STUDY ON THE DEVELOPMENT OF CERAMIC CUTTING TOOL (ZTA / ZTA-MGO) AND ITS MACHINING PERFORMANCE IN SLOT MILLING

By

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UNIVERSITI SAINS MALAYSIA

November 2010

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Dengan nama ALLAH Yang Maha Pengasih Lagi Maha Penyayang

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Mohd Nor Hakim Bin Hassan
November 2010.

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1.2 Mohd Nor Hakim Hassan, Mohamad Ikhwan Zaini Ridzwan, Zainal Arifin Ahmad. Design and Mold Fabrication for Pressing Alumina Powders. International Conference on Recent and Emerging Advanced Technologies in Engineering 2009 (iCREATE 2009). Kuala Lumpur International Airport Pan Pacific Hotel, Sepang, Malaysia. (23rd – 24th November 2009).

1.3 Mohd Nor Hakim Hassan, Mohamad Ikhwan Zaini Ridzwan, Zainal Arifin Ahmad. Machining Performance of Zirconia Toughened Alumina and Reinforced With MgO in Dry End Milling of AISI 1018 Steel. 2010 International Conference on Process Engineering and Advanced Materials (iCPEAM 2010). A conference of World Engineering, Science and Technology Congress (ESTCON). Kuala Lumpur Convention Centre, KLCC, Malaysia. (15th – 17th June 2010).

1.4 Mohd Nor Hakim Hassan, Mohamad Ikhwan Zaini Ridzwan, Ahmad Zahirani Ahmad Azhar, Zainal Arifin Ahmad. Machining Performance of ZTA Inserts and Reinforced with MgO Inserts in Dry End Milling of AISI 1018 Steel. International Journal Advance Manufacturing Technology (submitted and reviewed).

KAJIAN TERHADAP PEMBANGUNAN MATA ALAT PEMOTONG SERAMIK (ZTA / ZTA-MGO) DAN PRESTASI PEMESINANNYA MELALUI PENGISARAN LURAH

ABSTRAK

Daripada pelbagai bahan mata alat pemotong yang boleh didapati, bahan-bahan seramik mempunyai potensi untuk digunakan sebagai mata alat pemotong disebabkan ciri-ciri menarik seperti kekerasan panas yang tinggi, ketahanan lelasan dan kestabilan kimia tetapi bahan asas mengalami kekurangan dari segi had keliatan patah dan keupayaan rintangan kejutan haba yang rendah. Zirconia distabil yttria (YSZ) dan magnesia (MgO) telah dicampur dengan alumina (bahan seramik) untuk menambahkan keliatan alumina. Kajian sebelum ini menemukan penambahan 0.7 % MgO terhadap alumina diperkuat zirconia (ZTA) (80 % alumina + 20 % YSZ) dibentuk sebagai mata alat pemotong dalam operasi larik menghasilkan keluasan haus yang minimum. Walau bagaimanapun, potensinya di dalam operasi pemesinan tidak dikaji dengan lebih mendalam. Oleh itu, kajian ini menyiasat potensi mata alat pemotong yang terdiri daripada bahan ZTA, ZTA yang diperkuat dengan MgO dan mata alat komersial yang berada di pasaran menggunakan operasi pengisaran lurah. Tiga objektif telah dikenalpasti. Pertama, untuk mereka bentuk dan menghasilkan acuan yang boleh digunakan untuk pemampatan serbuk seramik. Kedua, untuk menyiasat prestasi mata alat pemotong ini melalui operasi pengisaran lurah. Ketiga, untuk membandingkan prestasi mata alat pemotong ini dengan mata alat Kennametal yang telah dipilih. Acuan telah direka bentuk menggunakan perisian Catia V5R17 dan dibina menggunakan keluli SKD 11. Bahan mentah mata alat pemotong terdiri daripada alumina, YSZ dan magnesia dicampur dan digaul mengikut komposisi yang ditentukan selama lapan jam. Acuan yang dibina digunakan untuk menekan serbuk seramik yang menghasilkan mata alat dalam keadaan hijau seterusnya mata alat tersebut dibakar dalam relau pada 1600 ^{o}C selama empat jam. Sampel-sampel ini kemudiannya menjalani analisis terhadap ciri-ciri mekanikalnya. Operasi pengisaran telah dirancang untuk menilai prestasi mata alat pemotong ini dan dilaksanakan menggunakan pelbagai kelajuan pemotongan, kadar pemotongan, kedalaman paksi dan kedalaman jejari pemotongan. Prestasi ditunjukkan oleh mata alat ZTA-MgO pada kelajuan pemotongan 84 dan 111 m/min adalah lebih baik sedikit daripada mata alat ZTA. Perbandingan jumlah masa pemotongan menunjukkan mata alat ZTA-MgO memotong lebih lama daripada mata alat ZTA. Prestasi terbaik mata alat ZTA-MgO adalah pada kelajuan pemotongan 111 m/min dan kadar pemotongan 0.20 mm/mata alat apabila berupaya memotong benda kerja selama 105 saat dibawah haus sisi maksimum iaitu 0.3 mm. Manakala, prestasi terbaik mata alat ZTA adalah pada kelajuan pemotongan 84 m/min dan kadar pemotongan 0.20 mm/mata alat apabila berupaya memotong benda kerja selama 115 saat dibawah haus sisi maksimum iaitu 0.3 mm. Bagaimanapun, keputusan terhasil jelas menunjukkan pada semua kelajuan pemotongan dan kadar pemotongan, prestasi mata alat Kennametal jauh mengatasi prestasi mata alat yang lain. Prestasi terbaik mata alat Kennametal adalah pada kelajuan pemotongan 84 m/min dan kadar pemotongan 0.20 mm/mata alat apabila berupaya memotong benda kerja selama 3750 saat dibawah haus sisi maksimum iaitu 0.3 mm. Secara dasarnya, nilai kekasaran permukaan yang baik diperolehi oleh kesemua mata alat yang haus sisinya adalah dibawah nilai 0.3 mm. Keputusan kekasaran permukaan terhasil daripada mata alat ZTA dan ZTA-MgO adalah setanding dengan mata alat Kennametal.

