Machinability of Titanium Alloys*

Mustafizur RAHMAN**, Yoke San WONG**
and A. Rahmath ZAREENA**

Titanium and its alloys find wide application in many industries because of their excellent and unique combination of high strength-to-weight ratio and high resistance to corrosion. The machinability of titanium and its alloys is impaired by its high chemical reactivity, low modulus of elasticity and low thermal conductivity. A number of literatures on machining of titanium alloys with conventional tools and advanced cutting tool materials is reviewed. The results obtained from the study on high speed machining of Ti-6Al-4V alloys with cubic boron nitride (CBN), binderless cubic boron nitride (BCBN) and polycrystalline diamond (PCD) are also summarized.

Key Words: Titanium, High-speed Machining, CBN, BCBN, PCD Tools, High-pressure Coolant

1. Introduction

In spite of being a difficult-to-machine material, titanium and its alloys find wide applications in aerospace, biomedical, chemical, automotive and petroleum industries because of their excellent physical and metallurgical properties. But Siekman pointed out that "machining of titanium and its alloys would always be a problem, no matter what techniques are employed to transfer this metal into chips⁽²⁵⁾". Komanduri and Reed have commented that "this is still true in so far as cutting tool materials are concerned"⁽¹⁵⁾. Thus in an attempt to find an appropriate cutting tool material for machining titanium alloys, a number of literatures about the machinability of titanium and its alloys and cutting tool materials that had been used for machining titanium alloys had been reviewed. Also literatures relevant to high speed machining and high pressure coolant are discussed.

2. Machinability of Titanium and Its Alloys

Machinability of a material can be defined and measured as an indication of the ease or difficulty with

which it can be machined. The machinability of a material may be assessed by tool life, limiting rate of metal removal, cutting forces, surface finish or chip shape⁽²⁸⁾.

Many research works have been carried out to study the machinability of titanium and its alloys. The machinability of titanium and its alloys is generally considered to be poor owing to their several inherent properties that classify them as difficult-to-machine materials.

The principal problems in machining them are the high cutting temperatures and the rapid tool wear. Most tool materials wear rapidly even at moderate cutting speeds. To minimize the tool wear, current machining practice limits the cutting speed to less than 60 m/min. The machining characteristics for titanium and its alloys are summarized as⁽²⁴⁾,

1. Titanium and its alloys are poor thermal conductors. As a result, the heat generated when machining titanium cannot dissipate quickly; rather, much of the heat is concentrated on the cutting edge and tool face.
2. Titanium has a strong alloying tendency or chemical reactivity with the cutting tool material at tool operation temperatures. This causes galling, welding and smearing along with rapid wear or cutting tool failure.
3. During machining, titanium alloys exhibit ther-

* Received 1st April, 2002 (Review)

** Department of Mechanical Engineering, National University of Singapore, Kent Ridge, Singapore-119260. E-mail: mpemusta@nus.edu.sg

mal plastic instability which leads to unique characteristics of chip formation. The shear strains in the chip are not uniform but they are localized in a narrow band that forms serrated chips.

4. The contact length between the chip and the tool is extremely short (less than one third the contact length of steel with the same feed rate and depth of cut). This implies that the high cutting temperature and the high stress are simultaneously concentrated near the cutting edge (within 0.5 mm).

5. Serrated chips create fluctuations in the cutting force. This situation is further promoted when alpha-beta alloys like Ti-6Al-4V are machined. The vibrational force together with the high temperature exerts micro-fatigue loading on the cutting tool, which is believed to be partially responsible for severe flank wear.

Titanium is chemically very reactive and therefore, has a tendency to weld to the cutting tool during machining, thus leading to chipping and premature tool failure. Its low thermal conductivity increases the temperature at the tool-work interface, which affects the tool life adversely. Additionally, its high strength maintained at elevated temperature and its low modulus of elasticity further impairs its machinability⁽⁷⁾.

Titanium and its alloys are notorious for their poor thermal properties and are classified as difficult-to-machine materials. In their review article, Xiaoping and Liu had listed the possible reasons making titanium and its alloy difficult-to-machine as the poor thermal properties, low thermal conductivity, high strength maintained at elevated temperature, high chemical affinity and low modulus of elasticity⁽³²⁾.

