Faculty of Manufacturing Engineering

CHARACTERIZATION AND WEAR PERFORMANCE OF FABRICATED ALUMINA BASED CUTTING TOOLS

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DECLARATION

I declare that this thesis entitled “Characterization and Wear Performance of Fabricated Alumina Based Cutting Tools” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ………………………………………
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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Manufacturing Engineering.

Signature : ………………………………………….

Supervisor name : Associate Professor Ir. Dr. Mohd Hadzley bin Abu Bakar ………………………………………….

Date : ………………………………………….

DEDICATION

To my beloved mother and father

ABSTRACT

Alumina (Al_2O_3) based cutting tool known to has a superior hardness and capable to cut metal in high speed machining without any present of coolant. However, this cutting tool possess brittleness that causes early chipping and breakage when engaged with workpiece material. The purpose of this research is to characterize the alumina, zirconia and alumina-zirconia mixture powder on the average particles size, surface area and microstructure. Then, to analyse the fabricated alumina and alumina-zirconia cutting tool based on dimension, density, hardness and flexural strength. Besides, to evaluate machining performance of alumina and alumina-zirconia cutting tools by varying cutting speeds and feed rates based on tool life. The process of fabricating Al_2O_3 and Zirconia Toughened Alumina (ZTA) cutting tool started with grinding and mixing of ceramic powder using ball mill. Especially for ZTA, the Al_2O_3 powder has been mixed with various ZrO_2 content (5, 10, 15, 20 and 25 wt.%) before undergone ball mill. Then, Al_2O_3 and ZTA powders were compacted using cold isostatic press (CIP) before sintered at 1400^oC for 9 hours to produce a solid insert cutting tool with specification of RNGN120600. The mechanical properties of each Al_2O_3 and ZTA cutting tool were evaluated based on density, hardness and fracture strength. The cutting tool that possess maximum hardness and flexural strength were selected for machining trials. The machining test was performed according to ISO 3685 with the cutting speeds of 200-350 m/min, feed rates of 0.1-0.175 mm/rev and constant depth of cut of 0.5 mm of by using AISI 1045 medium carbon steel as workpiece. It was found that ZTA cutting tool that consisted of 80 wt.% Al_2O_3 and 20 wt.% ZrO_2 recorded maximum density, hardness and fracture strength up to 96.51%, 70.1 HR_C and 1449.3 MPa respectively. This value is much better than the Al_2O_3 sample which records the density, hardness and fracture strength of 84.89%, 43 HR_C and 314.0 MPa respectively. In terms of wear performance, it was observed that the growth of flank wear for the Al_2O_3 cutting tool was more drastic than the ZTA cutting tool. Machining with ZTA cutting tool exhibited maximum tool life up to 224 s at a speed of 200 m/min and a feed rate of 0.125 mm/rev. Whereas the maximum life of the Al_2O_3 cutter is 151s at a speed of 200 m/min and a feed rate of 0.1 mm/rev. The ZTA cutting tool demonstrated gradual wear of abrasives, adhesives and built-up layers while Al_2O_3 was prone to breakage and flaking. On the analysis, it was found that the main factor affecting the good performance of ZTA cutting tool was the presence of ZrO_2 particles in matrix Al_2O_3 which helps to control grain growth of Al_2O_3 while forming a compact and stronghold grain boundary. Thus, it enhanced the density, hardness, flexural strength and wear performance of ZTA cutting tool. The results provide a new knowledge on the effectiveness and capability of ceramic material which can be used as guidance if these ceramic materials should be expanded in other fields such as automotive, electrical and electronic.