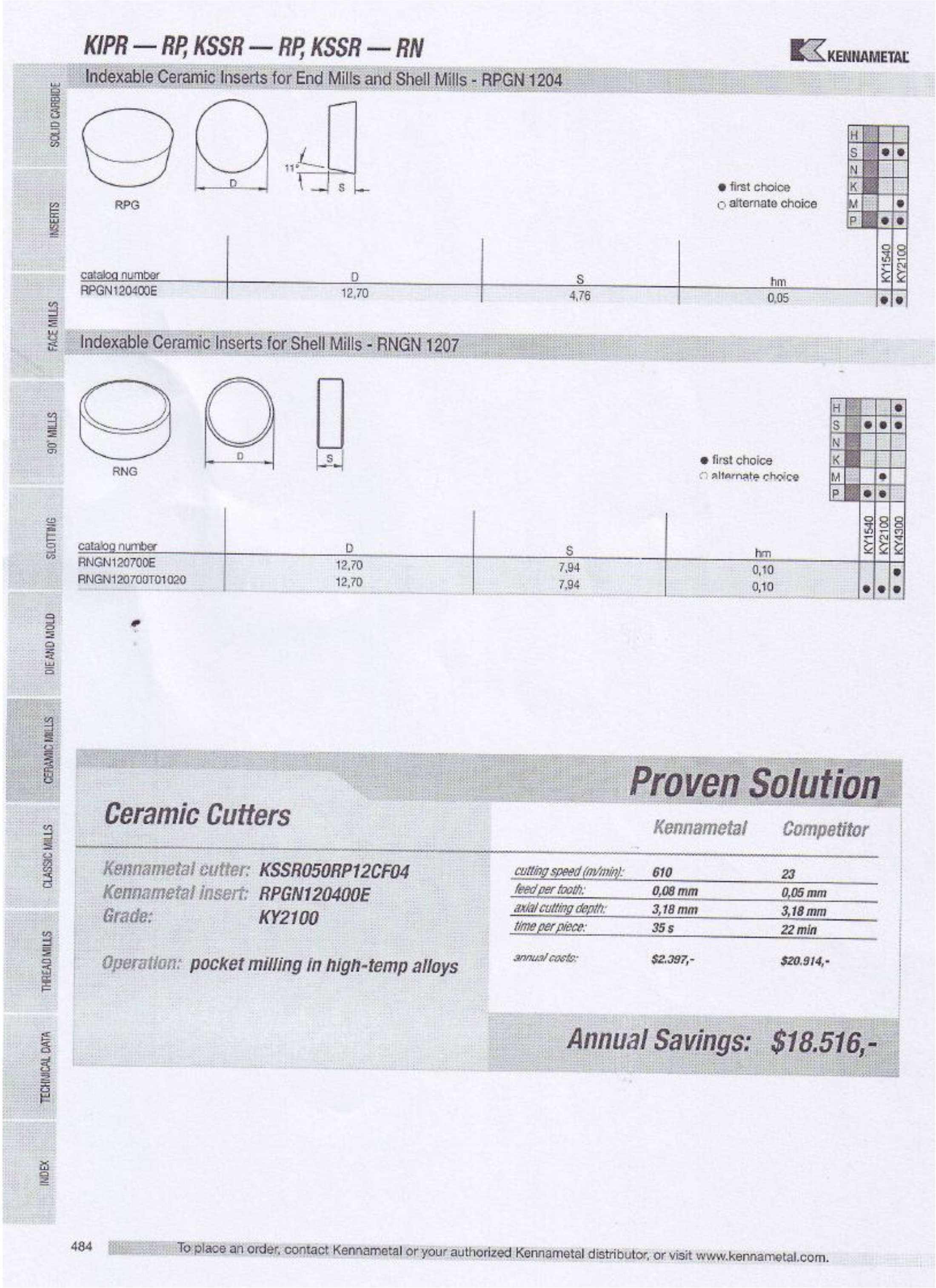
A STUDY ON THE DEVELOPMENT OF A CERAMIC CUTTING TOOL (ZTA / ZTA-MGO) AND ITS MACHINING PERFORMANCE IN SLOT MILLING

ABSTRACT

From the various cutting insert materials available, ceramic materials have the potential to be used as cutting insert due to the attractive properties such as high hot hardness, abrasion resistance and chemical stability but the base material suffers from the limitation of low fracture toughness and low thermal shock resistance capability. Yttria stabilized zirconia (YSZ) and magnesia (MgO) were introduced into the alumina (ceramic material) in order to toughen the brittle ceramics. Previous studies found that an addition of 0.7 wt % of MgO into the Zirconia Toughened Alumina (ZTA) matrix (80 wt % alumina + 20 wt % YSZ) as an insert in lathe machining, produced minimum wear area. However, the potential of these cutting insert compositions were not carefully investigated in lathe or milling operation. Therefore, this research investigated the potential of these inserts from ZTA material, ZTA reinforced with MgO and commercial available cutting insert in slot milling operation and three objectives were indentified. Firstly, to design and fabricate die used for pressing ceramic powder. Secondly, to investigate the performance of these inserts and thirdly, to compare the performance of these inserts with chosen Kennametal ceramic insert at the same slot milling operation. The die was designed using Catia V5R17 software and fabricated using SKD 11 tool steel. Raw materials consist of alumina, YSZ and magnesia were mixed with desired composition for eight continuous hours in mixing bottle. Hydraulic pressed were carry out using fabricated die to obtain the green body insert. These green bodies were sintered in pressureless condition at 1600 ^{o}C for four hours soaking time. The samples were subjected to analysis such as Vickers hardness, fracture toughness and microstructural observation. Slot mill operation was implemented to access insert cutting tools performance. Milling operation was carefully designed to access the performance of fabricated ceramic cutting inserts with various cutting speeds, feed rates, axial depth of cut and radial depth of cut. The performance showed by ZTA-MgO insert at cutting speed of 84 and 111 m/min was slightly better than showed by ZTA insert. ZTA-MgO was able to mill the workpiece with longer time than ZTA insert. The best performance obtained with ZTA-MgO insert at a cutting speed of 111 m/min and a feed rate of 0.20 mm/tooth which able to machine as many as 105 seconds of cutting time under the maximum flank wear of 0.3 mm. While the best performance obtained with ZTA insert at a cutting speed of 84 m/min and a feed rate of 0.20 mm/tooth which able to machine up to 115 seconds of cutting time at the maximum flank wear of 0.3 mm. However, the results clearly indicated at all feed rates and cutting speeds, the performance of Kennametal inserts outperformed the performance showed by the other inserts. The best cutting performance acquired with Kennametal insert was at a cutting of 84 m/min and a feed rate of 0.20 mm/tooth which able to machine the workpice as many as 3750 seconds of cutting time at the maximum flank wear value of 0.3 mm. Considerably good surface roughness values were obtained with all of unworn inserts. The results obtained with the ZTA and ZTA-MgO inserts were comparable to Kennametal inserts.

