High Speed Ball End Milling for Difficult-to-Cut Materials

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ABSTRACT

High speed machining (HSM), specifically end milling and ball end cutting, is attracting interest in the die/mold or aerospace industries for the machining of complex 3D surfaces. HSM of difficult-to-cut materials such as die/mold steels, titanium alloys or nickel based superalloys generates the concentrated thermal/frictional damage at the cutting edge of the tool and rapidly decreases the tool life. Following a brief introduction on HSM and related aerospace or die/mold work, the paper reviews published data on the effect of cutter/workpiece orientation and cutting environments on tool performance.

First, experimental work is detailed on the effect of cutter orientation on tool life, cutting forces, chip formation, specific force and workpiece surface roughness. Cutting was performed using 8 mm diameter PVD coated solid carbide cutters with the workpiece mounted at an angle of 45 degree from the cutter axis. A horizontal downwards cutting orientation provided the best tool life with cut lengths ~50% longer than for all other directions(horizontal upwards, vertical downwards, vertical upwards).

Second, the cutting environments were investigated for dry, flood coolant, and compressed chilly air coolant cutting. The experiments were performed for various hardened materials and various coated tools. The results show that the cutting environment using compressed chilly air coolant provided better tool life than the flood coolant or the dry.

Keywords: Difficult-to-Cut Materials, High-Speed Machining, Cutter Orientation, Horizontal Downwards, Tool Life, Horizontal Upwards, Vertical Downwards, Vertical Upwards, Compressed Chilly Air System

1. INTRODUCTION

High speed machining (HSM) is generally associated with end milling at rotational speeds up to 100,000 rpm, although a figure of 45,000 rpm is a more realistic upper limit. Feed rates of between 10 - 30 m/min are the norm, but values as high as 80 m/min are available. With the growing interest in the use of linear motors as opposed to ball screw arrangements, the trend is for higher feeds and associated accelerations. When cutting complex hardened steel dies or titanium and nickel alloy aerospace components, however, feed values above 10 m/min currently have little relevance. Current mainstream applications include the production of aluminium aircraft wing spars, hardened steel moulds/dies and copper/ graphite electrodes.[1,2]

Cutters are generally <10 mm diameter with tooling assemblies balanced to better than G6.3 [ISO 1940/1-1986]. High speed steel end mills / ball nose end mills are generally regarded as unsuitable for HSM applications due to poor hot hardness and inadequate stiffness. Cutters made from cemented tungsten carbide (WC), coated with either CrN, TiCN, TiAlN or TiAlCrYN are commonly used, irrespective of the workpiece material. Cermet, polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (PCBN) tools, are also used for specific applications.

The number of operating variables relating to high speed ball nose end milling is extensive. In addition to the more obvious factors such as cutting speed, the direction of cut/ orientation of the cutter, can have a significant influence on performance.

Over the past ten years, the effect of workpiece angle and cutter orientation on tool life and surface roughness has been investigated by various researchers, Boehner et.al.,[3], Dumitrescu et.al.[4], Gaida et.al.[5], Tonshoff et.al.[6], Schulz H et.el[7], Park, H.B et.al [8]. Much of the research, involved the HSM of hardened steel and utilised down milling on either a 3 or 5-axis milling centre. The majority of the researchers concluded that a downwards cutter orientation and a workpiece angle of between 10 to 20degree provided the best tool life and workpiece surface roughness. Work by Chu et.al. [9] on cutting force frequency analysis, concluded that when machining at steep workpiece angles, a downwards cutter orientation was more stable.

In order to reduce machining time, a "zigzag" cutting strategy is often employed. Here, both down and up milling occur. Hock [10] and Takahashi et.al.[11] discourage the use of such a cutting strategy as it generates poor surface roughness and low tool life.

