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High Speed End Milling of Cobalt Chromium Molybdenum Alloy using Solid Carbide Tool under MQL Condition

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Abstract. Cobalt chrome molybdenum (CoCrMo) alloy is among the biomedical materials which is considered difficult to cut materials due to their combination of high strength, high toughness, high wear resistance, and poor thermal conductivity. In this study, high speed end milling (HSEM) was performed experimentally to access the machinability of CoCrMo alloy using solid coated and uncoated tools at different cutting speeds of 125, 140 and 155 m/min under the minimum quantity lubricant (MQL) strategy. The axial and radial depth of cut were kept constant 4 mm and 1.5 mm respectively throughout the machining tests. The tool wear, tool life and tool wear mechanism were recorded and analyzed accordingly. It was observed that higher cutting speed significantly reduces the tool life due to rapid tool wear. Coated carbide tool performed better than uncoated carbide tool in terms of tool life for every cutting speed. It was also found that chipping, adhesion and cracks were the dominant wear mechanisms occurred on the cutting edge when high speed end milling of CoCrMo biomedical material.

INTRODUCTION

High Speed Machining (HSM) is recently introduced in machining advanced materials such as Cobalt Chromium Molybdenum (CoCrMo) alloy. HSM is widely used in order to increase the surface quality and dimension accuracy of the product as well to increase the productivity without increasing the production costs. Usually the cutting speed in HSM operation is 5~10 times higher than the ordinary machining [1]. High material removal rates, short production times, low cutting forces, low temperature at the workpiece, increased the form and shape accuracy as well as surface quality, reduced burr formation and reduced the influence on the surface layer are several advantages when using HSM [2]. Machining material from a soft material to hard material such as cobalt chromium alloys cause a great challenge to machinist.

With the combination of the cobalt and chromium elements, cobalt-chrome (Co-Cr) alloy can be categorized under the superalloys group material [3]. Its applications are widely found in the field that requires wear, heat and corrosion resistance such as nuclear, aerospace and gas turbine industries [4]. Other than that, cobalt base alloys are also considered as one of the metallic biomaterials besides titanium and stainless steel [5]. In the orthopedics implant application, Cobalt Chromium Molybdenum (CoCrMo) alloy [6-7] is one of the common cobalt base alloy

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used for knee and hip replacement due to their excellent properties such as high strength, high corrosion resistance, high hardness, high creep resistance, biocompatibility and greater wear resistance [3,5].

Based on several reviews, machining studies on CoCrMo alloys are still lacking, [8-9] especially in determining the suitable cutting tool and cutting parameters when dealing with these CoCrMo alloys. The combination of properties such as high strength, toughness, high hardness, high wear resistance and poor thermal conductivity makes this material a very difficult to machine material [10-11]. Previous studies of the CoCrMo alloys are more focused on optimizing the process parameters in machining operations by using several methods such as Design of Experimental (DOE), Genetically Optimized Neural Network System (GONNS), Genetic Algorithm (GA), Artificial Neural Networks (ANNs) and Response Surface Methodology (RSM) [4,12-16]. In addition, Song et al. [17] and H. Shao et al [18] studied the performance of coated and uncoated carbide cutting tool using turning operation.

Minimun Quantity Lubricant (MQL) or Near-Dry Machining [19] is one of the latest techniques in delivering cutting fluids to the tool and workpices region during cutting operation. This method was introduced a decade ago as a mean to address the issues of environmental intrusiveness and occupational hazard. Dry and MQL strategies have caught the attention of many researchers and technicians in the field of machining as an alternative to traditional fluids [20]. Karpuschewski, Pieper, & Döring [21] investigated the effect of different cooling system on surface integrity using a ceramic cutting tool when turning CoCrMo alloys.

METHODOLOGY

Workpiece Material

A cobalt chromium molybdenum alloy was selected as a workpiece material. The chemical compositions and mechanical properties of the CoCrMo alloy are shown in Tables 1 and 2 respectively. A rectangular block, 400mm in length, 40mm in width and 80mm in height, was used in the high speed end milling (HSEM) experiments.