APPENDIX 1:

Kennametal Catalogue pages: 484 and 485



SOLID CARBIDE
INSERTS
FACE MILLS
90° MILLS
SLOTTING
DIE AND MOLD
CERAMIC MILLS
CLASSIC MILLS
THREAD MILLS
TECHNICAL DATA
INDEX

Indexable Ceramic Inserts for End Mills and Shell Mills - RPGN 1204

● first choice
○ alternate choice

		KY1540	KY2100
H			
S		●	●
N			
K			
M			●
P		●	●

catalog number	D	S	hm	KY1540	KY2100
RPGN120400E	12,70	4,76	0,05	●	●

Indexable Ceramic Inserts for Shell Mills - RNGN 1207

● first choice
○ alternate choice

		KY1540	KY2100	KY4300
H				●
S		●	●	●
N				
K				
M			●	
P		●	●	

catalog number	D	S	hm	KY1540	KY2100	KY4300
RNGN120700E	12,70	7,94	0,10			●
RNGN120700T01020	12,70	7,94	0,10	●	●	●

Proven Solution

Ceramic Cutters

Kennametal cutter: **KSSR050RP12CF04**
Kennametal insert: **RPGN120400E**
Grade: **KY2100**

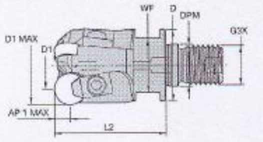
Operation: **pocket milling in high-temp alloys**

	Kennametal	Competitor
cutting speed (m/min):	610	23
feed per tooth:	0,08 mm	0,05 mm
axial cutting depth:	3,18 mm	3,18 mm
time per piece:	35 s	22 min
annual costs:	$2.397,-	$20.914,-

Annual Savings: $18.516,-

NEW!

- Use on high-temp alloys, PH stainless, and stainless steels
- For dry machining with internal air cooling.



Screw-On End Mills — RPGN1204

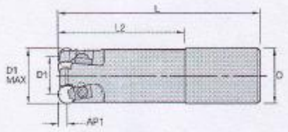
D1 max	order number	catalog number	Z	D1	D	L2	DPM	G3X	WF	Ap1 max	Max RPM
32	3101753	KIPR032RP12MF03	3	19,6	29	45	17	M16	22	6,3	20420

Spare Parts

D1 max	clamp	clamp screw	Nm
32	KCI3	129.512	6,0

NEW!

- Use on high-temp alloys, PH stainless, and stainless steels
- For dry machining with internal air cooling.



End Mills, cylindrical shank — RPGN1204

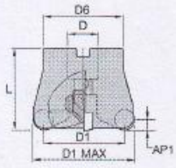
D1 max	order number	catalog number	Z	D1	D	L2	L	Ap1 max	Max RPM
32	3101754	KIPR032RP12CF03	3	19,6	32	50	110	6,3	20420
40	3101755	KIPR040RP12CF04	4	27,5	32	49	110	6,3	18260

Spare Parts

D1 max	clamp	clamp screw	Nm
32	KCI3	129.512	6,0
40	KCI3	129.512	6,0

NEW!

- First choice for face milling high-temp alloys.
- For dry machining with internal air cooling.



Shell Mills — RPGN1204

D1 max	order number	catalog number	Z	D1	D	D6	L	Ap1 max	Max RPM
50	3101756	KSSR050RP12CF04	4	37,5	16	44	50	6	16730
63	3101757	KSSR063RP12CF04	4	50,5	22	50	50	6	14900
80	3101758	KSSR080RP12CF05	5	67,5	27	60	50	6	13220
100	3101759	KSSR100RP12CF06	6	87,5	32	80	50	6	11830

Spare Parts

D1 max	clamp	clamp screw	Nm
50	KCI3	129.512	6,0
63	KCI3	129.512	6,0
80	KCI3	129.512	6,0
100	KCI3	129.512	6,0

Ordering Example:
1 x KIPR032RP12MF03
10 x RPGN120400E KY1540

CHAPTER ONE

INTRODUCTION

1.1 Research Background

Milling is a very commonly used manufacturing process in industry due to its versatility to generate complex shapes in variety of materials at high quality. Technology enhancement in machine tool, Computer Numerical Control (CNC), Computer Aided Design/Manufacturing (CAD/CAM), cutting tool and high speed machining in last couple of decades, increased the importance of milling role in industries such as aerospace, die and mould, automotive and component manufacturing.

Milling is a machining operation in which a workpart is fed past a rotating cylindrical tool with multiple cutting edges. There are two basic types of milling operation, peripheral milling and face milling. In peripheral milling, also called plain milling, the axis of the tool is parallel to the surface being machined and the operation is performed by cutting edges on the outside periphery of the cutter. In face milling, the axis of the cutter is perpendicular to the surface being milled, and machining is performed by cutting edges on both end and outside periphery of the cutter, as shown in Figure 1.1.