Zoya and Krishnamurthy⁽³⁴⁾ discussed the factors that affect the machining of titanium and its alloys. They have stated that the machining of titanium alloys is a thermally dominant process. With the increase in cutting speed, the temperature produced also increased (Fig. 1). During the machining of titanium alloys, tool wear progresses rapidly because of the high cutting temperature and strong adhesion between the tool and the work material, owing to their low thermal conductivity and high chemical reactivity⁽¹⁵⁾.

As illustrated in the Fig. 2, about 80% of the heat generated when machining titanium alloy Ti6Al4V is conducted into the tool because it cannot be removed with the fast flowing chip or into the workpiece due to the low thermal conductivity of titanium alloy, which is about 1/6 that of steels. The progress in the machining of titanium alloys has not kept pace with advances in the machining of other materials due to their high temperature strength, very low thermal

Fig. 1 Variation of cutting temperature with time⁽³⁴⁾

Fig. 2 Distribution of thermal load when machining titanium and steel⁽⁶⁾

conductivity, relatively low modulus of elasticity and high chemical reactivity⁽⁵⁾.

Therefore, success in the machining of titanium alloys depends largely on overcoming the principal problems associated with the inherent properties of these materials, such as high cutting temperature, high cutting pressure and chatter with additional criteria for tool materials. Thus machining of titanium alloys requires tools with high hardness, wear durability, hot hardness, good thermal resistance and high co-efficient of thermal conductivity.

3. Cutting Tool Materials for Titanium Alloys

The paramount qualities required by the tool materials to machine titanium alloys are (i) high hot hardness to resist the high stress involved, (ii) good thermal conductivity to minimize thermal gradi-

ents and thermal shock, (iii) good chemical inertness to depress the tendency to react with titanium, (iv) toughness and fatigue resistance to withstand the chip segmentation process and (v) high compressive, tensile and shear strength⁽⁶⁾.

Titanium and its alloys represent the most challenging materials in machining. With advances in cutting tool materials, many difficult-to-machine materials can now be machined at a higher metal removal rates. None of these tool materials, however seems to be effective in machining titanium alloys because of their chemical affinities with titanium. New development in tool coating also does not help titanium machining⁽²⁴⁾.

According to the Material Properties Handbook—Titanium alloys (ASM), general purpose high-speed tool steels such as M1, M2, M7 and M10 are often suitable for machining titanium alloys. However, best results are generally obtained with more highly alloyed grades, such as T5, T15, M33 and M40 series. The cutting speed of the HSS tools for machining Ti-6Al-4V alloys is restricted to 30 m/min. The straight tungsten carbide WC cutting tools, typically C-2 grades, performed best in operations such as turning and face milling, while the high-cobalt, high-speed steels were most applicable in drilling, tapping and end milling (88 m/min).

Traditionally, the advice was to carry out the machining of titanium-based alloys with uncoated tools. Manufacturing engineers were against using tools with a titanium nitride (TiN) or carbonitride (TiCN) coating, due to the possible chemical reactions amongst the different titanium components, given the high chemical reactivity of this material. Zirconium and Hafnium nitride coatings have been used with HSS tools and for the machining of titanium alloys, but they have not been very successful. However, Chrome nitride (NCr), titanium carbonitride (TiCN) and titanium aluminium nitride (TiAlN) appear to be more promising⁽²⁹⁾.

Lopez, et al.⁽¹⁷⁾ found that both the TiCN and NCr coated tools developed high flank wear in the cutting edges, as well as notch wear at the depth of cut level. Uncoated hard metal tools show maximum flank wear and formation of burrs at the initial stage of machining where as coated HSS mills suffer this wear a little later. Komanduri and Lee⁽¹⁴⁾ used cemented carbide ledge tools for turning and face milling of titanium alloys and concluded that the wear occurs predominantly by micro chipping, and also ledge tools produced excellent finish in both turning and face milling.

Straight tungsten carbide (WC/Co) cutting tools have proven their superiority in almost all machining

processes of titanium alloys and interrupted cutting (end milling, tapping, broaching and planing), drilling and reaming being performed best by high speed steel tools. Waiter, et al.⁽³⁰⁾ in their study advises that straight cobalt-base tungsten carbide cutting tools implanted with either chlorine or indium are very effective in the machining of titanium and their alloys.