TABLE 1. Chemical composition of CoCrMo alloy

	Chemical Composition								
Element	Cr	Mo	Fe	Mn	Si	C	Ni	N	Co
Weight	26.0 to 30.0	5.0 to 7.0	0.75	1.0	1.0	0.15 to 0.35	1.0	0.25	Balance

TABLE 2. Mechanical properties of CoCrMo alloy

Mechanical Properties				
Young' modulus (GPa)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Hardness (HV)
235 – 247	1290 – 1420	760 – 839	25 – 29	363 - 402

Cutting Tool And Cutting Parameter

Coated and uncoated solid carbide endmills with similar substrate and geometry were supplied by a local tool manufacturer, HPMT Industries Sdn. Bhd. Inc. They were then used in HSEM experiments and the detail of the cutting tools described in Table 3. The cutting parameters employed in this study were: feed *fz*=0.02 mm/tooth, cutting speed Vc=125, 140 and 155 m/min, axial depth of cut, a_p= 4 mm, and radial depth of cut, a_e=1.5 mm.

TABLE 3. Details of the cutting tools

Item	Description
Cutting tool material	a) Multilayer PVD coated (TiSi) b) uncoated (SE 45)
Tool diameter	6 mm
Rake Angle	3°
Helix Angle	40°
Number of Flute	4
Coating Properties	Coating Material : TiSi Based (Multilayer)
	Microhardness (HV 0,05)=3600
	Max Application Temperature (°C) ≤ 1200
	Friction coefficient = 0,3

Experimental Procedures

Machining experimentations were carried out on a MAHO DMC 835V CNC milling machine using side cutting process under MQL environment with down milling mode. For each experiment, a new solid carbide end mill used and mounted on the tool holder. Tool wear was measured by using a tool maker microscope after a specific machining time. The wear morphologies of the cutting edge were examined periodically, and any apparent change in the edge surface was closely examined with a ZEISS high power microscope. In order to study the tool wear mechanism, the worn cutting edge was observed under a scanning electron microscope (SEM). The tool rejection or failure was based on the following criteria:

1. Average flank wears VBave = 0.18 mm;
2. Maximum flank wears VBmax = 0.3 mm;
3. Excessive chipping/flaking or catastrophic fracture of the cutting edge.

Experimental trial was be stopped when any one of the above criteria is reached.

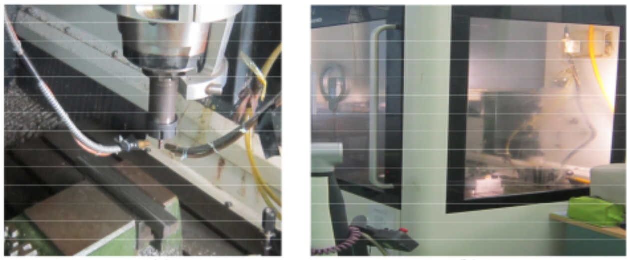

(a) (b)

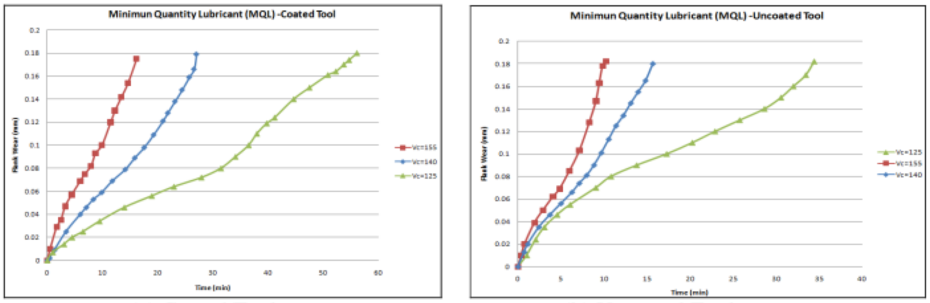
FIGURE 1. (a-b) CNC machine used in HSEM CoCrMo alloy

