A Review on High-Speed Machining of Titanium Alloys*

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Titanium alloys have been widely used in the aerospace, biomedical and automotive industries because of their good strength-to-weight ratio and superior corrosion resistance. However, it is very difficult to machine them due to their poor machinability. When machining titanium alloys with conventional tools, the tool wear rate progresses rapidly, and it is generally difficult to achieve a cutting speed of over 60 m/min. Other types of tool materials, including ceramic, diamond, and cubic boron nitride (CBN), are highly reactive with titanium alloys at higher temperature. However, binder-less CBN (BCBN) tools, which do not have any binder, sintering agent or catalyst, have a remarkably longer tool life than conventional CBN inserts even at high cutting speeds. In order to get deeper understanding of high speed machining (HSM) of titanium alloys, the generation of mathematical models is essential. The models are also needed to predict the machining parameters for HSM. This paper aims to give an overview of recent developments in machining and HSM of titanium alloys, geometrical modeling of HSM, and cutting force models for HSM of titanium alloys.

Key Words: High-Speed Machining, Titanium Alloys, Cutting Force Model, Tool Wear

1. Introduction

The inventor of HSM, C. Salomon, found that above a certain cutting speed machining temperatures start dropping again. His fundamental research showed that there is a certain range of cutting speeds where machining cannot be made due to excessively high temperatures. For this reason, HSM can also be termed as cutting speeds beyond that range. In compliance with modern knowledge, some researchers define high-speed machining as machining whereby conventional cutting speeds are exceeded by a factor of 5 to 10, as shown in Fig. 1(1).

With the wide use of CNC machines together with high-performance CAD/CAM systems, high-speed machining (HSM) has demonstrated its superior advantages to other rapid manufacturing techniques. In addition to increased productivity, HSM is capable of generating high-quality surfaces, burr-free edges, and virtually stress-free components after machining, and can be used to machine thin-wall workpieces, because the cutting forces involved in HSM conditions are lower. Another significant advantage of high-speed machining is minimization of effects of heat on machined parts. Most of the cutting heat is removed, reducing thermal warping and increasing the life of the cutting tool. In many cases, the need for a cooling fluid is eliminated. Furthermore, the elimination of

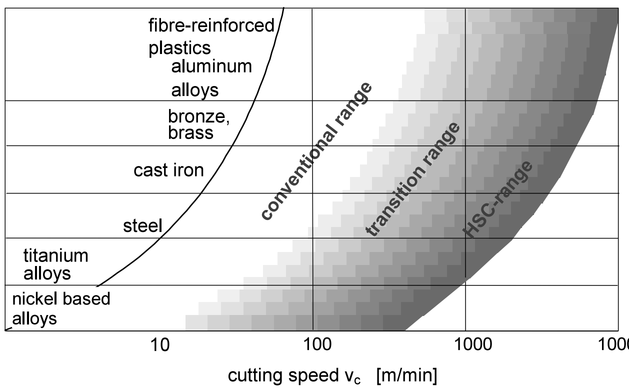

Fig. 1 Cutting speed area depends on material(1)

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cutting fluids reduces subsequent contribution to pollution and aids in the recovery and recycling of such expensive materials as aluminum-lithium alloys. Since HSM has so many advantages, it is widely used in the aerospace industry, automotive industry, precision engineering industry for machine tools, equipment, and tooling used in the manufacture of domestic appliances, optics, etc.

Although high-speed milling of aluminum has been applied in industries successfully for more than a decade, high-speed applications on difficult-to-cut materials, such as titanium alloys, are still relatively new. Boeing's military aircraft group has begun to apply its expertise with aluminum toward faster milling of titanium in St. Louis, Missouri. Jerry Halley is an engineering researcher there who has helped the company to realize more effective machining of both materials. And he concluded that compared to aluminum, titanium imposes certain constraints. Speed is constrained as heat builds up more quickly. But within those constraints, there is still considerable room for faster cutting (web site: http://www.mmsonline.com/articles/080103.html).

Titanium alloys have been widely used in the aerospace, biomedical, automotive and petroleum industries because of their good strength-to-weight ratio and superior corrosion resistance. However, it is very difficult to machine them due to their poor machinability. During the machining of titanium alloys with conventional tools, tool wear progresses rapidly because of their low thermal conductivity and high chemical reactivity, resulting in higher cutting temperature and strong adhesion between the tool and the work material[(2)]. Titanium alloys are generally difficult to machine at cutting speeds of over 30 m/min with high-speed steel (HSS) tools, and over 60 m/min with cemented tungsten carbide (WC) tools, resulting in very low productivity. The performance of conventional tools is poor when machining Ti6Al4V. In 1955, Siekmann[(3)] pointed out that machining of titanium and its alloys would always be a problem, regardless of the techniques employed to transform the metal into chips. The poor machinability of titanium and its alloys have led many large companies (for example Rolls-Royce and General Electrics) to invest much in developing techniques to minimize machining cost[(4)].