It has been proven that steel cutting grades of cemented carbides are not suitable for machining titanium alloys because of the greater wear rate of the mixed carbide grains than that of the WC grains because of their thermal properties. All coated carbide tools tested also show greater wear rates than those of straight grade cemented carbides⁽¹⁶⁾.

In their study, Kertesz et al.⁽¹¹⁾ stated that, even though ceramics have improved in quality and focused increased application in the machining of difficult-to-cut materials, especially high-temperature alloys, they have not replaced cemented carbides and high-speed steels due to their poor thermal conductivity and their relatively low fracture toughness and their reactivity with titanium.

PVD-TiN and CVD-TiCN+Al₂O₃ coated carbide inserts when used for face milling Ti-6Al-4V alloys, attrition and diffusion wear mechanism were responsible for the flank wear of both the coated tools. Generally, CVD coated tools outperformed the PVD coated tools. It was established that straight-grade cemented carbides are suitable for the machining of titanium alloys (Ti-6246). Diffusion-dissolution and attrition were the dominant wear mechanism of cemented WC-Co tools⁽⁸⁾.

Badzian et al.⁽¹⁾ suggested that crystalline silicon carbonitride has some physical properties like hardness, oxidation resistance and corrosion resistance that can compete with cubic boron nitride. The tool life of cemented carbide cutting tools was greatly improved by applying a diamond coating for processing non-ferrous materials⁽⁹⁾.

Superhard cutting tool materials such as cubic boron nitride and polycrystalline diamond have also shown good performance in term of wear rate in the machining of titanium. However, their applications are limited due to their high price⁽²⁸⁾. Different mechanisms, such as plastic deformation of flank materials, dissolution and low-cycle fatigue can be associated with the tool wear of CBN tools while machining titanium alloys⁽³⁴⁾. The recommended cutting speed range was 185 – 220 m/min.

In 1995, Bhaumik et al.⁽⁶⁾ developed a wBN-cBN composite tool obtained by high-pressure/high temperature sintering of wurtzite boron nitride powder, for machining Ti-6Al-4V alloys. Their investigation indicated that this composite tool can be used econom-

ically to machine titanium alloys. The success of the composite tools is due to its high fracture toughness coupled with high hardness and especially, hot hardness. The predominant wear mechanism has been identified to be due to diffusion-dissolution process.

High CBN content tool (CBN-H) and low CBN content tool (CBN-L) have distinct wear characteristics. CBN-H has better wear resistance to mechanical impact whereas the metallic binder cobalt and aluminum accelerates tool wear rapidly at high cutting speeds due to its affinity with work materials⁽¹²⁾. Zone and Din-yan⁽³³⁾ reported that CBN tools can be used for cutting hard-to-machine materials. In view of their superior quality in terms of the resultant surface roughness, it can replace a portion of the grinding work. Therefore, it possesses considerable economic potential. When CBN tools are used to cut hardened hard-to-cut materials, with a shallow depth of cut, the thrust force is greater than the cutting force. On the contrary, with a great depth of cut, the cutting force is greater than the thrust force.

In a study by Brookes et al.⁽⁴⁾ on the machining of titanium alloys with PCD tools, it was reported that the inter-diffusion of titanium and carbon resulted in the formation of titanium carbide layer on the rake face. This layer adhered to the substrate and prevented further diffusion of the tool material into the chip.

Beltrame et al.⁽²⁾ has reported that finishing milling of titanium alloy Ti-6Al-4V turbine blades with PCD cutter is promising. PCD cutters have low chemical solubility in titanium to reduce diffusion and it has sufficient hardness and mechanical strength to maintain physical integrity. Their conclusion is that PCD is thus a material worthy of being considered for machining titanium alloys.

When turning Ti6Al4V with PCD cutters at low cutting speed, (80 m/min), the wear is at a low level and is mainly determined by diffusion of the carbon from the diamond into chip material. In a cutting speed range of between 80 and 120 m/min, a transition-induced wear at a substantially higher level takes place, with the rate depending on the binder phase and diamond grain size of the PCD⁽¹⁶⁾. In his study, Farhad Nabhani⁽⁶⁾ had stated that PCD would appear to be the most functionally satisfactory commercially available cutting tool material for machining titanium alloys.