RESULTS AND DISCUSSION

Tool Wear And Tool Failure Mode

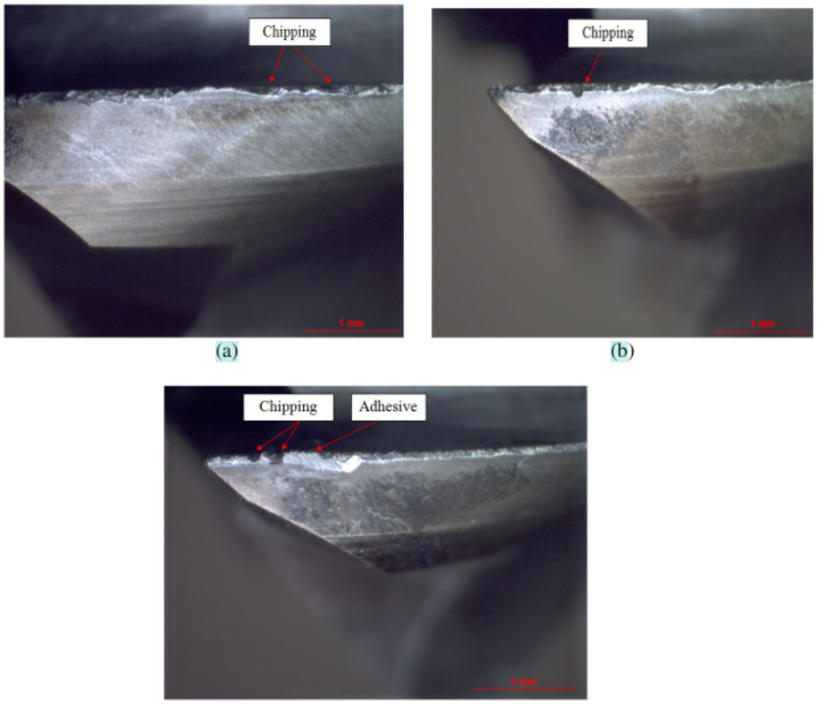
Figures 2(a-b) show the flank wear curve of the coated and uncoated solid carbide tool using HSEM. From the flank wear curve, it can be seen that the development of the flank tool wear was relatively rapid in general, especially at high cutting speed. The first region is the initial wear stage. In this region, the flank wear initially increases rapidly and later-on gradually reduces to a constant rate. The second region, also known as a steady state wear region. At this stage, the wear curve can be regarded as linear to cutting time. The third region is defined as the failure stage. At this stage, the flank wear increases drastically due to increase in cutting force and temperature as a result of a worn cutting edge which finally leads to the failure of the cutting edge. It was observed from Figures 3(a-c) that chipping and flaking were the main failure mode when HSEM CoCrMo alloy using coated cutting tools at the high cutting conditions of Vc=155 and Vc=140 m/min with feed 0.02 mm/tooth. Simultaneously, build-up edge

(BUE) also occurred at the edge of the flank at lower cutting speed of Vc=125 m/min. From the observation, chipping and flaking occurred after the coatings had worn with prolong machining. It was evident that flaking and chipping failure modes, started to appear at the stable region and final wear stage. Figures 4(a-c) reveal that notch wear at the flank face was found to dominate the tool failure mode at the final stage of tool wear for all cutting speeds when HSEM CoCrMo alloy using uncoated carbide tools. The characteristic of CoCrMo alloy of low thermal conductivity, high strain hardening, high hardness at elevated temperature and high wear resistance [22] are amongst the reasons for increasing tool wear and short tool life due to the large heat transmitted into the cutting edge during the cutting process.



