered Cubic
TRS	Transverse Rupture Strength
VHN	Vickers Hardness Number
M	Microwave Sintering
C	Conventional Sintering
RH	Rockwell Hardness
UTS	Ultimate Tensile Strength
HRB	Rockwell Hardness measured on the B scale
HEAs	High-Entropy Alloys
MSDS	Material Safety data sheet
HCCL	High Chromium Cast Iron
SEM	Scanning Electron Microscope
EDS	Energy Dispersive Spectroscopy
rpm	rotation per min
XRD	X-Ray diffraction
SS304	Stainless Steel 304
SE	Secondary Electron
HRA	Rockwell Hardness measured on the A scale

LIST OF SYMBOLS

m	meter
cm	centimeter
mm	millimeter
μm	micrometer
nm	nanometer
gm	gram
ppm	part per million
W	Watt
min	minute
HV	Vickers Pyramid Number
$\sum X$	X score sum
$\sum X^2$	square of X score sum
$\sum XY$	Sum of paired product
$\sum Y$	Y score sum
$\sum Y^2$	square of Y score sum
$^{\circ}\text{C}$	Celsius
Al	Aluminium
Al_2O_3	Alumina
Al- Al_2O_3	Aluminium-Alumina
Al-G	Aluminium-Graphite
Al-SiC	Aluminium-Silicon Carbide
CNT	Carbon Nanotube
Cr	Chromium
CrB_2	Chromium Diboride
Fe- Al_2O_3	Iron Alumina
Fe	Ferum
Fe-SiC	Iron Silicon Carbide
K	Wear coefficient
MPa	Mega Pascal
N	Number of scores given
R	Regression
TiB_2	Titanium Diboride
TiC	Titanium Carbide
V	Volume loss (cm^3)

W	Wear rate (cm^3/s)
W_1	mass of material 1, (g)
W_2	mass of material 2, (g)
W_3	mass of material 3, (g)
W_a	weight of dry specimen in air, (g)
W_b	weight of specimen when it is suspended in water, (g)
W_c	saturated weight of specimen, (g)
WC	Tungsten Carbide
W_n	mass of number n, (g)
ZrO_3	Zirconate
ρ_1	Density of material 1, (g/cm^3)
ρ_2	Density of material 2, (g/cm^3)
ρ_3	Density of material 3, (g/cm^3)
ρ_n	Density of material of number n, (g/cm^3)
P_T	Theoretical density of mixture, (g/cm^3)
K_{Ic}	Fracture toughness ($\text{MPa}\sqrt{\text{m}}$)

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Kesan Alumina keatas Komposit Matrik Logam Ferum-Kromium Disinter Gelombang Mikro Hibrid

ABSTRAK

Masalah utama pensinteran konvensional adalah kerana kadar pemanasan rendah yang menyumbang kepada tempoh pemprosesan yang panjang seterusnya menyebabkan penggunaan tenaga elektrik yang tinggi. Bagi mengatasi masalah ini, pensinteran dengan gelombang mikro telah diperkenalkan. Bagaimanapun, hasilnya masih baru dan terhad kepada beberapa logam tulen, seramik tulen dan beberapa jenis bahan komposit tertentu sahaja. Kajian ini melibatkan fabrikasi matrik logam ferum-kromium (Fe-Cr) bertetulang dengan partikel alumina (Al_2O_3) disinter tenaga gelombang mikro hibrid pada keadaan empat (4) parameter pensinteran yang berbeza iaitu tekanan mampatan, kadar pemanasan, suhu pensinteran dan masa menahan. Kajian telah difokuskan terhadap penentuan sifat-sifat mekanikal pada keadaan optima iaitu ketumpatan pukal, jumlah keliangan, kekerasan mikro dan ciri-ciri kehausan mekanikal dari segi penyusutan isipadu (mm^3), kadar kehausan (mm^3/s) dan pekali kehausan (K) masing-masing pada 700 MPa, $20^\circ\text{C}/\text{min}$, 1400°C dan 45 minit. Jumlah masa pensinteran tenaga gelombang mikro adalah berjumlah 130 minit berbanding pensinteran konvensional iaitu 340 minit, ini bermakna pensinteran gelombang mikro hibrid adalah 62% lebih pantas dari pensinteran konvensional. Penambahan partikel Al_2O_3 sebanyak 30 peratus berat ke matrik Fe-Cr menyebabkan kemerosotan nilai ketumpatan pukal dari $6.652 \text{ g}/\text{cm}^3$ ke minimum $4.08 \text{ g}/\text{cm}^3$. Pada masa yang sama peratusan jumlah keliangan meningkat dari 11.24% ke 22.60% dan nilai kekerasan mikro mencapai nilai tertinggi 170 HV. Kajian ini juga mendapati kehausan sederhana berlaku bagi sampel dengan partikel Al_2O_3 yang rendah pada peratus berat 5, 10, 15 dan 20. Kehausan yang teruk terutamanya disebabkan haus lelas adalah amat ketara berlaku bagi sampel dengan 25 peratus berat dan 30 peratus berat partikel Al_2O_3 . Pekali rintangan kehausan (K) didapati pada nilai tertinggi 1.2×10^{-1} bagi komposit Fe-Cr bertetulang dengan 30 peratus berat Al_2O_3 partikel. Kadar haus tinggi yang menyumbang kemerosotan ketahanan haus berlaku pada 25 peratus berat and 30 peratus berat Al_2O_3 . Kadar haus yang rendah yang menyebabkan tahan haus tertinggi berlaku apabila 5 peratus berat hingga 20 peratus berat partikel Al_2O_3 ditambah pada matriks Fe-Cr.