ABSTRAK

Alat pemotong alumina (Al_2O_3) yang diketahui mempunyai kekerasan yang unggul dan mampu memotong logam dalam pemesinan berkelajuan tinggi tanpa sebarang penyejuk. Namun, alat pemotong ini bersifat rapuh menyebabkan ia mudah terserpih dan pecah semasa melarik bahan kerja. Tujuan kajian ini adalah untuk mencirikan serbuk campuran alumina, zirkonia dan alumina-zirconia pada saiz partikel purata, kawasan permukaan dan struktur mikro. Kemudian, untuk menganalisis alat pemotong alumina dan alumina-zirconia yang difabrikasi berdasarkan dimensi, ketumpatan, kekerasan dan kekuatan lenturan. Di samping itu, untuk menilai prestasi pemesinan alat pemotong alumina dan alumina-zirconia dengan pelbagai kelajuan pemotongan dan kadar suapan berdasarkan hayat alat. Proses pembuatan alat Al_2O_3 dan Zirconia Toughened Alumina (ZTA) bermula dengan pengisaran dan pencampuran serbuk seramik menggunakan pengisar bebola. Khusus untuk ZTA, serbuk Al_2O_3 telah dicampurkan dengan pelbagai kandungan ZrO_2 (5, 10, 15, 20 dan 25 wt.%) sebelum ia dikisar. Kemudian, serbuk Al_2O_3 dan ZTA telah dipadatkan menggunakan isostatik sejuk sebelum disinter pada 1400°C selama 9 jam demi menghasilkan alat pemotong yang pejal sesuai dengan spesifikasi RNGN120600. Sifat mekanik setiap alat pemotong Al_2O_3 dan ZTA telah dinilai berdasarkan ketumpatan, kekerasan dan kekuatan patah. Alat pemotong yang mempunyai kekerasan dan kekuatan patah yang maksimum dipilih untuk ujian pemesinan. Ujian pemesinan dilakukan menurut ISO 3685 dengan kelajuan pemotongan 200-350 m/min, kadar suapan 0.1-0.175 mm/rev dan kedalaman pemotongan yang dimalarkan pada 0.5 mm dengan menggunakan keluli karbon sederhana AISI 1045 sebagai bahan kerja. Telah didapati ZTA yang terdiri daripada 80 wt.% Al_2O_3 dan 20 wt.% ZrO_2 mencatatkan ketumpatan, kekerasan dan kekuatan patah yang maksimum iaitu pada 96.51%, 70.1 HRC dan 1449.3 MPa masing-masing. Nilai ini jauh lebih baik daripada sampel Al_2O_3 yang merekodkan ketumpatan, kekerasan dan kekuatan patah sebanyak 84.89%, 43 HR_C dan 314.0 MPa masing-masing. Dari segi prestasi haus, diperhatikan bahawa pertumbuhan haus rusuk alat pemotong Al_2O_3 lebih drastik daripada alat pemotong ZTA. Pemesinan dengan alat pemotong ZTA mempamerkan hayat alat maksimum hingga 224s pada halaju 200 m/min dan kadar suapan 0.125 mm/rev. Manakala hayat maksimum alat pemotong Al_2O_3 pula adalah 151s pada halaju 200 m/min dan kadar suapan 0.1 mm/rev. Alat pemotong ZTA menunjukkan haus yang berkala akibat dari lelasan, lekatan dan lapisan pinggir terbina ketika Al_2O_3 pula terdedah kepada pecah dan terserpih. Secara analisis, didapati bahawa faktor utama yang mempengaruhi prestasi alat pemotong ZTA yang baik adalah kehadiran zarah ZrO_2 dalam matriks Al_2O_3 yang membantu mengawal pertumbuhan bijirin Al_2O_3 sambil membentuk sempadan biji yang lebih padat dan kuat. Oleh itu, ia meningkatkan ketumpatan, kekerasan, kekuatan patah dan prestasi haus alat pemotong ZTA. Dapatan kajian memberikan pengetahuan baru mengenai keberkesanan dan keupayaan bahan seramik yang boleh digunakan sebagai panduan jika bahan seramik ini perlu diperluas dalam bidang lain seperti automotif, elektrik dan elektronik.

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LIST OF ABBREVIATIONS

AISI	-	American iron and steel institute
Al	-	Aluminium
Al_2O_3	-	Aluminium oxide/ alumina
ASTM	-	American society for testing and materials
BUE	-	Built-up edge
CBN	-	Cubic boron nitride
CeO_2	-	Cerium oxide
CIP	-	Cold isostatic press
CNC	-	Computer numerical control
CrN	-	Chromium nitride
EN	-	Euro norm
F	-	Feed rate
Ff	-	Load at fracture
HIP	-	Hot isostatic press
HSS	-	High speed steel
ISO	-	International standard organization
L	-	Distance
Mg	-	Magnesium
MgO	-	Magnesium oxide/ magnesia
O	-	Oxygen

PM - Powder metallurgy

R - Radius

S_3N_4 - Silicon nitride

SEM - Scanning electron microscope

SiC - Silicon carbide

TiAlN - Titanium aluminium nitride

$TiBr_2$ - Titanium bromide

TiC - Titanium carbide

TiCN - Titanium carbon nitride

TiN - Titanium nitride

Vc - Cutting speed

W - Weight

Y_2O_3 - Yttrium oxide

Zr - Zirconium

ZrN - Zirconium nitride

ZTA - Zirconia toughened alumina

LIST OF SYMBOLS

% - Percentage

° - Degree

°C - Degree celsius

°C^{-1} - Per degree celsius

µm - Micrometer

µstrain/°C - Micro strain per degree celsius

g - Gram

g/cm^3 - Gram per cubic centimeter

GPa - Gigapascal

HB - Brinell hardness

HR$_C$ - Rockwell hardness c

J/kg°C - Joule per kilogram degree celsius

m/min - Meter per minute

m^2/g - Square meter per gram

mm - Millimeter

mm/rev - Millimeter per revolution

MPa - Megapascal

s - Second

W/m°C - Watt per meter degree celsius

wt.% - Weight percentage

LIST OF PUBLICATIONS

Faiz, M.M., Hairizal, M., Hadzley, A.B., Naim, M.F., Norfauzi, T., Umar, U.A.A., Aziz, A.A. and Noorazizi, S., 2019. Effect of Hydraulic Pressure on Hardness, Density, Tool Wear and Surface Roughness in The Fabrication of Alumina Based Cutting Tool. *Journal of Advanced Manufacturing Technology (JAMT),* 13(2 (1)), pp.23-37.