In high-speed machining of difficult-to-cut materials, many thermal/frictional problems occur, such as severe tool wear, high cutting temperature, etc. High cutting temperature lead to poor quality workpieces and generates concentrated thermal damage at the cutting edge of a tool. The mechanical energy required for the cutting process is transformed into heat. When the energy is continually consumed, the thermal/friction condition becomes more severe, resulting in a negative effect on the life of the tool, the dimensional tolerance and the material removal rate.

The authors to improve tool life in high speed machining have performed several studies. The use of high-pressured water-jet cooling to improve surface quality and tool life in milling was proposed by R.Kovacevic et.al.[12]. Z.Y.Wang et. al.[13] presented that life of the cutting tool improved three times when using liquid nitrogen cooling, instead of conventional cooling effect in turning Ti-6Al-4V alloy. Generally, the cutting fluid is used to improve lubrication and cooling effect at the tool chip interface. However, this pollutes the work environment and the costs in treating recyclable coolants/lubricants are high. Particularly, liquid nitrogen is expensive and does not recycle. In the high speed milling of harden steel dies, R.C.Dewes et al.[14]

showed that dry machining provided substantially better tool life than using a flood cutting fluid.

In metal cutting operations, the cutting fluid is regarded as the most influential element; more than any other condition of the environment and human body as well as on productivity. Reducing consumption and effective management of the cutting fluid have influenced the cutting economy under modern production installations.

In this study, the tool life is evaluated for various cutting environments, which involve dry, flood coolant, and compressed chilly air coolant.

2. EXPERIMENTAL WORK

2.1 Experimental set up

The machine tool employed was 3 axis CNC high speed machining centre with a continuously variable spindle speed of 200-20,000 rpm. Flank wear was measured using a toolmaker's microscope, equipped with digital micrometer heads giving a resolution of 0.001 mm.

Cutting force measurements (Fx, Fy and Fz) were made using a Kistler three component piezo-electric dynamometer type 9257A with a resonant frequency of 2.3 kHz(recommended operating frequency <760 Hz). The dynamometer was connected to a series of charge amplifiers (Kistler 5011A) and a 4 channel oscilloscope with a maximum sampling rate of 200 Msamples/sec.

A Fast Fourier Transform (FFT) module (Origin 4.0 software by Microcal) was used to evaluate frequency characteristics of the cutting force signatures.

A Rank Taylor Hobson Form Talysurf 120L unit was used to measure workpiece surface roughness (at a cut off length of 0.8 mm, evaluation length of 4.0 mm).

3. Effects of cutter orientation

3.1 Experimental parameters and procedure

To find the effects of cutter orientation when high speed ball end milling, Blocks(285x120x100 mm) of Inconel 718 were used with a chemical composition of 53% Ni, 19% Cr, 18% Fe, 5% Nb, 3% Mo, 0.9% Ti, 0.5% Al and C balance. These were solution treated and aged to a bulk hardness of 45±1 HRC.

Machining tests were carried out using 8 mm diameter, 2 flute solid carbide ball nose end mills, PVD coated with chromium nitride (CrN) and titanium aluminium nitride (TiAlN). Both types of tool had the same geometry. Selected physical property data for the coatings are detailed in Table 1.

Table 1. Selected physical property data for CrN and TiAlN PVD coatings [Doring et.al., 1998]

Coating material	CrN	TiAlN
Microhardness (HV 0.05)	1750	3500
Oxidation temperature (°C)	700	800
Coefficient of friction (dry)	0.5	0.4

A number of machining parameters were fixed throughout the course of the experiments. These were: Vmax 90 m/min, axial depth a_a 0.5 mm, feed/tooth 0.1 mm and radial depth of cut 2.0 mm. In addition, down milling was employed with tests performed dry. Tool overhang was 60 mm and tool runout was maintained at 8μm

Fig. 1 shows the starting point, feed, radial depth of cut direction and spindle rotation direction for the different cutter orientations.