The Effects of Alumina on the Hybrid Microwave Sintered Ferum-Chromium Metal Matrix Composites

ABSTRACT

The main problem with conventional sintering is because of the lower heating rate leads to longer processing time, resulted in higher energy consumption. To overcome the problems, sintering with microwave energy has been introduced. However, this research is still new and limited to some pure metals, pure ceramics and a few types of composite materials only. This study involves fabrication of ferum-chromium (Fe-Cr) matrix reinforced by alumina (Al_2O_3) particles sintered under hybrid microwave energy at four (4) different sintering parameters such as compaction pressure, heating rate, sintering temperature and holding time. The study were focused on determination of the optimum mechanical properties such as bulk density), total porosity and micro hardness and mechanical wear characteristics in-term of volume lost (mm^3), wear rate (mm^3/s) and wear coefficient (K) by varying the Al_2O_3 particles content from 5 wt.% to 30 wt.% of fe. Hybrid microwave sintering was performed using microwave furnace Hamilab-V3 at 2.45 GHz at output power of 3kW. This study found the optimum condition for compression pressure, heating rate, sintering temperature and holding time occurred at 700 MPa, 20°C/min, 1400°C and 45 minutes. Total sintering time under hybrid microwave energy at this setting was 130 minutes compare to 340 minutes achieved by conventional sintering. This means hybrid microwave sintering was 62% faster than conventional sintering. Incorporating of 30 wt.% Al_2O_3 particles to Fe-Cr matrix deteriorated the bulk density from 6.652 g/cm^3 to minimum at 4.08 g/cm^3 and concurrently, increase in total porosity percentage from 11.24% to 22.60%, microhardness achieved at highest value at 170HV. This study revealed that mild wear occurred for sample with low Al_2O_3 particles at 5 wt.%, 10 wt.%, 15 wt.% and 20 wt.%. Severe wear mostly by abrasive wear significantly occurred for samples with 25 wt.% and 30 wt.% of Al_2O_3 content. The wear resistant coefficient (K) was found at highest value 1.2×10^{-1} for the Fe-Cr composite reinforced with 30 wt.% of Al_2O_3 particles. The high wear rate that contributed aggravated wear resistant occurs at 25 wt.% and 30 wt.%, while the low wear rate that provide highest wear resistant was achieved when between 5 wt.% to 20 wt.% of Al_2O_3 particles is added to Fe-Cr matrix.

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CHAPTER 1 : INTRODUCTION

1.1 Research Background

Searching for new metal matrix composites (MMCs) with excellent properties have been endless. The advancement of engineering and technology demands for superior and multifunctional MMCs having advantages with finer microstructures, improved mechanical properties, cost effective, faster processing time and environment friendly that can be tailored to a specific application with special functions. The primary supports of MMCs were originally from the aerospace industry for spacecraft components but now, MMCs are widely used in other industrial sectors such as automotive, railways, oils and gas, machinery equipment, electronics etc (Vellingiri 2018; Bajakke et al. 2019).