The inability to improve cutting tool performance for machining of titanium alloys by developing new coating materials has been very frustrating. Likewise, very little improvement in productivity has been experienced by exploring new combinations of speeds, feeds, and depths. Some developments of interest include specially designed turning tools and milling cutters, along with the use of a special end-mill pocketing technique. With the evolution of a number of new cutting tool materials, advanced tool materials, such as cubic boron nitride (CBN) and polycrystalline diamond (PCD) are being considered to achieve HSM of titanium alloys.

King and Vaughn[(5)] stated that as the cutting speed increases above the conventional speed range, new dynamic effects are encountered in the cutting process, and Taylor's empirical equations are no longer adequate since they are not velocity-dependent. There is a necessity to investigate the mechanism of HSM of titanium alloys and establish comprehensive models to describe this process.

The objective of this paper is to give an overview of some of the more significant contributions to HSM of titanium alloys, which can provide a fundamental understanding of the mechanisms that prevail in the field of HSM of titanium alloys, In general, HSM may include several processes, such as high-speed turning, high-speed milling, and high-speed drilling, etc. This paper focuses only on the most widely used turning and milling processes. Both experimental and model-based studies carried out during the last decade, which lay the foundation for continuing research in this area, will be discussed in this study. This review begins with a discussion of experimental studies that have provided a clearer picture of the mechanisms that dominate in HSM. These studies include HSM of titanium alloys with uncoated and coated carbide tools, PCD and CBN tools, and a new tool material binderless CBN. Then, several recent modeling and simulation efforts are discussed, which both extend to the understanding of HSM and provide more tractable ways to characterize and assess HSM processes.

2. HSM of Titanium Alloys with Uncoated or Coated Carbide Tools

A major factor hindering the machinability of titanium alloys is their tendency to react with most cutting tool materials, thereby encouraging dissolution wear during machining. Ezugwu et al.[(6)] attempted to machine titanium alloys in an inert argon enriched environment, so that chemical reaction at the tool-chip and tool-workpiece interfaces may be minimized when machining titanium alloys at higher cutting speed conditions. They carried out machining trials with uncoated carbide (ISO K10 grade) tools in an argon-enriched environment at cutting conditions typical of finish turning operations. For comparison, experiments under conventional coolant supply were also done at the same cutting conditions. Experimental results showed that machining in an argon-enriched environment gave lower tool life relative to conventional coolant supply. Nose wear was the dominant tool-failure mode in all the cutting conditions investigated. They attributed this to argon being a poor conductor of heat; such that heat generated during machining tends to concentrate on the cutting region and accelerate tool wear. In addition, argon has poor lubrication characteristics, which leads to an increase in friction at the cutting interfaces during machining and an increase in cutting forces required for efficient shearing of the workpiece[6].

Li et al.[7] used uncoated carbide K10 for high-speed milling of Ti6Al4V. They proposed a reliable method to measure cutting temperature during HSM of Ti6Al4V. Based on the measurement of cutting temperature, they also analyzed the effects of cutting speed on the cutting temperature. They found that cutting temperature increased with cutting speed, and no reduction of cutting temperature at higher cutting speed was observed. In addition, the cutting temperature on the cutting edge had a slow change rate when the cutting speed was around 300 m/min.

Wang et al.[8] used uncoated carbide (WC) inserts for orthogonal continuous and interrupted cutting at conventional and high cutting speeds. In their study, the tool material H1 (Sumitomo's tool material reference number) has fine-carbide grain and maintains high wear resistance. The mechanical properties of H1 are given in Table 1[9]. The properties of CBN and ceramic materials from the Ref. (10) were also cited to highlight the fracture toughness of cemented carbide H1 as shown in Table 1. Table 1 also shows that cemented carbide H1 has higher Transverse Rupture Strength (TRS) value and fracture toughness, although its hardness value is lower. More importantly, cemented carbide tools are much cheaper than CBN and ceramic tools. Therefore, the higher TRS values and greater thermal conductivity of H1 make it more suitable for interrupted cutting. In their study, cutting performances under dry cutting, MQL and flood coolant have been investigated. For continuous cutting, dry cutting has been found to be only effective at lower cutting speed, and MQL is a more economical alternative cooling lubricant than flood coolant. At a higher feed rate of 0.15 mm/r and higher cutting speed in interrupted cutting, cutting forces under MQL are smaller than those under flood coolant, and MQL and flood coolant have similar effects on the thrust forces. They indicated that MQL was an effective alternative approach for flood coolant when high-speed turning of Ti6Al4V. Based on the investigation of the cutting forces with the different coolant lubricants, the mean friction coefficient in the sliding region at the tool-chip interface has been obtained and used in a finite element method (FEM) to simulate the deformation process of Ti6Al4V during turning. From the FEM simulation and Oxley's predictive machining theory, cutting forces have been estimated under different cooling supply strategies and verified experimentally.