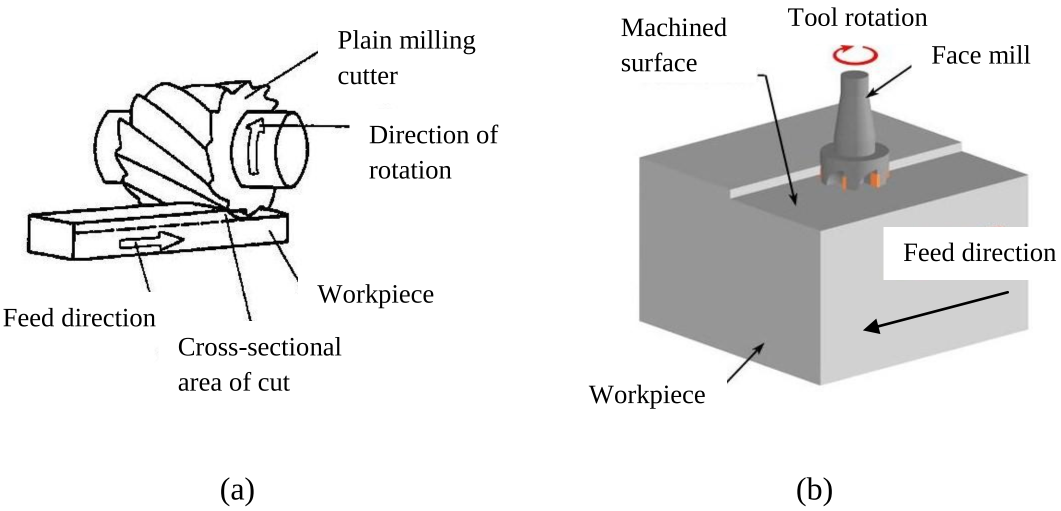


Figure 1.1: Machining operation (a) plain milling and (b) face mill

The cutting tool in milling machine is called a milling cutter and the cutting edges are called teeth, as shown in Figure 1.2. They remove material by their movement within the machine or directly from the cutters shape. Milling cutters come in several shapes and many sizes. There is also a choice of coatings, as well as rake angle and number of cutting surfaces. Insert or tip is the most commonly used as a cutting tool for machining steels.

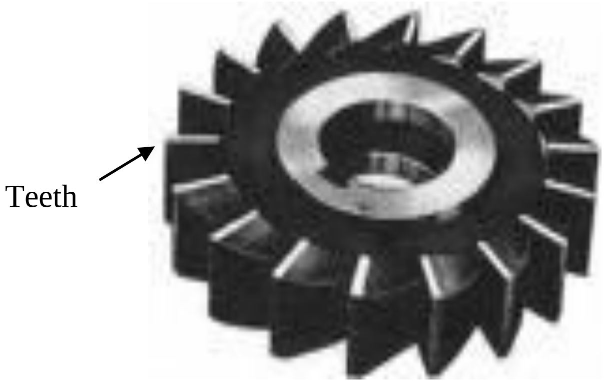


Figure 1.2: Milling cutter (taken from hssales.com)

A tipped tool or insert generally refers to any cutting tool where the cutting edge consists of a separate piece of material, screwed, brazed or clamped on to a separate body. Example in face mill, the tool consists of cutter body (with the appropriate machine taper) that is designed to hold multiple disposable carbide or ceramic inserts, often golden in colour, as shown in Figure 1.3. The inserts are not designed to be resharpened and are selected from a range of types that may be determined by various criteria, some of which may be; insert shape, cutting action required and material being cut. When the inserts are blunt, they may be removed, rotated (indexable insert) and replaced to present a fresh, sharp face to the workpiece, this increases the life of the insert and thus their economical cutting life.

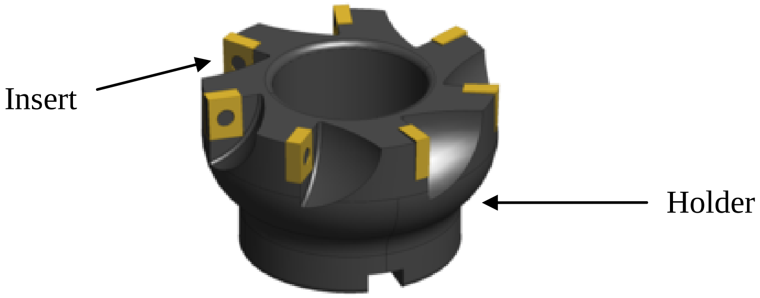


Figure 1.3: Carbide or ceramic inserts face mill cutting tool (taken from Wikipedia)

Nowadays, many studies are being done to develop cutting tool for optimal performance of machining. One of the problems that need to be overcome in achieving optimal performance is tool wear (Dutta et al., 2006). The origin and magnitude of various types of wear, such as flank wear, crater wear and notch wear are the dominant factors, which govern the machining performance of cutting tools. As a consequence, assessments of the performance of cutting tools are based on their wear behaviour and the primary assessment is often supplemented by characterization of chip morphology, cutting force and roughness of the generated surface (Ghani et al., 2002 and Smuk et al., 2003). All these factors for assessing the machining performance of a cutting tool are mutually inter-dependent, but Smuk et al., (2003) reported that the description of machining performance through progressive tool wear is considered most accurately assess the life of a tool, unlike the descriptions given by other parameters. Hence, studies related to tool wear are essential in the development of any advanced cutting tool material.

The range of material suitable for insert cutting tools for milling cutter of hardened steels includes cemented carbides, cermets, alumina based ceramics (Al_2O_3) and cubic boron nitride (CBN) (Camuscu and Aslan, 2005). Alumina-based materials are abundantly used as ceramic cutting tools because of their inherent properties of high hot hardness, abrasion resistance and chemical stability but the base material suffers from the limitation of low fracture toughness and low thermal shock resistance capability. In order to overcome the limitation of low fracture toughness, advanced alumina ceramics have been developed with the addition of zirconia, titanium carbide or silicon carbide (Azhar et al., 2009).

Kumar et al. (2006) reported that tool life of Ti[C,N] mixed alumina and zirconia toughened alumina ceramic cutting tool is affected by the flank wear at lower speed in lathe machining but on the other hand, at higher speed, it is affected by notch wear. The Ti[C,N] mixed alumina ceramic also be studied as an insert in end milling operation by Aslan (2005) and Camuscu and Aslan (2005). However, the tendency of this ceramic inserts to experience premature or catastrophic failure when machining in milling machine caused not many study about it was carried out in milling operation.

1.2 Problem Statement

This works examined the potential of a ceramic material developed as a tip or insert for slot milling operation in milling machine. The ceramic material developed by addition of yttria stabilized zirconia (YSZ) into the alumina matrix, known as zirconia toughened alumina (ZTA). ZTA can be further reinforced by adding the right amount of magnesium oxide (MgO). Due to its enhanced hardness, the likelihood of it experiencing fracture of failure and premature failure when machining is reduced.