Fundamentally, MMCs are not a single material, they are from a combination of materials where the mechanical properties can be tailored to have various properties such as lightweight, high porous, high specific strength with specific stiffness, high hardness with excellent wear resistance, low coefficients of friction with low thermal expansion, high thermal conductivity, high energy absorption, high damping capacity, improved fatigue and creep properties compared to the conventional engineering materials (Bahrami et al. 2016; Bajakke et al. 2019; Kumar et al. 2019).

Currently, MMCs are produced using several methods such as powder metallurgy (PM), stir casting, compo casting, squeeze casting etc (Dinaharan et al. 2018; Singh et al. 2019). However, PM method has ability to achieve a uniform and good distribution of

reinforcing particles among the other methods (Khuntia et al. 2018; Sharma et al. 2019). Another advantage of the PM method is due to its ability to manufacture near net shape product at a lower cost. Through PM methods the composite materials could be reinforced by dispersion particles, platelets, non-continuous fibres and continuous fibres before pressing and then followed by sintering process (Diener 2017; Fang et al. 2018). In normal practice, the PM parts are sintered the conventional sintering that using electric furnace at elevated temperatures about 60% to 90% from its melting temperature (Ghasali et al. 2016; Madhan et al. 2018; Panwar et al. 2018). Sintering is a densification process where powder compacts transformed to a strong, dense material body upon heating. Sintering process involve a diffusion mechanism to increases the cohesion and bonding between particles into a coherent, predominantly solid structure via mass transport events that often occur on the atomic scale (German 2010; He et al. 2018; Sengul et al. 2019)

1.2 Problem Statement

Current conventional sintering used electrical furnace that employs electrical resistant coils that placed inside the furnace as heating element. These coils convert the electrical energy to thermal energy before transfer the heat to green parts by the mechanisms of radiation and convection inside the furnace. Sintering through conventional furnace involve direct heating to sample but concurrently needs to heat unnecessary component inside the furnace such as entire walls and furnace atmosphere (Agrawal 2010; Buttress et al. 2015). This problem contributes to energy waste and the heating process becomes very slow for high temperature sintering. Most of conventional furnace only has capability to heat up the sample maximum at 10°C/min of heating rate (Ayyappadas et al. 2017; Madhan et al. 2018; Yang et al. 2018). In addition, lower heating rate would lead to longer processing time and result in higher energy consumption.

Furthermore, material's surface is first heated then followed by the heat moving inward. This means that there is a variation in temperature gradient from the surface to the inside. This situation leads to un-uniform and in-homogenous microstructure of final part resulting deterioration physical and mechanical properties of the final parts (Oghbaei et al. 2010; Ghasali et al. 2015; Olevsky et al. 2018; Manière et al. 2019). For these reasons, conventional furnace may not fulfil the current demands from the PM industry. A new alternative method on sintering is desirable. This new process must overcome the existing restrictions and surpass the capabilities of conventional sintering furnace. Thereby, several new alternative sintering methods was introduced, and microwave sintering is one the process that become great attention due its advantages over conventional furnace. Until now, microwave sintering has been viewed to be one of the most prospective sintering techniques in PM due to advantages offered exceed the existing conventional process in term of faster heating rates, reduced processing times, enhanced diffusion processes, reduced energy consumption, improved physical and mechanical properties, unique properties and lower environmental hazards which not been observed in conventional furnace (Gupta et al. 2018; Olevsky et al. 2018; Hossein-Zadeh et al. 2019; Marinel et al. 2019).

1.3 Research Objectives

The objectives of this research are:

- i. To evaluate the optimum processing condition of Fe-Cr- Al_2O_3 MMCs such as compaction pressure (MPa), heating rate ($^{\circ}\text{C}/\text{min}$), sintering temperature ($^{\circ}\text{C}$) and holding time (min).
- ii. To evaluate the overall processing time (in minutes) between microwave sintering and conventional sintering at the optimum processing condition.