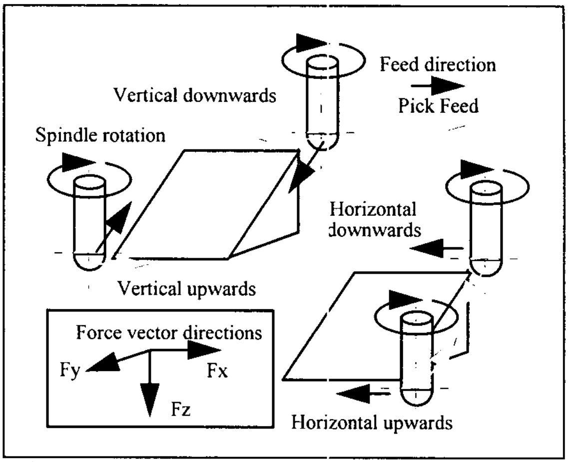


Fig. 1 Cutter orientations and force vector Details

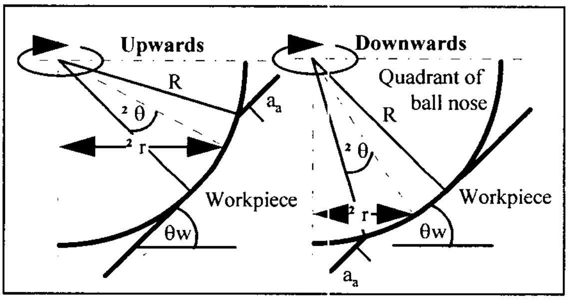


Fig. 2 Nomenclature for upwards and Downwards cutter orientations

It also shows the force vector measurement directions. Fig. 2 shows the nomenclature for upwards and downwards.

Table 2 Experimental test matrix with corresponding N & f values

	Cutter orientations			
	Vertical upwards	Vertical downwards	Horizontal upwards	Horizontal downwards
N (rpm)	3726	5064	3726	5064
f (mm/min)	745	1013	745	1013

Cutting forces were measured during the first 150 mm cut length. As far as possible the tool life tests were carried out in accordance with ISO 8688-2 [1989]. Tests were stopped when the maximum flank wear (VBmax) reached 0.3 mm or the maximum notch wear exceeded 1.0 mm. All surface roughness measurements were made parallel to the feed direction after a cut length of 300 mm. Table 2 details the test matrix. In some instances tests using a particular tool/cutter orientation were performed 3 times, in order to minimise variability.

3.2 Experimental results and discussion

The effect of tool coating and cutter orientation on length cut is shown in Fig. 3 (average data). In general, the TiAlN coating performed slightly better than the CrN product. This was no doubt due to the higher oxidation temperature and hardness of TiAlN when compared to CrN (see Table 1). Work by Sharman et.al. [1999] when ball nose end milling Inconel 718 and Gatto et.al. [1997] when turning Inconel 718, also showed that TiAlN out-performed CrN.

The longest length cut was achieved with a horizontal downwards cutter orientation. When machining in the vertical upwards direction, the TiAlN performed ~250% better than CrN. With the other cutter orientations, the difference in performance between the coatings was <5%. The worst cutter orientation was vertical downwards, which produced a length cut of <0.25 m for both tool coatings.

Fig. 4 shows resultant cutting force data when machining with TiAlN coated tools. These were measured effectively with new tools (VBmax <38μm). Higher forces were observed when machining with downwards rather than upwards cutter orientation. A possible reason for this was the lower average cutting speed and hence lower cutting temperatures that would be expected when machining with the former orientation. This would favour increased workpiece/tool adhesion and built up edge. Fig. 5 shows the peripheral speed response. When machining with a downwards cutter orientation, the average and minimum cutting speeds were 63.9 m/min and 35.2 m/min respectively, compared to 79.8 m/min and 66.2 m/min with a upwards cutter orientation. Higher cutting forces would also be expected to adversely affect tool life and this was in fact the case. The lowest cutting forces were measured when employing a horizontal upwards cutter orientation.

