

**WEAR RESISTANCE PERFORMANCE OF
ZIRCONIA TOUGHENED ALUMINA (ZTA)
CUTTING TOOL ADDED WITH MgO AND CeO₂**

AFIFAH BINTI MOHD. ALI

**UNIVERSITI SAINS MALAYSIA
2016**

**WEAR RESISTANCE PERFORMANCE OF ZIRCONIA
TOUGHENED ALUMINA (ZTA) CUTTING TOOL ADDED WITH
MgO AND CeO₂**

by

AFIFAH BINTI MOHD. ALI

**Thesis submitted in fulfilment of the requirements
for the degree of
Doctor of Philosophy**

July 2016

Dedication

*To my late father, my source of inspiration,
my mother, my greatest supporter
my husband and daughter,
my strength and hope.*

ACKNOWLEDGEMENT

Bismillahirrahmanirrohim. Alhamdulillah, with the granted from Allah S.W.T, this thesis can finally be completed.

Firstly, I would like to express my sincere gratitude to my supervisor Prof. Dr. Hj. Zainal Arifin bin Ahmad for the continuous support of my PhD research and personal life for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my PhD study. Besides my supervisor, I would like to thank my co-supervisor: Prof. Dr. Mani Maran Ratnam and Dr. Norazharuddin Shah bin Abdullah for their continuous support through their suggestions and guidance in the research and myself developments.

My special thanks to Dean, Prof. Dr. Zuhailawati binti Hussain, deputy deans, lecturers and all staffs of School of Materials and Mineral Resources, Universiti Sains Malaysia (USM) for their kind assistance and support. I am specifically grateful for the technical support from Mr. Shahrul Ami bin Zainal Abidin, Mr. Mokhtar bin Mohamad, Mr. Rashid bin Selamat, Mr. Khairi Bin Khalid, Mr. Mohamad Zaini bin Saari, Mr. Mohamad Shafiq bin Mustapa Sukri and Mrs. Hasnah binti Awang. My thanks also for Mr. Baharom bin Awang, Mr. Mohd Syahril bin Mohd Yusof and Mr. Mohd Shawal Faizal bin Ismail from School of Mechanical for their experimental and technical support.

I gratefully acknowledge the Ministry of Education, Malaysia and International Islamic University Malaysia (IIUM) for their sponsorship throughout my study under the SLAB/SLAI Scholarship Scheme.

My sincere thanks also goes to Dr. Hazman bin Seli, Dr. Ahmad Zahirani bin Ahmad Azhar, Dr. Nik Akmar bin Rejab, and Dr. Wan Fahmin Faiz bin Wan Ali, who help me throughout this research with their knowledge and expertise. Without their precious support, it would not be possible to conduct this research.

I would love to thank my fellow lab mates, Dr. Abdul Rashid bin Jamaludin, Mr. Muhammad Johari bin Abu, Mr. Hamdan bin Yahya, Mr. Mohd. Fariz bin Abdul Rahman, Mr. Ko Chun Min, Ms. Rosyaini binti Afindi Zaman, Ms. Nor Fatin Khairah binti Bahanurddin, Ms. Suhaida binti Shahabuddin, Ms. Saniah binti Abdul Karim and Ms. Maliha Siddiqui for the stimulating discussions, for the time we were working together and supporting each other and for all the fun we have had in the last three years.

I am also would like to thanks my friends, Ms. Norshahida binti Sarifuddin, Ms. Suhaily binti Mokhtar, Ms. Siti Norbahiyah binti Mohamad Badari, Ms. Farah Diana binti Mohd. Daud, Ms. Nur Farahiyah binti Mohammad, Ms. Siti Shuhadah binti Md. Saleh, Ms. Shazeela binti Ahmad, Ms. Roslina binti Ishak, Ms. Dalila Syairah binti Mohamad Zubir and Ms. Nazarulniza binti Kamarul Ariffin who were with me through thick and thin throughout my journey in finding knowledge. May Allah reward them for all of their help and sacrifices.

Last but not the least, I am grateful to my late father, Mohd. Ali bin Din who always inspire me to pursue my study and to do what I love. I would like to thanks my mother, Fatimah binti Othman, my greatest supporter emotionally and financially, my husband Mohd. Suhaili bin Sukami and my daughter Anis Safia binti Mohd. Suhaili who always be there and believe in me. Not to forget my eldest sister, my life counsellor and brothers for supporting me spiritually throughout my study and my life in general.