4. High-Speed Machining of Titanium Alloys

In general, for high productivity, the rate of metal removal can be increased by (i) increasing the depth of cut, (ii) increasing the feed rate or (iii) by increasing the cutting speed. But the increase in depth of cut and feed rate results in high cutting force and also affect the quality of the surface to be produced.

Thus the most effective way of increasing the metal removal is to increase the cutting speed, with tools that can retain hardness and strength at higher temperature so that they are suitable for the high cutting speeds⁽¹⁰⁾.

The definition for high-speed machining depends on the work and tool materials concerned. In general, when cutting plain carbon steels using sintered carbide tools, the most common combination, cutting speeds of over 300 m/min fall into the high speed machining range. For aerospace materials including titanium alloys, on the other hand, the conventional cutting speed range is from 30 to 100 m/min using sintered carbide tools⁽¹³⁾.

High speed machining (HSM) has received considerable interest because it improves the productivity of the metal removing operation and leads in general, to an excellent surface finish and dimensional accuracy⁽²⁷⁾. The advantages of high speed machining include, high material removal rate resulting in increased productivity and better utilization of the machine tool, lower cutting force and accuracy leading to improved part quality, better chip disposal and fewer burrs, and reduced cutting tool inventories since roughing and semi-finishing are carried out with a single tool. All these advantages have led to the usage of HSM in the machining of aerospace alloys⁽²¹⁾.

For the difficult-to-cut materials like titanium alloys, the demand for high speed machining is increasing in order to achieve high productivity and to save machining cost⁽²³⁾.

5. Application of High-Pressure Coolant

To overcome the high temperature produced during high speed machining, cutting fluids are used. In addition, cutting fluids are used to improve surface finish, to minimize welding and to reduce the residual stress while machining titanium alloys.

There are many problems encountered during the machining of titanium alloys, among which the prominent one is the high temperature produced during machining. Since the thermal conductivity of titanium alloys is very low (about 15 W/m°C) the cutting temperatures in the tool and the workpiece rise significantly during the machining of these advanced materials. The high temperature produced in the cutting tool and the workpiece leads to a shorter tool life and a poor surface quality⁽³¹⁾. Thus by reducing the cutting temperature, the machining performance can be enhanced.

High-pressure water jet coolant (Fig. 3) has been applied to reduce the cutting temperature on the insert. This method is promising in improving machinability of titanium and its alloys. Lopez et al.⁽¹⁷⁾

stated that improvement in the machining of hard-to-cut materials can be achieved by using high pressure coolant. This will reduce the high temperature produced during machining and thus improve the tool life.

Machado, et al.⁽¹⁹⁾ has reported that improved tool life by up to 300% (Fig. 4) been achieved when machining Ti-6Al-4V alloy using high pressure cooling, which ensures improved coolant penetration to the cutting interface, and thereby reduces the temperature of the cutting tool that in turn reduces diffusion wear rate. As shown in Fig. 5, the high-pressure coolant jet eliminates the welding of chip with tool by breaking and flushing the chips.

Maximum flank wear has been found to be the prominent failure mode when machining with both conventional and high-pressure cooling. High-pressure coolant seems to be very effective while machining at low feed rate. (Rahman et al.)

The use of LN_2 coolant largely decreases the temperature in the tool and workpiece that in turn increases the useful life of the tool. A new economical cryogenic machining approach developed by Hong et

Fig. 3 Coolant jet Geometry (dimensions in mm) Machado et al.

Fig. 5 Schematic diagram of chip fragmentation caused by High pressure cooling system (Machado, et al.)

al.⁽²⁴⁾ uses a minimum amount of LN_2 injected through a micro-nozzle formed between the chip breaker and the tool rake and assisted by the secondary nozzle for flank cooling. They claim that this cryogenic machining approach yields the best tool life compared with any machining method from current know sources.

6. Recent Study on High-Speed Machining of Ti-6Al-4V Alloy

In this study in National University of Singapore, high speed machining (end-milling) of Ti-6Al-4V alloys was carried out using CBN, Binderless CBN (BCBN) and PCD tools and the results obtained were compared. The BCBN tools, developed by Sumitomo Electric Industries Ltd., Japan, are yet to be commercially available. Experiments were done in a wide range of cutting speed (200 – 450 m/min), feed (0.05 – 0.2 mm/tooth) and depth of cut (0.05 – 0.2 mm) using high pressure coolant (40 bar).