Table 1 Properties of CBN, H1 and ceramic tool

Properties	CBN	H1 (5% Co)	Ceramic Si_3N_4
H_V (GPa)	35~40	16.05	21.58
TRS* (GPa)	1.40	2.06	0.793
k (W/mK)	100~130	109	29
ν	0.2~0.22	0.22	0.26
E (GPa)	600~800	646	338
K_{IC} (MPa$\sqrt{m}$)	3.5~6.7	10.9	6.2

HV: Vickers hardness, k: thermal conductivity, ν: Poisson's ratio, E: Young's modulus, K_{IC}: fracture toughness

Lei and Liu[11] developed a new generation of driven rotary lathe tool for high-speed machining of a titanium alloy Ti6Al4V. In their study, high-speed cylindrical turning experiments were conducted using the driven rotary tool (DRT) and a stationary cutting tool with the round tungsten carbide inserts. From the experimental results, they found that DRT can significantly increase tool life, and the increase in tool life with DRT is more than 60 times compared to that with a stationary cutting tool under certain conditions. The effects of the rotational speed of the insert were also investigated experimentally in their study. Cutting forces were found to decline slightly with increase in the rotational speed, and tool wear was observed to increase with the rotational speed in a certain speed range.

Muller et al.[12] used a fiber-optic two-color pyrometer with high spatial and temporal resolution to measure temperatures at an external turning process at conventional and high cutting speed. SiC-whisker reinforced oxide ceramic inserts were used for high-speed turning of Ti6Al4V. Based on the experiments, they observed that the measured temperature in turning titanium alloy Ti6Al4V showed very good reproducibility. But at much higher speed (such as $\geq$ 5 m/s), the measurement conditions became more and more difficult due to tool wear or failure that caused a wide spread of the measured temperature.

3. HSM of Titanium Alloys with CBN and PCD Tools

3.1 HSM of titanium alloys with CBN tools

Zoya and Krishnamurthy[2] used CBN tools for high-speed turning of titanium alloys and evaluated the machining performance. They concluded that the machining of titanium alloys is a thermally dominant process, and a critical temperature of 700°C can be a criterion for tool life. They also found that a good surface finish can be achieved with a cutting speed of 185 m/min, and a cutting speed range of 185 – 220 m/min can be recommended for the machining of titanium alloys with CBN tools. During the machining of titanium alloys, deformation at the cutting nose of CBN tools was observed, and they claimed that wear of CBN tools can also be due to diffusion wear.

Ezugwu et al.[13] evaluated the cutting performance of different CBN tool grades in finish turning Ti6Al4V (IMI 318) alloy at high speed cutting conditions of up to 250 m min^{-1}, with various coolant supplies. In their study, tool wear, failure modes, cutting and feed forces and surface roughness of machined surfaces were monitored and used to access the performance of the cutting tools. For comparison, uncoated carbide tools were also used to machine Ti6Al4V at a speed of 150 m min^{-1}. They observed that the cutting performance of CBN tools is poor relative to uncoated carbide tools in terms of tool life at the cutting conditions investigated. And they found that the possible reason for this is rapid notching and excessive chipping of the cutting edge associated with a relatively high diffusion wear rate that tends to weaken the bond strength of the tool substrate. It was also found that an increase in the CBN content of the cutting tool tended to accelerate notch wear rate, consequently diminishing tool life at the investigated cutting conditions.

Bhaumik et al.(14) used wBN-cBN composite tools to machine Ti6Al4V and investigated the wear mechanism of this type of tool. Based on X-ray dot mapping of compositional analysis, they indicated that titanium existed on the crater area, and the adherent layer might contain titanium in some compound form, such as titanium diboride or titanium nitride. When the adherent materials were taken away, accelerated attrition was observed on both the rake and flank faces. Some tests were also carried out with K20 grade cemented carbide tools to compare the machined surface quality and the swarf obtained with those using composite tools. The tool life of cemented carbide tools was found to be limited by rapid cratering on the rake face and deformation at the tool nose.

3.2 HSM of titanium alloys with PCD tools

König and Neises(15) used PCD tools for turning Ti6Al4V, and they found that the diffusion and dissolution processes were exacerbated by the high local temperature resulting from the poor thermal conductivity of the workpiece material.

The PCD cutter was also used to investigate the possibility of finish milling of titanium alloy Ti6Al4V by Kuljanic et al.(16) From the thermo-chemical data and stability of TiC, they inferred that titanium has the greater affinity to carbon. In their study, no crater or flank wear land was observed during machining, and the tool life of PCD cutters is very long (381 min) at cutting speed of 110 m/min, feed per tooth 0.135 mm/r, axial depth of cut 0.2 mm and radial depth of cut 5 mm. Their explanation for such a long tool life is that the formation of a titanium carbide film from a reaction between the work material and tool material on the diamond tool surface. This titanium carbide film can protect the tool, particularly the crater wear of the cutter. The inclination of the cutter and application of cooling lubricant was also investigated in their study. They found that the most suitable inclination angle was 10° for PCD cutters, and cooling lubricant, such as 7% oil and water, should be used for milling titanium alloys with PCD cutters.