TABLES OF CONTENTS

	Pages
ACKNOWLEDGEMENT	ii
TABLE OF CONTENTS	iv
LIST OF TABLES	ix
LIST OF FIGURES	x
LIST OF ABBREVIATIONS	xvii
LIST OF SYMBOLS	xix
ABSTRAK	xxi
ABSTRACT	xxiii
 CHAPTER ONE – INTRODUCTION	
1.1 Research Background.....	1
1.2 Problem Statement.....	4
1.3 Research Objectives.....	6
1.4 Project Approach.....	6
 CHAPTER TWO - LITERATURE REVIEW	
2.1 Development of ceramic cutting tools.....	8
2.1.1 Al ₂ O ₃ Based Cutting Tool.....	9
2.1.2 ZTA Cutting Tool.....	11
2.1.3 Additives Addition.....	12

2.1.3 (a) Magnesium Oxide (MgO).....	12
2.1.3 (b) Cerium Oxide (CeO ₂).....	15
2.2 Wear of Ceramic Cutting Tool.....	18
2.2.1 Flank Wear.....	19
2.2.2 Crater Wear.....	20
2.2.3 Nose Wear.....	20
2.2.4 Chipping.....	23
2.3 Effect of Cutting Parameters to Wear Resistance Performance.....	23
2.4 Effect of Cutting Chips Length and Form On The Wear Resistance Performance.....	26
2.5 Effect of Cutting Chips Morphology on The Wear Resistance Performance.....	32
2.6 Phase Transformation of ZrO ₂	33
2.7.1 Stress Induced Transformation Toughening.....	35
2.7.2 Microcrack Toughening.....	36
2.8 Effect of Machining Process to the Phase Transformation.....	37
2.9 Summary.....	37

CHAPTER THREE - MATERIALS AND METHODOLOGY

3.1 Introduction.....	40
3.2 Materials and Samples Preparation.....	40
3.2.1 Raw Materials Preparation.....	41
3.2.1 (a) Calculations.....	43

3.2.1 (b)	Mixing, Drying and Crushing.....	44
3.2.1 (c)	Compaction and Drying.....	45
3.2.1 (d)	Sintering.....	46
3.2.1 (e)	Phase Analysis by X- Ray Diffractometer.....	46
3.2.1 (f)	Microstructural Observation.....	47
3.2.1 (g)	Shrinkage Analysis.....	48
3.2.1 (h)	Vickers Hardness and Fracture Toughness.....	49
3.2.1 (i)	Bulk Density and Porosity Analysis.....	52
3.3	Part 1: The Effects of Machining Parameters to The Performance of ZTA Added With Mgo and CeO ₂ Ceramic Cutting Tools.....	53
3.3.1	Parameters.....	53
3.3.2	Machining.....	56
3.3.3	Tool Wear Measurement.....	58
3.3.3 (a)	Flank Wear.....	58
3.3.3 (b)	Crater Wear.....	58
3.3.3 (c)	Nose Wear.....	59
3.3.3 (d)	Chipping.....	60
3.3.4	Surface Roughness Measurement.....	61
3.4	Part 2: The Effect Of Cutting Chip Morphologies On The Wear Performance Of ZTA Added with Mgo and CeO ₂ Ceramic Cutting Tools.....	61
3.5	Part 3: The Effects of Phase Transformation Due to Machining Process to The Hardness, Fracture Toughness and Microstructure of ZTA Added With MgO and CeO ₂ Ceramic Cutting Tools.....	61

3.5.1	XRD and (hkl) Analysis.....	62
3.5.2	Microstructural Observation.....	64
3.2.3	Hardness and Fracture Toughness.....	64

CHAPTER FOUR - RESULTS AND DISCUSSIONS

4.1	Introduction.....	65
4.2	Characterization of Raw Materials.....	65
4.2.1	Aluminium Oxide (Al ₂ O ₃).....	65
4.2.2	Ytria Stabilised Zirconia (YSZ).....	67
4.2.3	Magnesium Oxide (MgO).....	70
4.2.4	Cerium Dioxide (CeO ₂)	71
4.3	Properties of the Samples.....	72
4.3.1	X-Ray Diffraction Analysis (XRD).....	72
4.3.2	Shrinkage, Microstructural, Porosity and, Bulk Density Analysis.....	75
4.3.3	Vickers Hardness and Fracture Toughness.....	79
4.4	Part 1: The Effects Of Machining Parameters To The Performance Of ZTA Added with MgO and CeO ₂ Ceramic Cutting Tools.....	79
4.4.1	Flank Wear.....	80
4.4.2	Crater Wear.....	83
4.4.3	Nose Wear.....	85
4.4.4	Chipping.....	90
4.4.5	Effect of Parameters to Surface Roughness.....	90
4.5	Part 2: Effect of Chip to Wear	95