(a) Coated Tool (b) Uncoated Tool

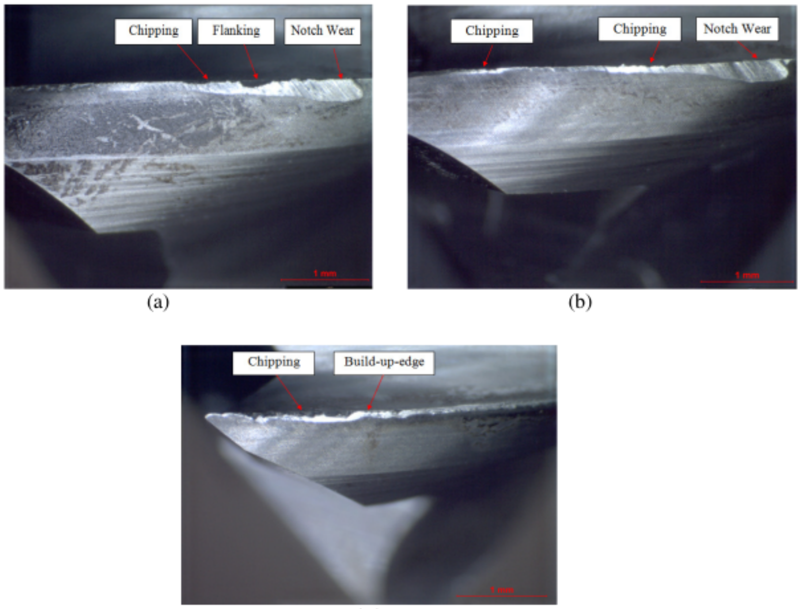
FIGURE 2.(a-b) Flank wear versus machine time when HSEM CoCrMo alloy under MQL with coated and uncoated tool at cutting speeds of 125, 140 and 155 m/min.



(a) (b)

(c)

FIGURE 3.(a-c) Flank wear of coated tool at cutting speed (a) 155 m/min, (b) 140 m/min and (c) 125 mm/min



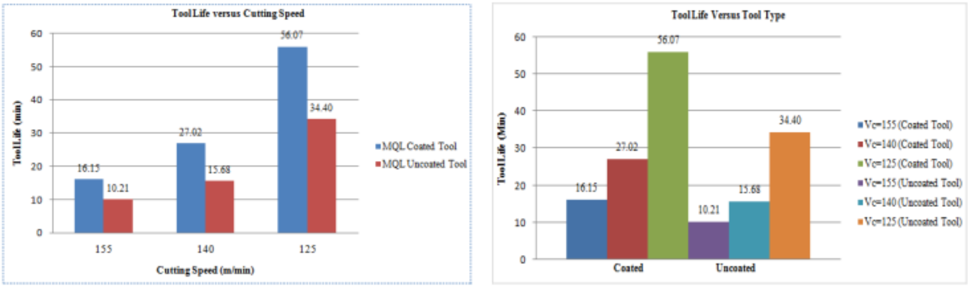
(a) (b)

(c)

FIGURE 4.(a-c) Uncoated Flank wear at cutting speed 155, 140 and 125 m/min using HSEM.

Tool life

Figures 5 (a-b) show the effect of cutting speed and tool type on tool life when HSEM CoCrMo using MQL. Results from Figure 4 (b) shows that at feed rate of 0.02 mm/tooth, the effect of cutting speed on tool performance was more significant at lower speed of 125 m/min using coated and uncoated carbide tools. Machining at the higher cutting speed of 155 m/min resulted in shorter tool lives as shown in Figure 4 (a) when using uncoated carbide tool. Severe chipping, flaking and notch wear at the cutting edge caused the tool failure as shown in Figures 2 (a-c). At lower cutting speed of 125 mm/min, both tools recorded a higher tool life of 56.07 minutes (coated tool) and 34.40 minutes (uncoated tool) with increment of 247.80% and 236.92% of tool life for coated and uncoated tools respectively. In general, coated tool outperformed uncoated tool under all cutting speeds with high percentage of improvement in tool life when HSEM CoCrMo alloy under MQL condition. An increment of 62.96% of tool life was recorded when HSEM at cutting speed of 125 m/min using coated carbide tool. From the result it can be concluded that when machining with high cutting speed were increase cutting temperature and thermo mechanical stresses at the cutting zone was evident that increase in wear rate at high cutting speed, adversely affect the tool life due to significant increase in cutting temperature and thermo mechanical stresses at the cutting zone.