Nabhani(17) compared the performance of PCD and polycrystalline CBN (PCBN) with that of coated tungsten carbide tool when machining titanium alloys. Diffusion and dissolution exacerbated by higher cutting temperature were observed as the predominant tool wear mechanisms, and the tool wear probably resulted from a combination of dissolution/diffusion and attrition processes. They also found that the failure of carbide tools was the result of plastic deformation under compressive stress in the presence of high temperatures generated close to the cutting edge. From the study, the coated layers on the carbide tools seem to have no beneficial effect on their performance, since these layers are rapidly removed, which causes the tungsten carbide substrate to be vulnerable to cratering. For PCBN tools, they found that wear mechanisms are the same as those for carbide tools except that PCBN tools have lower wear rate and better machined surfaces have been achieved. Based on the experimental results, Nabhani(17) concluded that PCD tools have the lowest wear rate and produce the best workpiece surface quality. PCD would be the most functionally satisfactory commercially available cutting tool material for machining titanium alloys in comparison to carbide and PCBN tools.

4. HSM of Titanium Alloys with Binderless CBN Tools

4.1 Binderless CBN tool material

CBN tools are currently very expensive. In addition, they cannot maintain their hardness and strength at higher temperature, and consequently are not suitable for machining titanium alloys at high cutting speed. Conventional CBN sintered tools are composed of CBN powder and metal or ceramics binder materials, which determine the bonding strength of the CBN particles. Therefore, the mechanical and thermal properties of these conventional CBN tools strongly depend on the type and quantity of these binder materials.

Recently, some single-phase CBN sintered tools without any binder materials are available. The binderless CBN (BCBN) tool used by H. Sumiya(18) is one of this type of tools, which is made by direct sintering method. To synthesize the BCBN tool, a high-purity hexagonal boron nitride (hBN) particle is first chosen as the starting material, which is 1.75×10^3 kg/m^3 in density containing less than 0.03 wt% of impurity (B_2O_3). The hBN material is then placed in a Ta capsule and sintered at a pressure of about 7.7 GPa at various temperature settings (1 900°C to 2 700°C) using ultra high-pressure equipment(18). Finally, the high-purity polycrystalline CBN with superior mechanical characteristics is obtained.

The binderless CBN sintered product contains neither a binder nor a sintering agent or catalyst. The raw material of hBN is completely converted to a cubic phase at a high temperature and under an extremely high pressure. The converted particles of CBN are bonded together, keeping the particle size extremely fine. The mechanical properties

Table 2 Mechanical and thermal properties of CBN and BCBN

Properties		BCBN	CBN	Cemented carbide 6% Co	Ceramic $Si3N_4$ Hot-press
CBN contents (vol%)		>99.9	85 – 90	—	—
CBN grain size (micron)		<0.5	1 – 3	—	—
Other constituents		-(comp. hBN)	Binder (Co etc.)	—	—
Process		Direct conv.	CBN + Binder	—	—
Hardness (GPa)	Room temp.	50 – 55	35 – 40	15.69	21.58
	1000°C	20	12	—	—
TRS*(GPa)	Room temp.	1.35	1.40	2.20	0.793
	1000°C	1.60	0.55	—	—
Thermal conductivity (W/mK)		360 – 400	100 – 130	95	29
Thermal stability (K in air)		1620	1270	—	—

of BCBN and CBN are shown in Table 2. The properties of cemented carbide and ceramic materials[19] were also cited for highlighting the hardness of BCBN material as shown in Table 2. From Table 2, it can be seen that cement carbide (6% of Co) has higher TRS value, but its hardness value is smaller. On the contrary, BCBN has the higher hardness and less TRS values. Normally, making hardness of a material higher also reduces its TRS. Although the TRS value of the binderless CBN material is slightly less than that of CBN containing binder material at room temperature, it has much higher hardness and thermal conductivity than CBN. More importantly, at 1 000°C, the BCBN material has higher hardness and larger TRS values than the corresponding CBN tool material. Except excellent mechanical properties, the BCBN tools also exhibit superior thermal stability because the sintered body contains no secondary phases and consists of extremely fine CBN particles[18]. Excellent results had been achieved when this type of tool was used for high-speed milling of gray cast iron. Therefore, tools of this type show great promise for high-speed milling of difficult-to-cut materials. The main advantageous features of the binderless CBN sintered product are as follows[20]:

- It has high thermal conductivity as well as outstanding resistance to heat and thermal shock because it is a sintered product made of single-phase CBN. Thus, it minimizes the possibility of thermal cracks and chipping occurring at the cutting edge.
- It is suitable for interrupted cutting, having superior mechanical characteristics, such as hardness and strength, because it is made of fine particles not larger than 0.5 microns, which are solidly bonded to one another without a binder or a sintering agent/catalyst in the grain boundaries.

It can be cut and brazed to create desired shapes for turning and milling, as well as the manufacturing of special brazing tools.