4.5.1	Chip Length, Form and Morphology at Different Machining Parameters.....	96
4.5.1 (a)	Chip Length and Forms.....	97
4.5.1 (b)	Chip Morphology.....	101
4.5.2	Effect of Chip Length, Form and Morphology to the Wears and Surface Roughness.....	107
4.5.3	Summary Part 2.....	112
4.6	Part 3: The Effect of Phase Transformation ZrO_2 to the Properties and Performance of ZTA Based Ceramic Cutting Tool.....	119
4.6.1	XRD – Phase Analysis.....	119
4.6.2	Microstructure.....	122
4.6.3	Hardness and Fracture Toughness.....	124
4.6.4	Summary of Part 3.....	126

CHAPTER FIVE - CONCLUSION AND FUTURE RECOMMENDATIONS

5.1	Conclusions.....	128
5.2	Recommendations.....	129
	REFERENCES.....	131
	LIST OF PUBLICATIONS.....	146

LIST OF TABLES

		Pages
Table 2.1	Chronology of the Al ₂ O ₃ based cutting tool development.	10
Table 2.2	Previous researches related to ZTA added with MgO and ZTA added with MgO and CeO ₂	39
Table 3.1	List of raw materials used in the research.	41
Table 3.2	Weight percentage of raw materials	43
Table 3.3	Calculated weight of raw materials	44
Table 3.4	Cutting parameters for ZTA ceramic cutting insert	55
Table 3.5	Properties of workpiece stainless steel 316L.	55
Table 3.6	Summary of previous works on machining by using Al ₂ O ₃ based cutting tool	56
Table 4.1	Elemental quantitative analysis on the YSZ particles.	69
Table 4.2	Hardness and fracture toughness value of samples.	79
Table 4.3	Comparison of tetragonal and monoclinic phase of samples before sintering,	122
Table 4.4	Comparison of hardness and fracture toughness before and after the machining process	125

LIST OF FIGURES

		Pages
Figure 2.1	Effect of MgO addition to hardness of ZTA (Azhar et al. 2010)	14
Figure 2.2	Effect of MgO addition to fracture toughness of ZTA (Azhar et al. 2010)	14
Figure 2.3	Wear performance of ZTA cutting insert with addition of MgO (Azhar et al. 2010)	15
Figure 2.4	Results of average grain size for both ZrO ₂ and Al ₂ O ₃ grain size added with varied wt.% of CeO ₂ (Rejab et al. 2013).	17
Figure 2.5	Effect of CeO ₂ addition on fracture toughness and Vickers hardness of ZTA (Rejab et al. 2013)	17
Figure 2.6	Effect of ceria to thermal expansion of ZTA (Mangalaraja et al. 2003)	18
Figure 2.7	Common type of wear of ceramic cutting tool.	19
Figure 2.8	Flank wear illustration on the flank surface of the tool (Childs et al. 2000)	19
Figure 2.9	Typical crater wear on the rake face of the cutting tool (Childs et al. 2000)	21
Figure 2.10	Illustration on nose wear (Fang et al. 2012)	22
Figure 2.11	Surface profile analysis on the effect of nose wear to surface profile (a) unworn tool surface profile b) worn tool surface profile (Shahabi & Ratnam, 2009)	22

Figure 2.12	Effect of cutting speed to the flank wear (Camuşcu, 2006)	25
Figure 2.13	Average surface roughness versus cutting speed (Camuşcu, 2006)	25
Figure 2.14	Collection of standard chip form (ISO 3685:1993)	27
Figure 2.15	Various types of chip form during machining (George, 2002)	28
Figure 2.16	Various types of wear with the chips morphology (Altin et al. 2007)	30
Figure 2.17	Study of wear by analysis of chip by (Dutta et al. 2006)	31
Figure 2.18	Simulation and experimental result on the cutting chips and their effects on crater wear (Childs et al., 2000).	32
Figure 2.19	Chip formation mechanism classification (Toenshoff et al. 2014)	33
Figure 2.20	The XRD patterns showing phase transformation of ceramic cutting tool during machining of SG iron at $V= 200$ m/min (Sornakumar et al. 1993)	38
Figure 3.1	Flow chart of raw materials and samples preparation.	42
Figure 3.2	The CAD drawing showing the mould dimension used in this research. The dimensions are in mm.	45
Figure 3.3	Sintering profile used to sinter the green body	46
Figure 3.4	Inner circle (iC) measured on the samples.	48
Figure 3.5	Indentation schematic for Vickers hardness measurement.	50
Figure 3.6	Typical crack configuration for determination of fracture toughness via Niihara equation.	51
Figure 3.7	Flowchart for machining process and data analysis	54