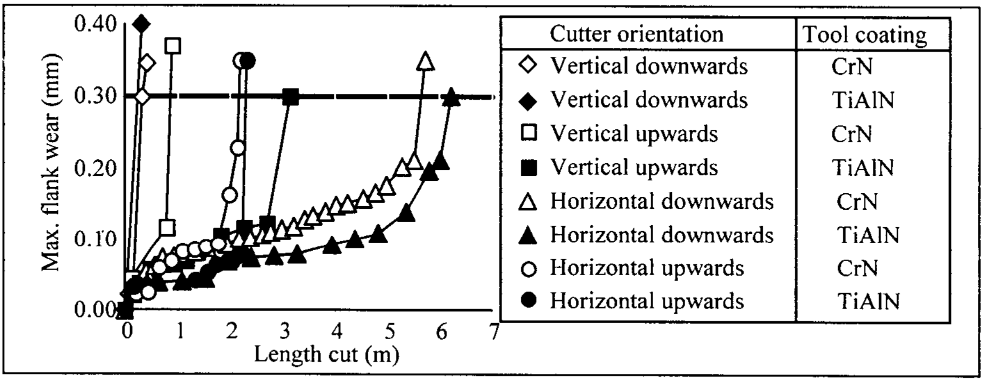


Fig. 3. Effect of tool coating and cutter orientation on length cut

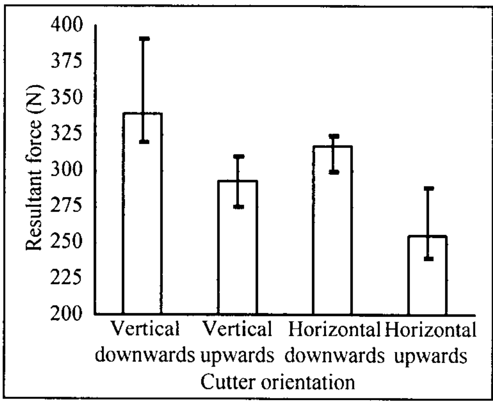


Fig. 4 Cutting forces measured with different cutter orientations

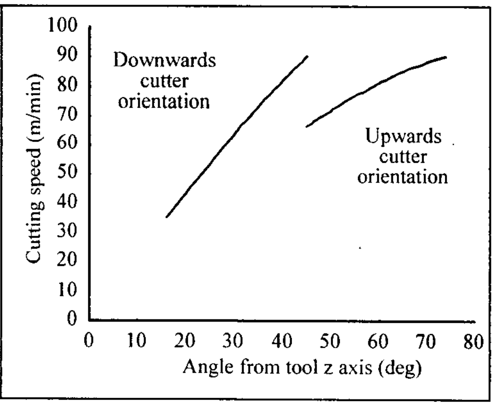


Fig. 5 Peripheral speed distribution with upwards and downwards cutter orientation