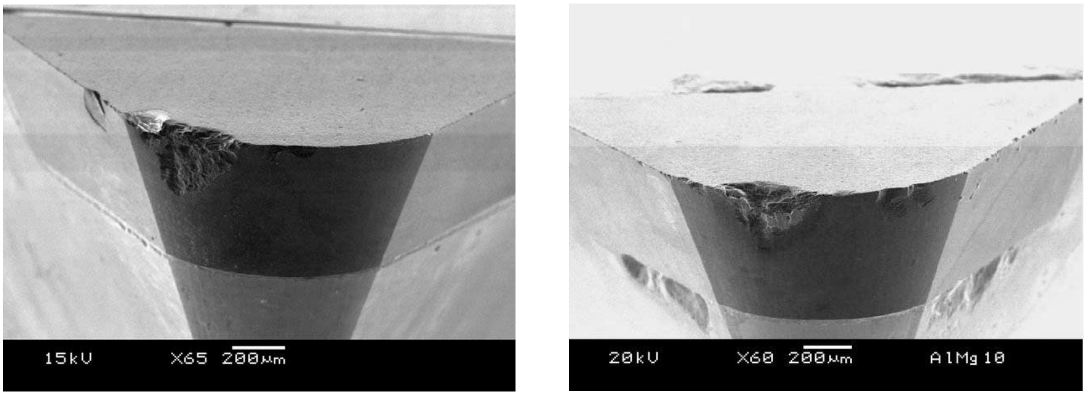
4.2 HSM of titanium alloys with BCBN tools

In their study of CBN, PCD and BCBN tools for high-speed slot milling of Ti6Al4V, Zareena[21] found that CBN tools exhibit better performance at higher cutting speed (400 m/min), lower feed rate (0.05 mm/tooth), and low depth of cut (0.05 mm) conditions. The primary reason for tool wear was found to be the result of chemical reactivity between titanium and the binder element cobalt of the CBN tools. Similar to CBN tools, PCD tools were also observed to undergo diffusion-dissolution wear. The performance of BCBN tools in terms of tool life was found to be almost similar to that of PCD tools, and even better at certain cutting conditions (high cutting speed, low feed rate and depth of cut). The high thermal conductivity of BCBN tools and the absence of binder element were found to be the reason for longer tool life for these tools. Surface finish had also been investigated. BCBN and PCD tools were found to produce good surface roughness in comparison to CBN tools.

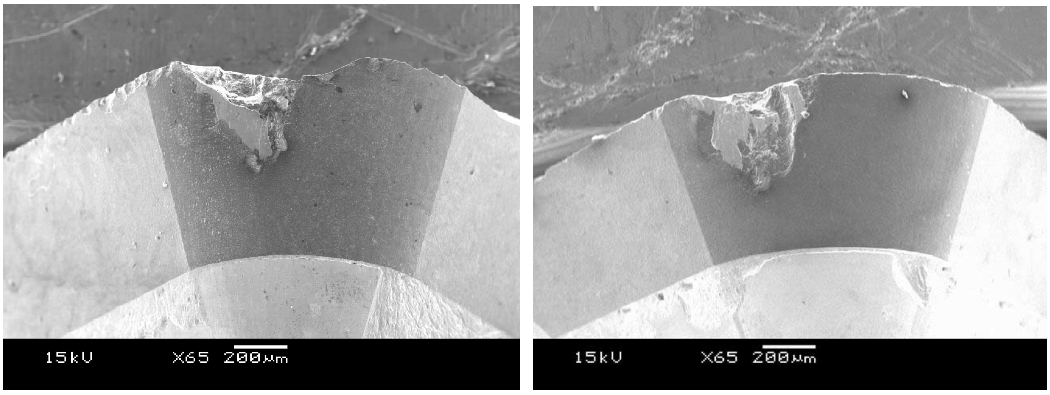
A binder-less PCBN tool was also attempted by Hirosaki et al.[22] in the machining of a vanadium-free titanium alloy Ti-6Al-2Nb-1Ta to improve processing efficiency. This tool, which is also prepared through the direct conversion sintering of h-BN under both high pressure and temperature, shows an improved high thermal durability. They found that this binder-less PCBN tool exhibited lower flank wear and kept sharper cutting edge compared to the tools made of materials such as sintered carbide, conventional PCBN and polycrystalline diamond with Co-based binder, after turning at cutting speed of 4.2 m/s, feed rate of 0.15 mm/rev, depth of cut of 0.5 mm under an application of a high pressure coolant. In addition, according to their milling tests with a radius end mill tool whose tip was made of the binder-less PCBN material, it is possible to increase the cutting speed to 8.3 m/s for high-speed milling.

Wang et al.[23],[24] also used BCBN tools for high-speed milling of titanium alloy Ti6Al4V. The performance and the wear mechanism of the BCBN tool had been investigated when slot milling Ti6Al4V in terms of cutting forces, tool life and wear mechanism. It was found that non-uniform flank wear was the dominant wear pattern of BCBN tools when high-speed milling Ti6Al4V, as shown in Fig. 2. Compared with the tool life results of CBN and PCD tools obtained by Zareena[21], BCBN tools show longer tool life. Owing to its excellent mechanical properties (such as hardness and strength at higher temperature), BCBN appears to become a promising new cutting tool material for high-speed machining of titanium alloys with superior cutting performance.