Figure 3.8	The orientation of machining process	57
Figure 3.9	Machining process by using the fabricated ceramic cutting insert.	57
Figure 3.10	Example of flank wear measurement.	58
Figure 3.11	Crater wear area highlighted with the wear area calculated by the Matlab software.	59
Figure 3.12	Wear measurement process for nose wear.	60
Figure 3.13	Example of SEM image of chipping observed on the cutting tools.	60
Figure 3.14	Observation made on the chips collected from the machining process.	62
Figure 3.15	Process flowchart on the analysis of phase transformation.	63
Figure 4.1	XRD result for Al ₂ O ₃ powders, ICDD reference 00-10-0173.	66
Figure 4.2	Result of particles size analysis for Al ₂ O ₃ particles.	66
Figure 4.3	Morphology of Al ₂ O ₃ particles at 20 K magnification.	67
Figure 4.4	XRD results for YSZ powders, ICDD reference files for tetragonal (t) and monoclinic (m) are 00-89-9068 and 00-78-1808 respectively.	67
Figure 4.5	Results of particle size for YSZ particles.	68
Figure 4.6	Morphology of YSZ particles at 20 K magnification	68
Figure 4.7	EDX results of YSZ particles.	69

Figure 4.8	XRD results for MgO nanoparticles, which (*) is MgO with ICDD reference 98-005-3326 and (o) is brucite Mg(OH) ₂ with ICDD reference 98-004-4736.	70
Figure 4.9	Results for particles size for MgO nanoparticles.	70
Figure 4.10	Morphology of MgO nanoparticles	71
Figure 4.11	XRD result of CeO ₂ powders refer to ICDD reference file 00-034-0394.	71
Figure 4.12	Results of particles size for CeO ₂ powders.	72
Figure 4.13	Morphology of CeO ₂ particles.	72
Figure 4.14	XRD analysis of ZMM cutting insert after sintering	73
Figure 4.15	XRD analysis of ZMN cutting insert after sintering	74
Figure 4.16	XRD analysis of ZNC cutting insert after sintering	74
Figure 4.17	Comparison on shrinkage percentage of ZMM, ZMN and ZNC cutting insert	75
Figure 4.18	SEM micrographs of (a) ZMM samples, (b) ZMN samples and (c) ZNC samples	77
Figure 4.19	Porosity percentage for ZMM, ZMN and ZNC samples	78
Figure 4.20	Bulk density for ZMM, ZMN and ZNC samples	78
Figure 4.21	Result of flank wear versus spindle speed at different feedrate (a) 0.1 mm/rev, (b) 0.3 mm/rev and (c) 0.5 mm/rev	81
Figure 4.22	Result of flank wear versus feedrate at different spindle speed (a) 1500 rpm, (b) 1750 rpm and (c) 2000 rpm	82

Figure 4.23	Result of flank wear versus spindle speed at different feedrate (a) 0.1 mm/rev, (b) 0.3 mm/rev, (c) 0.5 mm/rev and (d) enlarge view of (c)	84
Figure 4.24	Figure 4.24: Result of crater wear versus feedrate at different spindle speed (a) 1500 rpm, (b) 1750 rpm and (c) 2000 rpm	86
Figure 4.25	Result of nose wear versus spindle speed at different feedrate (a) 0.1 mm/rev, (b) 0.3 mm/rev and (c) 0.5 mm/rev	87
Figure 4.26	Result of nose wear versus feedrate at different spindle speed (a) 1500 rpm, (b) 1750 rpm and (c) 2000 rpm	88
Figure 4.27	Chipping condition at different feedrate ZMM, ZMN and ZNC cutting insert.	91
Figure 4.28	Result of surface roughness versus spindle speed at different feedrate (a) 0.1 mm/rev, (b) 0.3 mm/rev and (c) 0.5 mm/rev	93
Figure 4.29	Result of surface roughness versus feedrate at different spindle speed (a) 1500 rpm, (b) 1750 rpm and (c) 2000 rpm	94
Figure 4.30	Long ribbon form chips collected during machining process	96
Figure 4.31	Snarled ribbon form chip collected during machining process	96
Figure 4.32	Long and short tubular form chips collected during machining	97
Figure 4.33	SEM micrograph of the tubular chip produced.	97
Figure 4.34	Chip form of ZMM cutting inserts at different parameters.	99
Figure 4.35	Chip form of ZMN cutting inserts at different parameters.	100
Figure 4.36	Chip form of ZNC cutting inserts at different parameters.	101
Figure 4.37	Examples of (a) continuous chips and (b) segmented chip	103