Fig. 4 Tool lives obtained after machining Ti6Al4V with both conventional and high pressure coolant system at various cutting conditions. (Machado, et al.)

Excellent results were obtained when BCBN tools were used for machining gray cast iron. The cutting edge of BCBN tools remained sharp after long time machining because high purity CBN maintains the binding strength between CBN particles even at high temperature during machining. On the other hand the tip of conventional CBN tools became round. This is because of the dropping of the CBN from the cutting edge due to weakening of the mechanical strength of the binder material at high temperature⁽²⁶⁾.

From the obtained results it was found that the tool life of CBN tools remained shorter than the BCBN and PCD tools under all cutting conditions. The tool life of BCBN and PCD tools was almost the same and in certain cutting conditions like high speed (400 m/min), low feed (0.05 mm/tooth) and low depth of cut (0.05 mm), the tool wear of BCBN tools was less than that of PCD tools (Fig. 6).

This is attributed to that fact that PCD tools at this cutting condition seems to rub on the work surface rather than to cut it. Thus the surface quality produced by PCD tools was also poor. However,

Fig. 6 Tool wear of CBN, BCBN and PCD insert at 400 m/min cutting speed, 0.05 mm depth of cut and 0.05 mm/tooth feed

CBN, BCBN and PCD tools produced good surface finish.

Also, the cutting force of the PCD tools was less than BCBN tools and that of CBN tools was very high. The SEM photographs in Fig. 7 shows the tool wear of CBN, BCBN and PCD inserts.

When analyzed for the mechanism for tool wear, it was found from the EDX analysis that diffusion of binder element, cobalt from the CBN tools had caused the tool wear. Diffused cobalt was found in the chips obtained from the initial stages of machining. Later, as the binder material had already diffused, boron also diffused-dissolved thus causing the tool wear (Fig. 8). Even with PCD tools, the diffusion of the binder material cobalt and later that of carbon was identified in the chips (Fig. 9). But no such diffusion had taken place in the chips machined by BCBN tools that resulted in longer tool life (Fig. 10).

7. Summary

A review of the research works on the machining of titanium alloys reveals that,

- Titanium and its alloys are hard-to-cut materials mainly because of their low thermal conductivity and high chemical reactivity.
- Titanium alloys machined so far with many types of conventional tools are found to be less compatible even at normal cutting speeds.
- The use of advanced cutting tool materials like CBN and PCD and their drawbacks are not well explored.
- Most of the research works are carried out with turning operation and not much work has been done in the end milling of titanium alloys.
- High-speed machining of titanium alloys with high-pressure coolant has not been given any attention.

The results obtained from the recent study on high-speed machining of titanium alloys are summarized as,

Conventional CBN Inserts

Binderless CBN Inserts

PCD Inserts

Fig. 7 SEM photographs of worn inserts (cutting speed=350 m/min, depth of cut=0.05 mm/tooth, feed rate=0.05 mm)

Fig. 8 Chips machined with conventional CBN inserts with diffused Boron and Cobalt

Fig. 9 Chips machined with PCD inserts with diffused Carbon and Cobalt

Fig. 10 Chips machined with BCBN inserts without diffused Boron and Cobalt

• The high chemical reactivity of titanium alloys with the binder materials of the CBN and PCD tools causes the tool wear.

• BCBN tools are free from the binder element cobalt that will readily react with titanium. Chips produced by BCBN tools have not shown any diffusion of the tool materials. This is associated with longer tool life of BCBN tools.

• High-pressure coolant produces better lubrication and better cooling effect in the chip-tool interface. Thus the coefficient of friction and thereby the cutting force is reduced. The cooling effect eliminates the welding of the tool and chip and improves the tool life as well as the surface finish.

• Since the BCBN tools show significantly improved tool life, good surface finish and low cutting forces, it can be concluded that BCBN tools are the most suitable cutting tools for machining titanium alloys both economically and functionally.