Wang et al.[23] found that at lower feed rate (0.075 mm/r) and the same depth of cut, the tool life at higher cutting speed is longer than that at lower cutting speed. The higher cutting speed and lower feed rate are found to be more optimal cutting conditions. A strong bond was observed at the tool/workpiece interface, and the adhered workpiece material to the flank face was helpful in reducing wear rate. However, when the adhered workpiece material was subsequently removed, it not only



(a) $a = 0.05$ mm, $f = 0.05$ mm/r, $v = 350$ m/min (b) $a = 0.10$ mm, $f = 0.075$ mm/r, $v = 350$ m/min



(c) $a = 0.125$ mm, $f = 0.075$ mm/r, $v = 400$ m/min (d) $a = 0.075$ mm, $f = 0.075$ mm/r, $v = 400$ m/min

Fig. 2 SEM of the flank of BCBN tools at four different conditions where the non-uniform flank wear is the dominant wear for these four cases

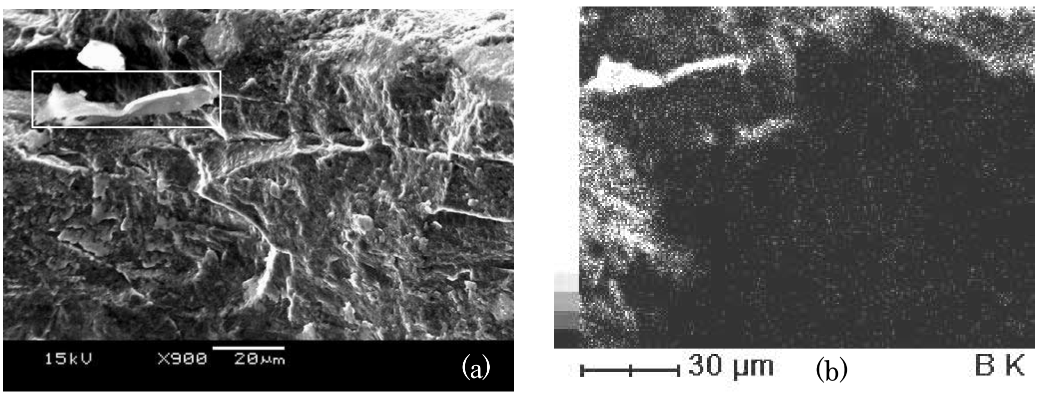


Fig. 3 SEM and EDX of the flank face (a) An enlarged rectangular region of flank face under cutting conditions of $a = 0.100$ mm, $f = 0.10$ mm/r, $v = 350$ m/min; (b) EDX of (a) shows the fragment in the rectangular region of Fig. 3 (a) coming from the tool material

would cause some removal of aggregate of tool material, but also result in accelerated attrition wear on the flank face. The removal of grains of the tool material by the adherent chip or workpiece was observed on the flank face after milling Ti6Al4V, as shown in Fig. 3 (a). EDX analysis of Fig. 3 (a) as shown in Fig. 3 (b) shows that the fragment comes from the aggregate particles of the tool material. Wang et al.(23) also found that some workpiece materials adhered to the rake face when milling Ti6Al4V at higher depth of cut, feed rate, and cutting speed. However, at other cutting conditions, there are only some adhered materials, which are mainly found on the flank face, rather than on the rake face after failure of the tool. Based on the EDX output of chips, the dissolution of material from the tool by diffusion into the adjacent zones of the chip happens. This may cause diffusion-dissolution wear for BCBN tools, but it is not the main wear mechanism.

5. Modeling and Simulation of HSM of Titanium Alloys

Sandstrom and Hodowany[25] used finite element analysis (FEA) to model orthogonal cutting of 7050-T7451 aluminum and Ti6Al4V, in which a Lagrangian formulation with explicit dynamics was used. In their study, dynamics of chip formation was analyzed when machining Ti6Al4V at high cutting speed. Segmented chip formation was observed, which also caused the fluctuation of cutting forces with very high frequency. They concluded that the frequency of the fluctuating forces was so high that it did not cause chatter or oscillation of machine tools. In addition, the tool force oscillations associated with segmented chip formation may well be important in tool wear performance.

Molinari et al.[26] analyzed chip serration for orthogonal cutting of Ti6Al4V in the range of cutting speed $0.01\,\mathrm{m/s} \leq v \leq 73\,\mathrm{m/s}$, and adiabatic transformed shear bands were observed for ballistic test at speed range $12\,\mathrm{m/s} \leq v \leq 36\,\mathrm{m/s}$. The patterning of the adiabatic shear bands has been identified in their experiments. They found that this patterning was strongly dependent on the cutting speed v. The width of the transformed adiabatic shear bands ($v \geq 12\,\mathrm{m/s}$) decreased with the cutting velocity as v^{-1}. The separation distance decreases approximately as $v^{-3/4}$ for $v \geq 12\,\mathrm{m/s}$. Based on results on adiabatic shear banding obtained from findings by other researchers for the separation distance, a theoretical modeling of these findings was proposed. The dependence of the adiabatic shear band patterning upon the cutting velocity was well predicted.