Figure 4.38	Chip morphology of ZMM at 200 and 500 magnifications for different feedrate (a) 0.1 mm/rev, (b) 0.3 mm/rev and (c) 0.5 mm/rev	104
Figure 4.39	Chip morphology of ZMN at 200 and 500 magnifications for different feedrate (a) 0.1 mm/rev, (b) 0.3 mm/rev and (c) 0.5 mm/rev	105
Figure 4.40	Chip morphology of ZNC at 200 and 500 magnifications for different feedrate (a) 0.1 mm/rev, (b) 0.3 mm/rev and (c) 0.5 mm/rev	106
Figure 4.41	Chip morphology of ZMM at 200 and 500 magnifications for different spindle speed (a) 1500 rpm (b) 1750 rpm and (c) 2000 rpm	108
Figure 4.42	Chip morphology of ZMN at 200 and 500 magnifications for different spindle speed (a) 1500 rpm (b) 1750 rpm and (c) 2000 rpm	109
Figure 4.43	Chip morphology of ZNC at 200 and 500 magnifications for different spindle speed (a) 1500 rpm (b) 1750 rpm and (c) 2000 rpm	110
Figure 4.44	The chip effect on the wears of ZMM cutting insert at different feedrate	114
Figure 4.45	The chip effect on the wears of ZMM cutting insert at different spindle speed	115

Figure 4.46	The chip effect on the wears of ZMN cutting insert at different feedrate	116
Figure 4.47	The chip effect on the wears of ZMN cutting insert at different spindle speed	117
Figure 4.48	The chip effect on the wears of ZNC cutting insert at different feedrate	118
Figure 4.49	The chip effect on the wears of ZNC cutting insert at different spindle speed	119
Figure 4.50	The XRD analysis of ZMM after machining process	120
Figure 4.51	The XRD analysis of ZMN after machining process	121
Figure 4.52	The XRD analysis of ZNC after machining process after sintering and after machining process for ZMM, ZMN and ZNC cutting insert.	121
Figure 4.53	Microstructure of the ZMM, ZMN and ZNC samples before and after the machining	123
Figure 4.54	Comparison of hardness value before and after machining process.	124
Figure 4.55	Comparison of fracture toughness value before and after machining process.	125

LIST OF ABBREVIATIONS

Al ₂ O ₃	Alumina
ASM	American Society for Metals International
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
CeO ₂	Cerium Oxide
CNC	Computer Numerical Control
DPH	Diamond Pyramid Hardness
EDAX	Energy Dispersive Spectroscopy
FESEM	Field Emission Scanning Electron Microscope
GPa	Giga Pascal
HV	Vickers Hardness
ICCD	International Centre for Diffraction Data
ISO	International Standards Organization
MgO	Magnesium Oxide
MPa	Mega Pascal
NL	Number of grains intercept
Pt	Platinum
PSZ	Partially Stabilised Zirconia
Ra	Average Roughness
SEM	Scanning Electron Microscope
USA	United State of America

XRD	X-Ray Diffractometer
YSZ	Yttria Stabilised Zirconia
ZMM	ZTA added with micro particle MgO
ZMN	ZTA added with nano particle MgO
ZNC	ZTA added with nano particle MgO and CeO ₂
ZrO	Zirconium Oxide
ZTA	Zirconia Toughened Alumina

LIST OF SYMBOLS

n	Integer
λ	Wavelength
θ	Angle
d	Distance between planes in Angstrom unit
\AA	Angstrom unit
L_0, L_1	Length
F	Force
A	Area
K_{IC}	Fracture Toughness
H	Vickers hardness
E	Modulus of Elasticity
A	Half distance of indent length
c	Crack length
I_m	Intensity monoclinic phase
I_t	Intensity tetragonal phase
f	weight fraction of the reinforce materials
E_r	Modulus of elasticity of the reinforce or additive materials
E_m	Modulus of elasticity of the matrix
W_d	Dry weight of the samples
W_s	Soaked weight of the samples