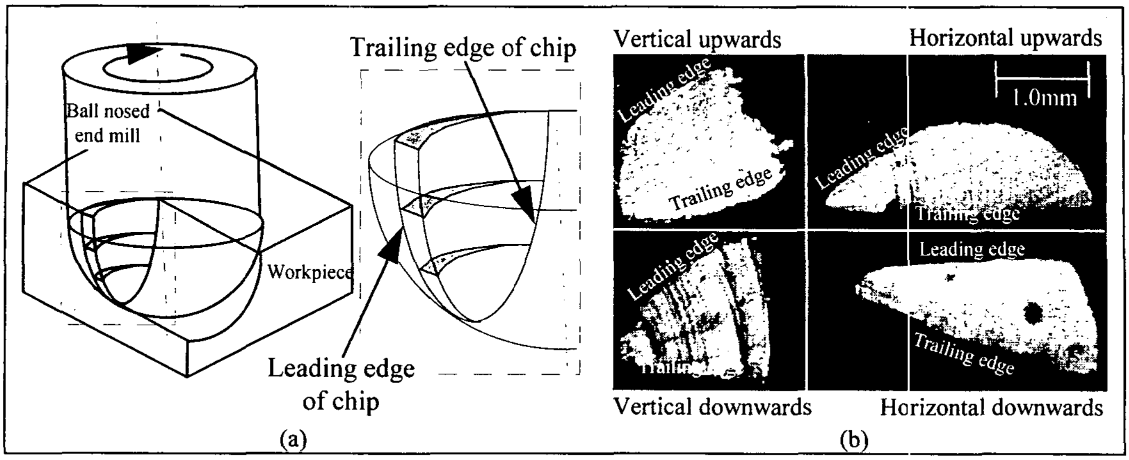


Fig. 6 (a) Schematic of chip formation when ball end milling and (b) chip form produced with different cutter orientations

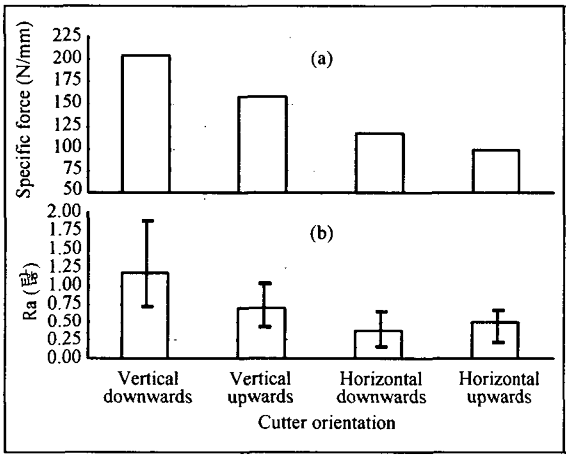


Fig. 7 (a) Effect of cutter orientations on specific force acting on the tool and (b) workpiece surface roughness

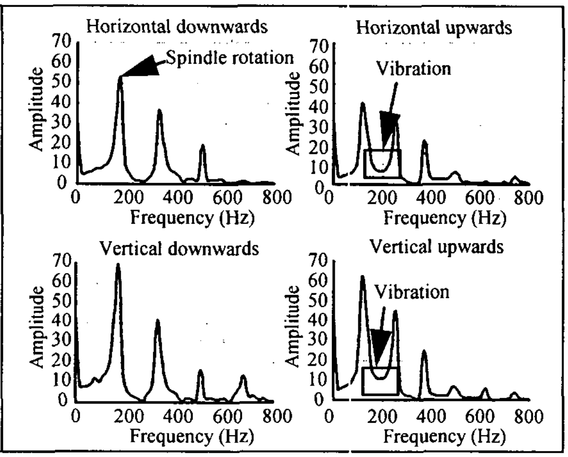


Fig. 8 Effect of cutter orientations on vibration

A schematic of chip formation when ball end milling and actual chip forms produced with different cutter orientations are shown in Fig. 6. Vertical upwards and downwards cutter orientation produced chips of similar form and edge length. The chip profile for horizontal upwards and downwards cutter orientation were also similar but the edge length of the chip differed substantially. As can be seen in Fig. 6b, the leading edge length for the horizontal upwards orientation is shorter than the trailing edge. For the horizontal downwards cutter orientation, both the leading and trailing edges are approximately similar in length. Mean specific force (N/mm) data (mean resultant force ÷ mean edge length) is shown in Fig. 7a. Specific force values were highest when machining with vertical downwards cutter orientation. This in part, explains the extremely short tool life experienced when using this operating mode. If this reasoning is followed through, one would expect the low specific force results for the horizontal upwards cutter orientation to be associated with the longest tool life. However this was not the case, the most likely reason being due to tool vibration. The effect of cutter orientation on machined surface roughness (Ra) when using TiAlN coated carbide cutters is shown in Fig. 7b. The data were averaged from 10 readings for each cutter orientation taken at a length cut of 300 mm. A possible explanation for the poor surface finish with the vertical downwards cutter orientation, was the high wear rate induced by the high resultant cutting force acting on the tool. The average Ra value for horizontal downwards cutter orientation was lower than for horizontal upwards.