CHAPTER 1

INTRODUCTION

This chapter provide an overview about the project which focuses on wear performance and failure mode of newly develop alumina-based ceramic cutting tool in lathe machining. The tool was fabricated through powder metallurgy (PM) process. Topic such as research background, problem statement, objectives, scope, and significance of the study are elaborated in this chapter.

1.1 Background of study

Machining is a process of removal raw material to produce the product according to the desired shape (Kalpakjian et al., 2014). The process involved with rough, semi finishing and finishing stages depending on the required accuracy. Some example of machining process that are turning, milling or drilling. Since the revolution of manufacturing industry in Malaysia at the 1980s, the machining process being dominant in automotive industries to produce car components such as engine blocks, gears and pistons. Nevertheless, machining process also being very important in the metal stamping and plastic industries in production mould, tool and dies.

In machining process, selection of cutting tools can be considered major necessities as it applied mostly in finishing parts production. Materials that commonly applied as cutting tool varied from polycrystalline diamond, cubic boron nitride, carbide, ceramic and cermet (Cui et al., 2013). There are many classes of the cutting tools according to the shape and cutting edge such as rectangular, square, round, straight, bent, crank or chamfered (Dogra et al., 2011). The shape of the cutting tools was designed depended on the specific function, such as the materials that need to be cut and the process conditions (Sugihara et al., 2017).

Among various cutting tools that available in industry, alumina based cutting tool being among most frequently applied due to excellent hot hardness, high abrasive resistance and good chemical stability (Mondal et al., 2014). Alumina based cutting tools are more inert than high speed steel and carbide cutting tools at high temperatures, which make this cutting tool ideal for machining with high cutting speed. Another advantage of using alumina based cutting tool is that it does not require cooling fluids to reduce the cutting temperature that provide more towards sustainable machining (Wang et al., 2017).

The properties of optimal alumina based cutting tool depended on the characteristics of raw powders such as particle size, surface area, thermal expansion, able to bind themselves naturally and able to growth in uniform grain size to avoid stress concentrations between the structure (Manshor et al., 2017). Nevertheless, the properties of alumina cutting tool also depended on the process parameters during powder compaction such as sintering temperature, soaking time and pressing force to compact the insert (Hirata et al., 2017). All parameters are important to produce cutting tool properties that capable to shear the metal without catastrophic failure.

Even though alumina possesses holistic characteristic with its excellent properties, this material also has its weakness such as lack of toughness and brittleness. This deficiency gives a bad impression in the early machining as the brittleness could causes premature chipping at the edge of cutting tools (Singh et al., 2016). This weakness can be improved by adding secondary material like zirconia (Norfauzi et al., 2018). According to a study conducted by the Vasudevan et al. (2012), reinforcement zirconia into alumina matrix associated with the several factors such particles size and shape as well as the stability of zirconia phases. The addition of stable zirconia in alumina structure would yield toughening phase transformation by interfering microcrack generation from continuing to spread, especially at the grain boundary (Fan et al., 2017).

In the past, the development of alumina-zirconia cutting tools have been explored by the several authors (Szutkowska et al., 2012; Azhar et al., 2012; Manshor et al., 2016; Sabuan et al., 2018). For example, Szutkowska et al. (2012) evaluated the different properties of cutting tools that fabricated based on pure alumina and alumina-zirconia composites, Azhar et al. (2012) and Manshor et al. (2016), focused on the effect of tertiary materials on alumina-zirconia cutting tools and recently Sabuan et al. (2018) try to explore the compatibility of Copper (Cu) on alumina-zirconia composites.

Although the authors reported the capability of alumina-zirconia can be blended and compacted into the solid dense material, most of the authors only focussed on the microstructure and mechanical properties of alumina-zirconia. For example, the studies conducted by Azhar et al. (2012) only focused on the microstructure and mechanical properties of alumina-zirconia-chromia with limited of machining test. Szutkowska et al. (2012) only focusing on fracture toughness for alumina-zirconia composite, Sabuan et al. (2018) analysis the sintering effect of Cu on alumina based cutting tool, and Manshor et al. (2016) only tried to enhance the microstructure of ZTA by addition of Mg. It should be noted that the wear performance of alumina-zirconia still did not get much attention.

In this study, series of fabrication of cutting tools based on alumina and zirconia powders were implemented. Focus on the capability of new alumina powders that been compacted with zirconia, the fabricated cutting tool have been evaluated based on microstructure, density, hardness and shrinkage. Further, the alumina-zirconia cutting tool have been tested in machining trials of AISI 1045 at various cutting parameters. The wear mechanism for selected cutting tool have been assessed to further understand the characteristics of alumina-zirconia partnership in high stress and temperature application. This study will provide better understanding regarding characteristic of alumina and zirconia particles for wear and tribological application.

1.2 Problem statement

In the case of Malaysia industry, some machinist preferred to use carbide cutting tools due to availability in the market. However, some carbide cutting tool consumed high cost and most of the machining process using carbide cutting tool involving coolant to reduce the temperature inside