Analysis of wear by Azhar et al. (2009) clearly indicates that the cutting inserts with 20 wt % YSZ mixed with alumina ceramic showed the lowest wear area of 0.039 mm^2 when turning 25 mm mild steel rods (AISI 1018). These inserts also experienced less wear compared to the inserts with bigger and smaller amounts of YSZ addition. A similar observation was made by Smuk et al. (2003) where the same composition showed the best mechanical properties.

A further study by Azhar et al. (2010) found that an addition of 0.7 wt % of MgO into the ZTA matrix (80 wt % alumina + 20 wt % YSZ) produced minimum wear area. When the amount of MgO was increased to more than 0.7 wt %, the wear area increased from 0.019 mm^2 to 0.065 mm^2. Thus, it can be concluded that ZTA cutting inserts fabricated with 0.7 wt % MgO show 50% improvement of wear compared to ZTA cutting inserts without MgO addition.

Previous researches, Azhar et al., (2009 and 2010) investigated the optimum material composition of ZTA reinforced with MgO but did not prove that the optimum composition will result in optimum performance when machining in lathe or milling. Also, the potential of these cutting inserts were not carefully investigated in lathe or milling operation.

Therefore, this research investigated the potential of these inserts from ZTA material, ZTA reinforced with MgO and commercial available cutting insert in slot milling operation. The performance of these cutting inserts when machining mild steel was investigated. Cutting tools performance was evaluated according to flank wear of the tool and surface roughness of the workpiece by using the appropriate microscope and surface surftest.

The amount of machining cutting times occupied by inserts that indicates inserts performances were evaluated according to the maximum flank wear of 0.3 mm measured from the flank wear image taken with Optical 3D Surface Metrology (ISO 8688-2, 1989). Workpiece surface roughness was evaluated to the maximum average roughness, R_a of 1.6 µm measured using Surftest Sufrcom 130A (ASME B46. 1-1995 Standard, 1996). This slot milling operation used AISI 1018 mild steel as a workpiece material.

1.3 Research Objectives

This research investigated the potential of ZTA material and ZTA reinforced with addition of MgO developed as inserts for machining in slot milling operation. The objectives of this study were indentified:

i. To design and fabricate die for pressing ceramic powder and subsequently used to produce ZTA and ZTA-MgO inserts from combination of mixing alumina, YSZ and MgO powders.
ii. To investigate the performance of ZTA and ZTA-MgO inserts through suitable slot milling operation based on machining cutting time and surface roughness on workpiece.
iii. To compare the performance of these inserts with chosen commercial ceramic insert at the same slot milling operation.

1.4 Thesis Outline

Chapter One explained about an introduction and initial setup for running this research. The current problem of the research was discussed. This chapter also explained about research objectives and methodology.

Chapter Two defined literature review used in this research. The metal removal processes were discussed. It explained types of operation involved in metal removal process and parameter that contribute to the performance of metal removal process. The researches and studies about materials and machining processes were review carefully.

In Chapter Three, explained about the procedure concerning the study on the die, ceramic cutting tools and milling machining. It was discussed the methodology and procedure to design and fabricate the die for powder pressing, preparing the ceramic cutting tool and setup the assessment for insert performance in slot milling operation.

Chapter Four explained the finding onto the raw materials used in this research. It also discussed the data acquired from the slot milling operation. The data was compared and the result was discussed.

Chapter Five accumulated the finding and result obtained from the testing. The conclusion for this research was explained. It also discussed the suggestion for the next research.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the literature review on metal removal process, the types of operation involved in metal removal process and parameter that contribute to the performance of metal removal process. It also discussed cutting tool which involved in metal removal process, its material and tool wear.

2.2 Metal Removal Process

There are many ways to remove excess material from a workpiece in material removal processes and leaving the desired final geometry. Material removal processes as illustrated in Figure 2.1, consist of three types. The most important of the process is conventional machining, in which a sharp cutting tool is used to mechanically cut the material to achieve the desired geometry.

The three principal of machining process are turning, drilling and milling. The other machining operations include shaping, planning, broaching and sawing. Another group is abrasive processes, which mechanically remove material by the action of hard, abrasive particles. The other abrasive processes include honing, lapping and superfinishing. Finally, there are the nontraditional processes, which use various energy forms other than a sharp cutting tool or abrasive particles. The energy includes mechanical, electrochemical, thermal and chemical (Groover, 2007).

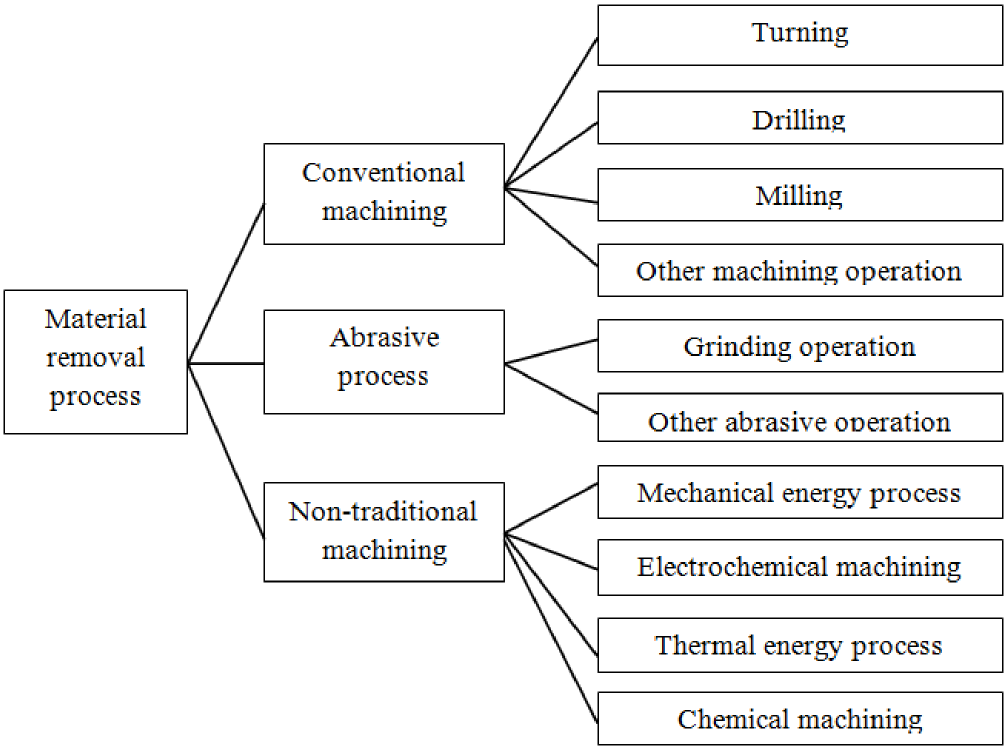


Figure 2.1: Classification of material removal processes

Machining is a manufacturing process in which a sharp cutting tool is used to cut away material to leave the desired part shape. The predominant cutting action in machining involves shear deformation of the work material to form a chip; as the chip is removed, a new surface is exposed. Machining is most frequently applied to shape metal (Groover, 2007).