W_a	Suspended weight of the samples
ρ_{water}	Density of water (1 g/cm ³)
ρ	Bulk density (g/cm ³)
v	Volume fraction
N	Number of atom per unit cell
V	Unit cell volume (cm ³)
MW	Molecular weight (g)
N_a	Avogadro number

PRESTASI RINTANGAN HAUS MATA PEMOTONG ALUMINA DIPERKUAT ZIRKONIA DENGAN TAMBAHAN MgO DAN CeO₂

ABSTRAK

Prestasi rintangan haus alumina diperkuat zirkonia (ZTA) dengan bahan tambah MgO dan CeO₂ diselidik. Komposisi optimum bahan tambahan telah digunakan dalam alumina / zirkonia terstabil yttria (YSZ). Tiga jenis komposisi adalah ZTA + 0.7 wt.% MgO (ZMM, partikel mikro), ZTA + 1.1 wt.% MgO (ZMN, partikel nano) dan ZTA + 0.7 wt.% MgO (partikel zarah) + 5.0 wt.% CeO₂ (ZNC). Komposisi-komposisi ini dicampur, ditekan dalam satu arah ke dalam acuan berbentuk mata pemotong rombus 80° dengan 0.8 mm jejari muncung dan disinter pada suhu 1600 °C selama 4 jam dibawah keadaan tanpa tekanan. Analisa pemotongan dilakukan ke atas rod keluli tahan karat kormesial 316L dengan diameter 50 mm sebagai bahan kerja. Bahan kerja ini telah dipotong pada 1500, 1750 dan 2000 rpm. Kadar suapan dibezakan pada 0.1, 0.3 dan 0.5 mm/putaran manakala kedalaman potongan dikekalkan pada 0.2 mm. Faktor - faktor yang memberi kesan kepada prestasi alat memotong ZTA iaitu parameter pemesinan, serpihan pemotongan dan transformasi fasa yang disebabkan oleh proses pemesinan telah dikaji. Rintangan haus dan kekasaran permukaan bahan kerja diukur. Empat jenis kelakuan rintangan haus dapat dilihat iaitu haus rusuk, haus kawah, haus hidung dan sumbing. Kelajuan putaran dan kenaikan kadar suapan menyebabkan semua jenis haus meningkat terutamanya haus rusuk dan haus hidung. Haus kawah sangat dipengaruhi oleh pembentukan serpihan semasa proses pemotongan. Pembentukan serpihan sebaliknya sangat dipengaruhi oleh kenaikan kadar suapan kerana beban berlebihan pada mata pemotong. Kebanyakan sumbing

diperhatikan apabila kadar suapan berada pada 0.5 mm/putaran. Kekasaran permukaan sebaliknya menurun dengan kenaikan kelajuan putaran dan meningkat dengan kenaikan kadar suapan. ZMM sangat terkesan dengan haus rusuk dan haus kawah kerana kekerasannya yang rendah. ZMN sebaliknya terkesan oleh serpihan di mana luas sumbing alat pemotong ZMN adalah lebih besar berbanding dengan ZMM dan ZNC. Selain itu, ZNC memberikan nilai tertinggi haus hidung. Mata pemotong ZMM memberikan nilai kekasaran permukaan yang terbaik dengan kekasaran paling rendah di mana-mana parameter manakala ZMN memberikan nilai kekasaran permukaan yang paling tinggi. Panjang dan bentuk serpihan juga memberi kesan kepada kemajuan haus kawah. Serpihan yang panjang menyebabkan haus kawah menjadi teruk. Serpihan berbentuk tiub panjang yang paling teruk menjejaskan alat pemotong seramik. Ini dapat dilihat daripada corak haus kawah di mana kawasan haus kawah tertinggi dapat diperhatikan apabila serpihan berbentuk tiub panjang terhasil semasa proses pemesinan. Disebabkan transformasi fasa dalam alat pemotongan berlaku semasa proses pemesinan, kekerasan meningkat manakala keliatan patah menurun bagi semua jenis alat pemotong (ZMM, ZMN dan ZNC). ZMM menunjukkan kadar tertinggi kenaikan kekerasan (22.0%) dan susutan keliatan patah (21.1%) diikuti oleh ZNC dengan masing-masing 11.8% dan 9.4%. ZMN mempunyai kenaikan terkecil kekerasan sebanyak 2.6% dan pengurangan keliatan patah sebanyak 8.4%. Kesimpulannya, ZMN menunjukkan prestasi yang terbaik sebagai alat pemotong berbanding ZMM dan ZNC.