Fig. 8 shows the FFT frequency analysis of cutting force in the Fx direction with different cutter orientations. Similar signatures were also found in the Fy and Fz force vector directions. The frequency range used in the analysis was limited to below 800 Hz to exclude detecting the resonant frequency of the dynamometer

(~766Hz). For the horizontal or vertical downwards cutter orientations, the first peak is at 168.8 Hz. This frequency is a function of the rotational speed of the spindle and the number of cutter teeth (N÷ 60 x 2(number of teeth)). The amplitude decreases to zero after the first peak for the horizontal and vertical downwards cutter orientations, however, this is not the case when using the other two cutter directions. Vibration is evident between 160 to 215 Hz (see Fig. 8). When machining with downwards cutter orientation, the resultant forces will act at an angle of 16 to 45° from the tool z axis (refer to Fig. 5). Therefore, the majority of the force will be transmitted to the tool z axis. With the upwards cutter orientation, the cutting tool engages the workpiece between 45 and 73.9° from the tool z axis. This results in a greater tendency for chatter, as the majority of the resultant force is acting to push the tool away from the machined surface.

4. Effects of cutting environments

4.1 Experimental parameters and procedure

Fig. 9 shows the schematic diagram of the compressed chilly air system. The cooling system uses the compressed air in which moisture is fully removed by the main line filter and the air drier. The dried air exchanges the heat in the cooling air system. The air temperature is cooled down to about -2℃ after the heat exchange because the heat conductivity of air is lower than that of liquid. The compressed chilly-air is jetted through the nozzle enabling the adiabatic expansion at that moment. The air temperature at that time is about -12℃ and the pressure of the compressed chilly-air is about 7.5 kgf/cm^2. To provide the compressed chilly air to the contact point of the cutting edge and the workplace under the cutting process, a nozzle of about 5mm in diameter is used.

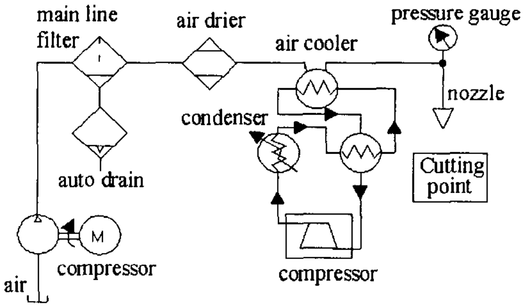


Fig. 9 Schematic diagram of compressed chilly air

The hardness of workpieces ranged from HRc 28 to HRc 60. The carbide tool coated with TiAlN and the HSS tool coated TiN were used. In order to find the influence of cutting environments on the tool life, the experiments were performed under a dry cutting, flood coolant (4bar) cutting, and compressed chilly air cutting. The cutting speed is set at 90m/min and 210m/min, respectively. The feed direction is set as horizontal downward for down milling.

4.2 Experimental results and discussion

Fig. 10 to 13 shows the variation of tool life according to cutting environments. Fig. 10 shows the results of tool wear for HP-4M (HRc28) using a HSS tool coated with TiN at the cutting speed of 210m/min. When the tool wear reaches the tool life criteria of 0.3 mm, the cutting length is about 2m and 5m, *respectively* under a dry cutting and by flood coolant. For the compressed chilly air, the cutting length is about 9m and is longer than those in the flood and dry coolants. The tool wear like chipping rapidly occurred over the flank wear 0.1mm.