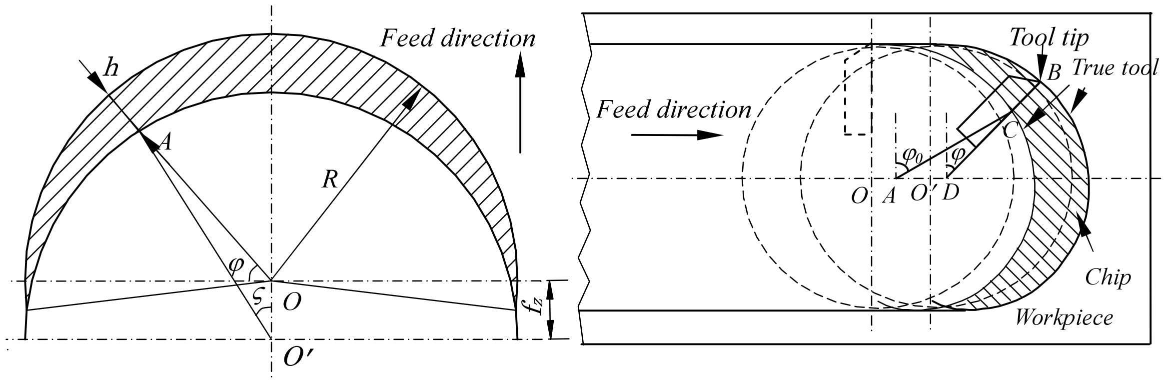
Kitagawa et al.[27] investigated high-speed milling of Inconel 718 and Ti-6Al-6V-2Sn alloys from a thermal point of view. In the end milling of the titanium alloy, high-speed machining of up to a cutting speed of 628 m/min was found to be possible for sintered carbide tools. They also found that the feasibility of high-speed end milling depends on a transient temperature drop through the use of a coolant. Finally, they proposed a numerical model to validate the measured temperature from the experiments, which can predict the temperature with reasonable accuracy.

Jiang and Shivprui[28], found crater wear to be the predominant wear mechanism influencing tool life and productivity when using cemented carbide cutting tools to machine titanium alloys. They proposed an analytical wear model that relates crater wear rate to thermally driven cobalt diffusion from the cutting tool into the titanium chip. In their model, this cobalt diffusion is a function of cobalt mole fraction, diffusion coefficient, interface temperature and chip velocity. The wear analysis included theoretical modeling of the transport-diffusion process, and obtaining tool-chip interface conditions by a non-isothermal visco-plastic finite element method (FEM) model of the cutting process. Based on the comparison of predicted crater wear rate with experimental results from published literature and from high speed turning with WC/Co inserts, they concluded that their model can predict wear rates with good accuracy for different cutting speeds and feed rate.

In milling, each tooth of the cutter produces chips with variable thickness. Unlike turning, the instantaneous chip thickness (h) in milling varies periodically as a function of time-varying immersion angle φ. One of the key issues in the geometrical models for milling processes is to model the undeformed chip thickness. The often used circular geometry of chip formation in milling is shown in Fig. 4 (a).

Although the circular tooth-path approximation makes it easy to establish a model of the milling process, it also affects the accuracy of the model. For high speed milling or micro-milling, there is greater need for higher accuracy whereby the circular tooth-path could not meet the requirement.

In milling, the undeformed chip thickness is deter-



(a) Circular geometry of chip formation (b) Practical geometry of chip formation

Fig. 4 Geometry of chip thickness of the milling process. f_z is the feed rate (mm/rev-tooth); φ is the instantaneous angle of immersion; $R = D/2$, where D is the diameter of the cutter mined by the distance between two consecutive cut surfaces. This distance varies with the instantaneous angle of immersion during the chip formation of a cutting tooth (insert) and is measured in the direction perpendicular to the preceding cut surface. Consider the case where only one flat end milling insert is used. For the convenience of analysis, the point on the tip of the insert is selected to describe the true tooth trajectory. The true tooth trajectories of two consecutive cut are the two solid curves shown in Fig. 4 (b), and the undeformed chip thickness is decided by these two curves. The position of the center of the cutter is located at points O and O′, when these two consecutive cuts start. When the tooth tip is at point B for the second cut, the angular position of the tooth is φ. At this time, the undeformed chip thickness depends on the locations of points B and C, and the position of point C is determined by the tooth tip with the angular position φ_0 for the first cut. According to the aforementioned considerations, the analytical solution to the undeformed chip thickness can be obtained[29].

In the study by the authors[29], the nose radius of the indexable tooth is larger than the axial depth of cut so that different parts of the nose involved in the cutting are under different cutting load. In order to investigate the effects of the nose geometry, it is necessary to simulate the cutting process around the tooth tip. For this purpose, there is a need to establish a 3-D model of the milling process, which requires longer computation time even for computers with faster computation speed. An alternative approach is to represent the 3-D milling with 2-D metal deformation process. The authors[29] represented the undeformed chip around the nose with an equivalent chip of uniform thickness. With this equivalent chip representation, the milling process can be assumed to be a facing process in turning with depth of cut a_e and the changing feed-rate $h(\phi)$. Finally, the plain deformation of the turning process can be simulated with FEM.