2.2.1 Milling

Milling is a very commonly used manufacturing process in industry due to its versatility to generate complex shapes in variety of materials at high quality. Milling is a machining operation in which a workpart is fed past a rotating cylindrical tool with multiple cutting edges. The axis of rotation of the cutting tool is perpendicular to the direction of feed. The machine tool that traditionally performs this operation is a milling machine. Milling is an interrupted cutting operation; the teeth of the milling cutter enter and exit the work during each revolution. This interrupted cutting action subject the teeth to a cycle of impact force and thermal shock on every rotation. The tool material and cutter geometry must be designed to withstand these conditions.

There are two basic types of milling operation, peripheral milling and face milling. In peripheral milling, also called plain milling, the axis of the tool is parallel to the surface being machine and the operation is performed by cutting edges on the outside periphery of the cutter. Several types of periphery milling are:

a) Slab milling

   The basic form of peripheral milling in which the cutter width extends beyond the workpiece on both sides.

b) Slotting also called slot milling

   Width of the cutter is less than the workpiece width, creating a slot in the workpiece.

c) Side milling

   The cutter machines the side of the workpiece.

d) Straddle milling

   Same as side milling, only cutting takes place on both sides.

While in face milling, the axis of the cutter is perpendicular to the surface being milled, and machining is performed by cutting edges on both the end and outside periphery of the cutter, as shown in Figure 2.2.

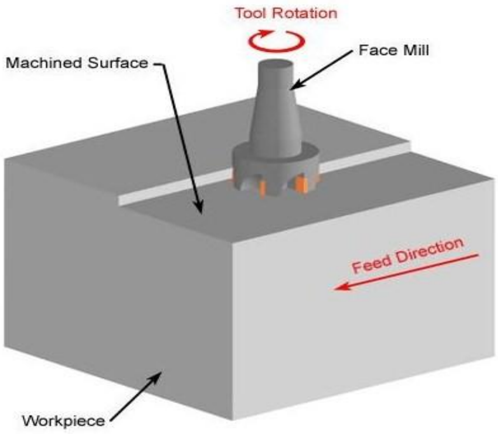


Figure 2.2: Machining operation, face mill (from custompartnet.com)

As in peripheral milling, various forms of face milling exist like:

a) Conventional face milling

   The diameter of the cutter is greater than the workpiece width, so the cutter overhangs the work on both sides.

b) Partial face milling

   The cutter overhangs the workpiece on only one side.

c) End milling

   The diameter of the cutter is less than workpiece width, so a slot is cut into the part.

d) Profile milling

   A form of end milling in which the outside periphery of a flat part is cut.

e) Pocket milling

   Another form of end milling used to mill shallow pockets into flat parts

f) Surface milling

   In which a ball nose cutter is fed back and forth across the work along a curvilinear path at close intervals to create a three dimensional surface form.

2.3 Dry Machining

In some cases, machining without using cutting fluids (dry machining) can successful be implemented in the industrial machining applications. Dry machining has two main impacts: an ecological impact and an economic one. Indeed, the absence of cutting fluids preserves the environment and reduces the production costs of 16% to 20% (Sreejith and Ngoi, 2000). That is why several European countries incite the metal cutting industries to use dry machining.

Cutting fluids are used in metal cutting process as a lubricant and coolant. Their absence in machining means a high friction and a high cutting temperature at the tool – workpiece interface. This drastically affects tool wear and tool life. Therefore, dry machining represents a great challenge to manufacturing engineers because of the high temperatures generated especially when machining aerospace materials as titanium and nickel based superalloys. For dry machining applications, the cutting tool can be design in three different ways by: using new tool materials, adapting new tool geometries and applying different coating materials (Nouari and Ginting, 2006).

2.4 Cutting Tool

Developments in cutting tools and machine tools in the last few decades have made it possible to cut material in their hardened state. The advantages of producing components in hardened state can be listed as: reduction of machining costs, reduction of lead time, reduction of number of necessary machine tools, improved surface integrity, reduction of finishing operations and elimination of part distortion caused by heat treatment (Koshy et al., 2002 and Fallbohmer et al., 2000).

Alumina (Al_2O_3) based ceramics are considered to be one of the most suitable cutting tool materials for machining hardened steels because of their high hot hardness, wear resistance and chemical inertness (Dewes and Aspinwall, 1997). On the other hand, Al_2O_3 based tools have a high degree of brittleness which usually leads to a short tool life due to excessive tool chipping or fracture especially when machining hardened materials. In order to improve toughness, Al_2O_3 based ceramic cutting tools are usually reinforced with TiC, TiN, ZrO_2, (W,Ti)C, Ti(C, N), SiC_p, SiC_w, TiB_2 additions (Baldoni and Buljan, 1998; Li, 1994 and Jianxin and Xing, 1997). These additions result in some improvement, but the toughness of Al_2O_3 based tools are still much less than that of other tools such as cemented carbides. As a result, the possibility of sudden failures when machining hardened materials with Al_2O_3 based ceramics is very high (Aslan, 2005).

The wear performances of cutting tools such as cubic boron nitride (CBN), ceramic, coated carbide and fine-grained carbide in high-speed face milling were investigated by Liu et al. (2002) when cutting cast iron, 45# tempered carbon steel and 45# hardened carbon steel. The results showed that the tool wear types differed in various matching of materials between the cutting tool and the workpiece. The dominant wear patterns observed were rake face wear, flank wear, chipping, fracture and breakage. The main wear mechanisms were mechanical friction, adhesion, diffusion and chemical wear promoted by cutting forces and high cutting temperature.