References

- (1) Badzain, A., Badzian, T., Drawl, W.D. and Roy, R., Silicon Carbonitride: A Rival to Cubic Boron Nitride, Diamond and Related Materials, Vol. 7 (1998), pp. 1519-1525.
- (2) Beltrame, M., Kuljanic, E., Fioretti, M. and Miani, F., Titanium Alloy Turbine Blades Milling with PCD Cutter, Advanced Manufacturing Systems and Technology, (1996), pp. 121-128.
- (3) Bhaumik, S.K., Divakar, C. and Singh, A.K., Machining of Ti-6Al-4V Alloy with wBN-cBN Composite Tool, Materials and Design, Vol. 16 (1995), pp. 221-226.
- (4) Brookes, C.A., James, R.D. and Nabhani, F., IDR, Vol. 36 (1991), pp. 89-93.
- (5) Ezugwu, E.O. and Wang, Z.M., Titanium Alloys and Their machinability—A Review, Journal of Materials Processing Technology, Vol. 68 (1997), pp. 262-274.
- (6) Farhad Nabhani, Machining of Aerospace Titanium Alloys, Robotics and Computer Integrated Manufacturing, Vol. 17 (2001), pp. 99-106.
- (7) Hong, H., Riga, A.T., Cahoon, J.M. and Scott, C.G., Wear, (1993), pp. 34-39.
- (8) Jawaid, A., Sharif, S. and Koksai, S., Evaluation of Wear Mechanisms of Coated Carbide Tools When face Milling Titanium Alloy, Journal of Materials Processing Technology, Vol. 99 (2000), pp. 266-274.
- (9) Kanda, K., Takehana, S., Yoshida, S., Watanabe, R., Takano, S., Ando, H. and Shimakura, F., Application of Diamond-coated Cutting Tools, Surface Coatings Technology, Vol. 73 (1995), pp. 115-120.
- (10) Kempster, M.H.A., Principles of Jig and Tool Design, (1968), The English University Press, Ltd., London.
- (11) Kertesz, K., Pryor, R.J., Richerson, D.W. and