The yield stress of a metal under uniaxial condition is defined as the flow stress or effective stress. The metal starts deforming plastically when the applied stress reaches the values of flow stress. The flow stress is mostly influenced by temperature, strain, strain-rate, and material properties. Accurate and reliable flow stress models are very important for describing the deformation behavior of the work material during practical machining processes. The widely used constitutive model of flow stress is the JC strength model proposed by Johnson and Cook. The JC model represents the flow stress $\bar{\sigma}$ of a material as the product of strain, strain-rate, and temperature.

The authors[29] used FEM to simulate the cutting process, which is an extension of FEM application in the analysis of metal-forming. During practical machining, cutting heat is generated. Thus, the consideration of temperature effects in the analysis of plastic deformation during

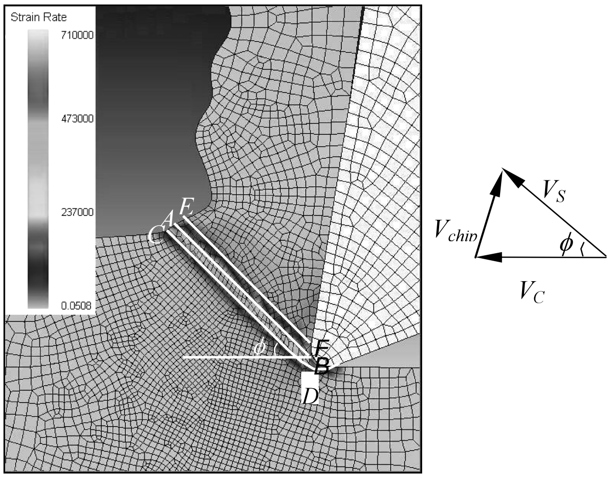


Fig. 5 Deformation zones of FEM simulation in machining of Ti6Al4V. V_C is the cutting speed, ϕ is the shear angle

machining process is very important. So in machining, the work material deforms viscoplastically under the cutting load. Although there still exists elastic deformation except viscoplastic one, viscoplastic strain outweighs elastic strain. So it is reasonable to assume that the cutting tool and workpiece combination with a rigid-viscoplastic material behavior. A typical FEM simulation of the HSM of Ti6Al4V is shown in Fig. 5. The area between the boundary CD and EF is the chip formation zone or the shear zone.

From FEM simulation, the value of strain rate constant for chip formation zone C' can be calculated based on the JC model and FEM simulation results[29]. In his predictive machining theory, Oxley predicted the value of C' based on the assumption of uniform normal stress at the tool-chip interface. The authors used the JC model and FEM simulation results to estimate the value of C', thus the impractical assumption in Oxley's theory is not needed. In their study, the following procedure was used to estimate the cutting forces. Firstly, based on FEM simulation, the values of shear angle ϕ and shear stress along shear plane k_{AB} are found at different instantaneous chip thickness. The required value of C' is then determined, and the value of angle θ is also obtained. Finally, the cutting forces are obtained based on Oxley's theory. With this procedure, the cutting forces can be calculated accurately and realistically. Experiments were also carried out to verify the estimated cutting forces, and the cutting forces can be predicted with good accuracy for all three directions.

6. Conclusions

The poor thermal conductivity of titanium alloys results in the concentration of high temperatures at the tool-workpiece and tool-chip interfaces, which accelerates tool wear and consequently increases manufacturing cost. Traditional cutting tool materials can only be used to machine titanium alloys at moderate cutting speed. Advanced tool materials, such as PCD and CBN, are capable of machining titanium alloys at high cutting speed. However, their tool life is limited by the extremely high cutting temperature and high stresses generated at the cutting edge during machining of titanium alloys. All of these tool materials could not maintain their hardness at higher temperature, but the BCBN tool offers an alternative which can withstand the severe cutting temperature and cutting pressure, and maintain hardness at high temperature (around 1 000°C). In addition, the BCBN tools exhibit excellent mechanical properties and superior thermal stability. BCBN would appear to be the most functionally satisfactory cutting tool material now available for machining titanium alloys. The generation of mathematical models of high-speed milling is essential to deeper understanding of this advanced process. Therefore, an analytical model is needed to be established to predict the cutting forces, tool wear and cutting temperature for high-speed milling of Ti6Al4V. Based on FEM simulation and Oxley's machining theory, the authors have proposed a hybrid cutting force model[(29)], and this model has been found to predict the cutting forces with good accuracy.

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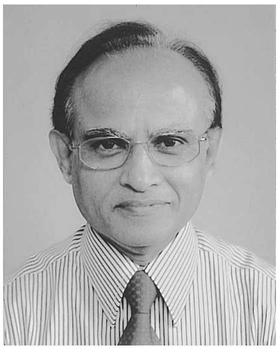

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