Carbides are the most common tool material for machining of castings and alloy steels. These tools have high toughness, but poor wear characteristics compared to advanced tool materials such as CBN and ceramics. In order to improve the hardness and surface conditions, carbide tools are coated with hard materials such as TiN, TiAlN, and TiCN by physical vapour deposition (PVD) and chemical vapour deposition (CVD). The cutting tools used in high speed cutting of different work materials include CBN and Si_3N_4 for cast iron, TiN and TiCN coated carbide for alloy steel up to 42 HRC and TiAlN coated carbide for alloy steels with 42 HRC and over (Dewes and Aspinwall, 1997). CBN inserts with appropriate edge preparation can be used for special applications especially hard turning with 60–65 HRC (Liu et al., 2002).

Despite the superior hardness and cutting performance of CBN tools, ceramic tools are generally preferred for high speed continuous machining because of their much lower cost (Kumar et al., 2006). The use of polycrystalline boron nitride and ceramic tools in machining hard die and tool steels was discussed by Dewes and Aspinwall (1997). In that study, tool life data was presented for a range of materials in turning and end milling operations.

2.4.1 Ceramic Cutting Tool

Ceramics cutting tool material are introduced in the early 1950s, which consists of primarily fine grained, high purity aluminium oxide or alumina (Al_2O_3). They are pressed into inserts shapes at room temperature and under high pressure, sintered at high temperature and called white, or cold pressed ceramics (Kalpakjikan and Schmid, 2003).

Al_2O_3-base ceramic tools have very high abrasion resistance and hot hardness. Furthermore, they are chemically stable than high speed steels and carbides. Thus, they have tendency to adhere to metals during cutting and hence, less tendency to form a built up edge. Good surface finish is also obtained with ceramic tools in cutting cast irons and steels. Unfortunately, ceramics especially Al_2O_3 lack of toughness which result in premature tool failure by chipping or catastrophic failure (Kalpakjikan and Schmid, 2003).

The shape and setup of ceramic tool are important. Negative rake angles, and hence large included angles, are generally preferred in order to avoid chipping due to poor tensile strength. The occurrence of tool failure can be reduced by increasing the stiffness and damping capacity of machine tools, mounting and work holding devices thus reducing vibration and chatter (Kalpakjikan and Schmid, 2003).

Trent and Wright, (2000) also reported that Al_2O_3 is one of the refractory oxides have been among the many substances of high hardness and melting point investigated as potential cutting tool materials. Throw-away tool tips consisting of nearly 100% Al_2O_3 has been available commercially for more than 30 years, and has been used in many countries for machining steel and cast iron.

The successful tool materials consist of fine-grained (less than 5 μm) Al_2O_3 of high relative density, containing less than 2% porosity. Several different methods have been used to make tool tips which combine these two essential structural features, including:

(i) Pressing and sintering of individual tips by a process similar to that used for cemented carbides. Sintering is carried out in air and the tool tips are white.

(ii) Hot pressing of large cylinders of Al_2O_3 in graphite moulds, the tool tips being cut from the cylinders with diamond cutting wheels. The tool tips are dark gray (Trent and Wright, 2000).

Nowadays, a wide range of neoceramics type are currently being used and developed as cutting tools, including Al_2O_3, Al_2O_3/ZrO_2, SiC whiskers reinforced Al_2O_3, Al_2O_3/TiC and Si_3N_4 composites. Furthermore, microstructures are being optimized for high strength, toughness and hardness (D`Erico et al., 1999).

2.4.2 Al_2O_3 as a Cutting Tool

With the development of modern ceramic tool materials, Al_2O_3-based ceramic cutting tools are widely used for machining hard materials such as cast irons having wide range of hardness, plain carbon steels and alloy steels having a hardness range of HRC 34 to HRC 66, stainless steels and high temperature alloys as they have high hot hardness and very good chemical stability (Kumar et al., 2003). At present, Al_2O_3-based ceramic tool material is one of the most widely used in practice. Researches on the Al_2O_3-based ceramic tool materials during the past years are primarily focused on the addition of one or several of the reinforcement phases, such as TiC, TiN, TiB_2, (W,Ti)C, Ti(C,N), ZrO_2, SiC_P and SiC_W into Al_2O_3 matrix (Xu et al., 2001). Table 2.1 shows the mechanical properties of Al_2O_3 which makes it one of the widely chosen material for cutting tools application.

Table 2.1: Mechanical properties of Al_2O_3 (Uday, 2000)

Properties	Values
Density (g/cm^3)	3.96
Poisson ratio	0.2
Elastic modulus (GPa)	400
Flexural strength (MPa)	340
Vickers hardness (HV)	1900
Fracture toughness ($MPa.m^{1/2}$)	4.0

2.4.3 Problem with Al_2O_3 Monolithic Cutting Tools

In spite of the variety of useful physical properties of sintered oxide ceramics based on chemically and thermally stable alpha modification of α-Al_2O_3 , their application as cutting tool inserts working under mechanical loads and thermal shock conditions is limited due to their brittleness and low strength. One of the methods to improve these properties is by making use of the transformation strengthening process, through phase transformation of some amount of ZrO_2 introduced into Al_2O_3 (Smuk et al., 2003).

Like most oxides, Al_2O_3 has high chemical stability that allows it to be inert in most environments. A disadvantage is the low resistance of Al_2O_3 to thermal and mechanical shocks compared with tungsten carbide. The poor toughness and resistance to fracture can be improved by addition of zirconium oxide. The thermal shock properties can be improved by addition of a secondary ceramic phase. The material that is more commonly added is titanium carbide, but other materials can also be used, such as titanium nitride. However, the resistance to mechanical shock remains low (D`Erico et al., 1999).

Xu et al., (2001) stated that the brittle nature that exists inside monolithic Al_2O_3 plays as a fatal weakness even with modern and high technology way of processing. To overcome this problem, efforts have been made by reinforcing Al_2O_3 with SiC whiskers and ZrO_2 particles.

2.4.4 Alumina Based as Cutting Insert for Milling

Alumina-based composite ceramic cutting tools are widely used for machining hard material such as cast iron having wide range of hardness, plain carbon steels and alloy steels having a hardness range of HRC 34 to HRC 66, stainless steels and high temperature alloys as they have high hot hardness and very good chemical stability (Kumar et al., 2003).