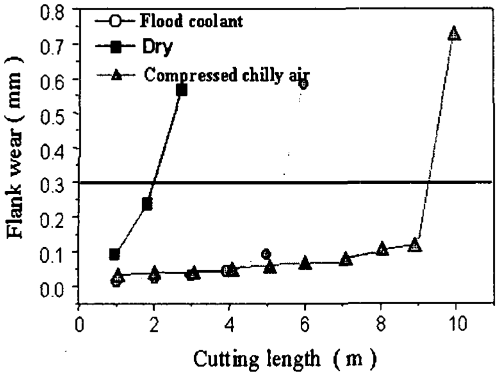
Fig. 11 shows the cutting length according to the change in the cutting environment for the die steel STF4 (HRc42) using a carbide tool coated with TiAlN at the cutting speed of 210m/min. When the tool wear reaches the tool life criteria of 0.3 mm, the cutting length was 110m and 65m, respectively, under a dry environment and by flood coolant. By the compressed chilly-air, the cutting length is 220m. Using the compressed chilly air, the tool life is prolonged 3.5 times as much as that with flood coolant and twice as much as that under a dry cutting. In the milling process, heating of the tool edges is repeated due to the interrupted cutting. As a result, it can be seen that high speed machining of hardened steel with the flood coolant generates much more thermal fatigue of the tool than that with the compressed chilly air.

Fig. 12 shows the results of the workpiece of HRc50 using a carbide tool coated with TiAlN at the cutting speed of 210m/min. Under a dry cutting or by compressed chilly air, the cutting length is 6.6 m and 9 m respectively; however, cutting by flood coolant at the cutting length of 1.2m. The compressed chilly air method has improved the machinability by 2 m more than the cutting under a dry environment and by 8 m more than cutting by flood coolant. A flaking due to the thermal impact occurred by flood coolant, but under a dry cutting and by compressed chilly air, the chipping is the main cause of the wear. As mentioned above, the ball end-milling operation has an intermittent cutting form which periodically repeats the heating under cutting and cooling under non-cutting. When using a flood coolant, the cutting edges show severe thermal fatigue from the cooling operation using a cutting fluid. This, in turn, results in a shorter tool life as compared with dry cutting and by compressed chilly air cutting. Due to its aerial property, chilly air has lower heat conductivity than a flood coolant as fluid. The cutting heat is not cooled down as much as by flood coolant, and the thermal impact on the tool is reduced; thus resulting in a prolonged tool life.

Fig. 13 shows the cutting length during machining Inconel718. Fig.13(a) shows the results experimented at the cutting speed of 90 m/min. Through dry cutting, the cutting length is 1.4 m, and by compressed chilly air, it is 2.2 m. Fig.13(b) shows the result experimented at the cutting speed of 210 m/min. It represents almost similar cutting lengths, 1.1m ~ 1.3m under any environmental conditions. Because Inconel718 has hot strength and high toughness, the tool receives great pressure at the tool-chip and tool-workpiece interface during high speed machining. Severe thermal friction occurs. Under such conditions, cutting fluid and compressed chilly-air fail to infiltrate into the interface of the tool-chip or tool-workplace and there is no prolongment of the tool life.

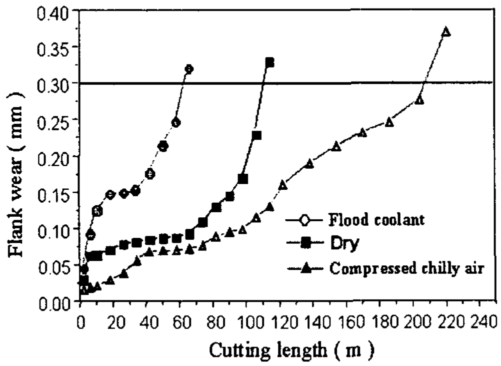
5. CONCLUSIONS

The effects of cutter orientation and cutting environments in high-speed machining for the difficult to cut materials were investigated. From the results for the cutter orientation, the longer chip edge length for horizontal downwards cutter orientation induced a lower specific force in spite of a higher resultant force, when compared to a vertical upwards cutter orientation. And workpiece surface roughness was best when