- Cutler, R.A., *Journal of Materials*, Vol. 40, No. 5 (1988), pp. 50-51.
- (12) Kevin Chou, Y. and Chris J. Evans, Cubic Boron Nitride Tool Wear in Interrupted Hard Cutting, *Wear*, 225-229 (1999), pp. 234-245.
 - (13) Kitagawa, T., Kubo, A. and Maekawa, K., Temperature and Wear of Cutting Tools in High-speed Machining of Inconel 718 and Ti-6Al-6V-2Sn, *Wear*, 202 (1997), pp. 142-148.
 - (14) Komanduri, R. and Lee, M., High Speed Machining of Titanium Alloys with a New Cutting Tool Insert: The Ledge Tool, *Advanced Machining: The Handbook of Cutting Technology/Graham T. Smith*, (1989), pp. 217-223.
 - (15) Komanduri, R. and Jr. Reed, W.R., Evaluation of Carbide Grades and a New Cutting Geometry for Machining Titanium Alloys, *Wear*, 92 (1983), pp. 113-123.
 - (16) Konig, W., Proc. 47th Meeting of AGARD Structural and Materials Panel, Florence, (1978), pp. 1.1-1.10.
 - (17) Lopez de lacalle, L.N., Perez, J., Llorente, J.I. and Sanchez, J.A., Advanced Cutting Conditions for the Milling of Aeronautical Alloys, *Journal of Materials Processing Technology*, Vol. 100 (2000), pp. 1-11.
 - (18) Lopez de Lacalle, L.N., Perez-Bilbatua, J., Sanchez, A., Llorente, J.I. and Gutierrez, A., Using High Pressure Coolant in the Drilling and Turning of Low Machinability Alloys, *Int. J. Adv. Manuf. Technology*, Vol. 16 (2000), pp. 85-91.
 - (19) Machado, A.R., Wallbank, J., Pashby, I.R. and Ezugwu, E.O., Tool Performance and Chip Control When Machining Ti6Al4V and Inconel 901 Using High Pressure Coolant Supply, *Machining Science and Technology*, Vol. 2, No. 1 (1998), pp. 1-12.
 - (20) *Material Properties Hand Book — Titanium Alloys*, ASM International, (1994), pvii-xi.
 - (21) *Metals Handbook*, Ninth Edition, Machining, ASM International, (1989), p. 16.
 - (22) Rahman, M., Senthil Kumar, A. and Choudhury, M.R., Identification of Effective Zones for High Pressure Cooling in Milling, *Annals of the CIRP*, Vol. 49, No. 1 (2000), pp. 47-52.
 - (23) Schulz, H. and Moriwaki, T., High Speed Machining, *Annals CIRP*, Vol. 41 (1992), pp. 637-643.
 - (24) Shane, Y. Hong, Irel Markus and Woo-Cheol Jeong, New Cooling Approach and Tool Life Improvement in Cryogenic Machining of Titanium Alloy Ti-6Al-4V, *International Journal of Machine Tools & Manufacture*, Vol. 41 (2001), pp. 2245-2260.
 - (25) Siekman, H.J., *How to Machine Titanium*, Tool Engineer, (1955), pp. 78-82.
 - (26) Sumiya, H., Uesaka, S. and Satoh, S., Mechanical Properties of High Purity Polycrystalline CBN Synthesized by Direct Conversion Method, *Journal of Material Science*, Vol. 35 (2000), pp. 1181-1186.
 - (27) Sutter, G., Molinari, A., Faure, L., Klepaczko, J.R. and Dudzinski, D., An Experimental Study of High-speed Orthogonal Cutting, *Journal of Manufacturing Science and Engineering*, Vol. 120 (1998), pp. 169-172.
 - (28) Trent, E.M., *Metal Cutting*, (1991), p. 139.
 - (29) Vigneau, J. and Derrien, S., High Speed Milling of Difficult to Machine Alloys, First French and German Conference on High Speed Machining, Metz, (1997).
 - (30) Waiter, J.L., Skelly, D.W. and Minnear, W.P., *Wear*, 170 (1993), pp. 79-82.
 - (31) Wang, Z.Y. and Rajurkar, K.P., Cryogenic Machining of Hard-to-cut Materials, *Wear*, 239 (2000), pp. 168-175.
 - (32) Xiaoping Yang and Richard Liu, C., Machining Titanium and Its Alloys (Review Article), *Machining Science and Technology*, Vol. 3, No. 1 (1999), pp. 107-139.
 - (33) Zone-Ching Lin and Din-Yan Chen, A Study of Cutting with a CBN Tool, *Journal of Materials Processing Technology*, Vol. 49 (1995), pp. 149-164.
 - (34) Zoya, Z.A. and Krishnamurthy, R., The Performance of CBN Tools in the Machining of Titanium Alloys, *Journal of Materials Processing Tech.*, Vol. 100 (2000), pp. 80-86.

Mustafizur Rahman

Mustafizur Rahman graduated from Bangladesh University of Engineering and Technology in Mechanical Engineering in 1969. He obtained his M. Eng. and Ph.D. degrees from Tokyo Institute of Technology in 1976 and 1979 respectively. He worked with Makino Milling Machine Co. Ltd. (Japan) from 1979 to 1982. In 1982, he joined the Mechanical and Production Engineering Department of the National University of Singapore and currently he is an Associate Professor. His main research interests are in the fields of machining of metals and non-metals, micro machining, development of machine tools especially miniature machine tools for micro and nano machining, new materials for machine tools and cutting tools, computer aided machining, bio-machining and high speed machining.

Yoke San Wong

Y.S. Wong is currently Head of the Manufacturing Division and Associate Professor, Mechanical Engineering Department of the National University of Singapore. A major area of his teaching and research interests is in machining characterization, optimization and condition monitoring. He has published more than 120 papers in refereed journals and international conferences and contributed 3 chapters to books, and participated in several local and overseas funded projects.

Ms. A. Rahmath Zareena

Ms. A. Rahmath Zareena is currently working as a Visiting Research Associate in Singapore Institute of Manufacturing Technology, Singapore. She obtained her B. Eng. degree in Mechanical Engineering from Madurai Kamaraj University, India in 1995. She worked as a lecturer in mechanical engineering from 1995 to 1998 in India and as a CAD/CAM engineer in Singapore for one year. From 2000 to 2002 she did her research on "High-speed machining of Titanium alloys" under the supervision of Prof. M. Rahman and Prof. Y.S. Wong in National University of Singapore for her M. Eng degree and graduated in the year 2002. She has published 3 international conference papers and a journal paper.