Alumina based ceramic cutting tools are mainly classified as plain oxide alumina ceramic cutting tool, mixed alumina ceramic cutting tool and whisker reinforced alumina ceramic cutting tool. When zirconium oxide is added to the aluminium oxide matrix, the resulting ceramic tools are called plain oxide ceramic cutting tools. Fracture toughness of the ceramic composite increases by the addition of zirconia in alumina matrix (Sornakumar, 1995). When non oxide particles like TiC and TiN are added in the aluminium oxide matrix, they are called mixed alumina ceramic cutting tools. The addition of TiC and TiN in the alumina matrix increases hardness and thermal conductivity (Kim, 1994). When whiskers like silicon carbide are reinforced in the aluminium oxide matrix, they are called whisker reinforced alumina ceramic cutting tools. SiC whisker reinforcement in alumina matrix increases the fracture toughness of the composite. The main advantage of the whisker reinforcement is the improved strength and toughness (Kim, 1994).

Aslan (2005) used the TiCN mixed alumina ceramic in end milling operation using hardened tool steel as a workpiece. The result showed that the mixed ceramic tools can be used confidently up to a certain limit but then sudden failure occurred and rapidly completed its life because of excessive chipping. Another research by Camuscu and Aslan (2005) stated that the TiCN mixed alumina ceramic tools can be used in end milling of hardened tool steels. However, the mixed alumina tool underwent excessive chipping and rapidly completed its life after machining a certain limit of workpiece. Another TiCN mixed alumina ceramic tools study was made by Grzesik (2009) which examined the wear progress and appropriate wear mechanisms in turning alloy steel of 60 HRC hardness.

Other than that, alumina can be reinforced with YSZ. Analysis of wear area by Azhar et al. (2009) clearly indicates that the cutting inserts with YSZ addition produced lower wear area compared to alumina cutting inserts without YSZ addition when turning 25 mm mild steel rods (AISI 1018). Azhar et al. (2010) also investigated the potential of mixture with MgO additive.

The application of alumina reinforced with YSZ and added with MgO was investigated at turning operation by Azhar et al. (2009 and 2010). However, the potential of these cutting tools was not carefully investigated in milling operation. Therefore, this research investigated the potential of these cutting tools in end milling operation.

2.5 Zirconia

Zirconium dioxide (ZrO_2), widely known as zirconia, is a white crystalline oxide of zirconium. Its most naturally occurring form, with a monoclinic crystalline structure, is the rare mineral, baddeleyite. The high temperature cubic crystalline form, called 'cubic zirconia', is rarely, if ever, found in nature, but is synthesized in various colors for use as a gemstone (Basu, 2005).

Zirconia oxide is one of the most studied ceramic materials. Pure ZrO_2 has a monoclinic crystal structure at room temperature and transitions to tetragonal and cubic at increasing temperatures. The volume expansion caused by the cubic to tetragonal to monoclinic transformation induces very large stresses, and will cause pure ZrO_2 to crack upon cooling from high temperatures. Several different oxides are added to zirconia to stabilize the tetragonal and/or cubic phase: magnesium oxide (MgO), yttrium oxide, (Y_2O_2), calcium oxide (CaO), and cerium oxide (Ce_2o_3), amongst others (Basu, 2005).

According to Basu (2005), transformation toughening occurs when the zirconia is in the metastable tetragonal phase. This can be achieved by stabilizing the tetragonal phase with another oxide. For example, by adding yttria to zirconia, the transformation temperature can be reduced to 550 ^{o}C as shown in Figure 2.3. An additional driving force is needed to overcome the large nucleation barrier in stabilised zirconia. The necessary driving force can be provided by external stresses such as a crack tip, and residual stress. The residual stress increases with increasing grain size so that the grain size must be sufficiently small to avoid the phase transformation during cooling.

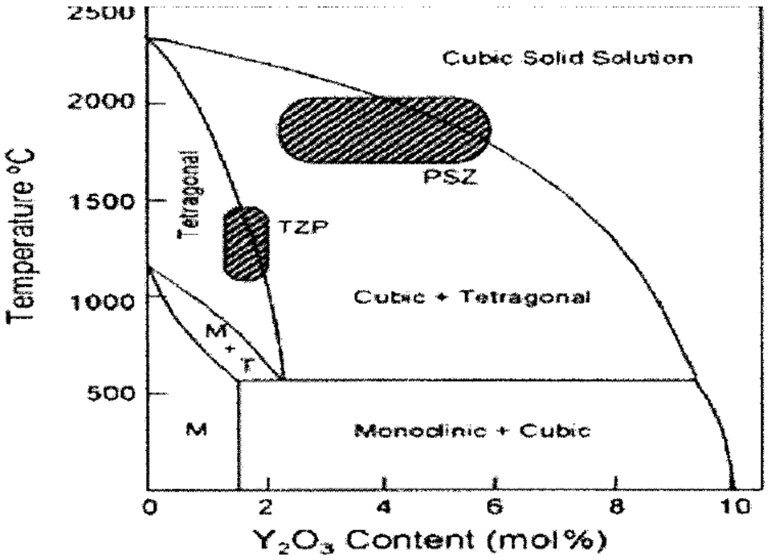


Figure 2.3: Phase diagram for zirconia-yttria system (Basu, 2005).

The influence of the grain size on the transformation process can be explained with a simple model. Consider a corner inside a grain of tetragonal zirconium oxide, embedded in a matrix with a different coefficient of thermal expansion. Due to thermal stresses, a stress singularity will form in this edge, and the stresses near the edge will thus be very large. In a certain region near the corner, the stress is sufficiently large to initiate the phase transformation. To grow, this transformed region must be sufficiently large. The size of the region in which the necessary stress is reached is proportional to the grain size. Therefore, the transformation can occur during cooling in large grains, but not in small ones (Basu, 2005).

2.5.1 Yttria Stabilized Zirconia (YSZ)

Sergo et al., (1998) reported that zirconia toughened Al_2O_3 have been established as a good alternative compared to traditional cemented carbide tools due to their lower wear rate. They also noted that previous statement eliminates any major bulk transformation due to firing or sintering conditions.