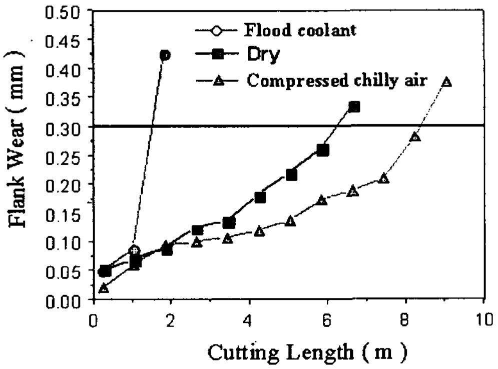
Cutting speed : 210m/min, Feed rate : 0.1mm/tooth
Axial depth of cut : 0.5mm,Radial depth of cut : 2mm
Workpiece : HRc28, Tool : HSS(coated TiN)

Fig. 10 Effect of cutting environments on length cut



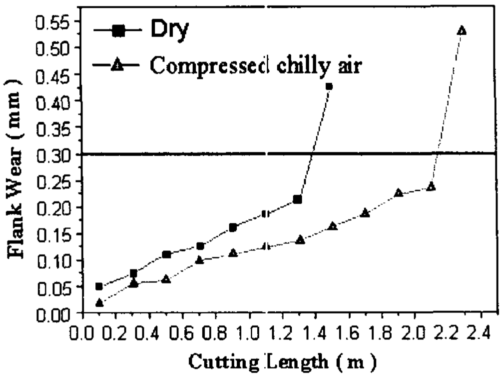
Cutting speed : 210m/min, Feed rate : 0.1mm/tooth
Axial depth of cut : 0.5mm,Radial depth of cut : 2mm
Workpiece : HRc42, Tool : Carbide (coated TiAlN)

Fig. 11 Effect of cutting environments on length cut

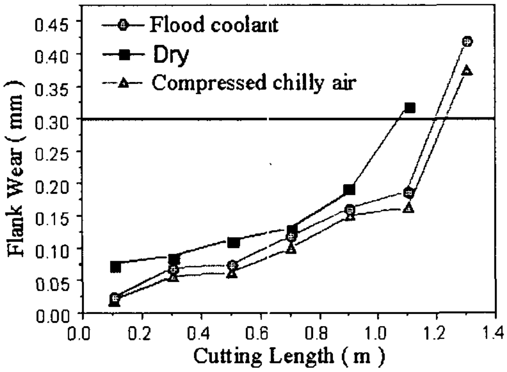


Cutting speed : 210m/min, Feed rate : 0.1mm/tooth
Axial depth of cut : 0.5mm,Radial depth of cut : 2mm
Workpiece : HRc50, Tool : Carbide (coated TiAlN)

Fig. 12 Effect of cutting environments on length cut



Cutting speed : 90m/min, Feed rate : 0.1mm/tooth
Axial depth of cut : 0.5mm,Radial depth of cut : 2mm
Workpiece:Inconel718(HRc43),Tool:Carbide (coated TiAlN)
(a) Cutting speed 90m/min



Cutting speed : 210m/min, Feed rate : 0.1mm/tooth
Axial depth of cut : 0.5mm,Radial depth of cut : 2mm
Workpiece:Inconel718(HRc43),Tool:Carbide (coated TiAlN)
(b) cutting speed 210m/min

Fig. 13 Effect of cutting environments on length cut

machining with a horizontal downwards cutter orientation. This was primarily due to the low tool wear rate and minimal vibration. The results for the cutting environments show that the cutting length for the die steel of HRc42 by the compressed chilly air cooling is increased twice longer than the dry cutting, and 3.5 times longer than the flood coolant.

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