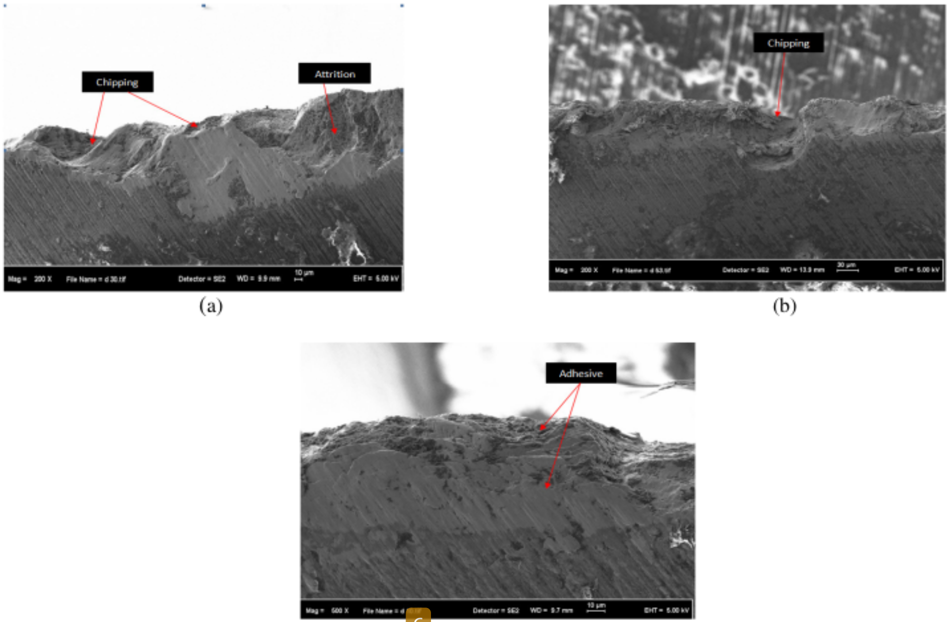


(a) (b)

FIGURE 5. (a-b) The effect of cutting speed and type of cutting tool when HSEM CoCrMo alloy

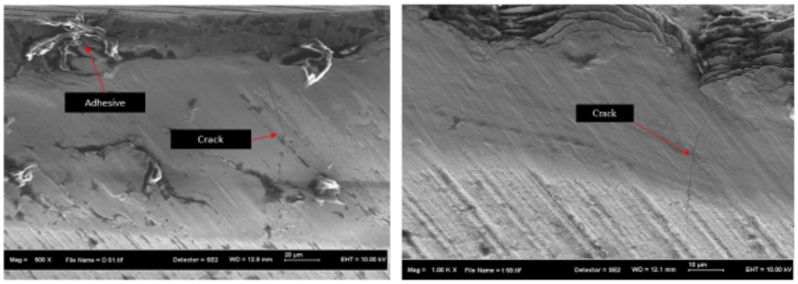
TOOL WEAR MECHANISM

From the Figures 6 (a-c) and Figures 7 (a-b), it can see that attrition, adhesion and cracks were the dominant wear mechanism during HSEM CoCrMo alloy, using coated and uncoated tools. These wear mechanisms were directly associated with the concentration of high stresses and heat at a small area of tool chip contact at the cutting edge. Figure 7(a-b) showed that thermal cracks appear at the flank face of uncoated tool when machining at cutting speed of 155 m/min and 140 m/min. According to Trent and Wright (2000) [23] these cracks are promoted because of the cyclic expansion and contraction of the surface layer of the cutting tool when they are cyclically heated and cooled during cutting processes.



(a) (b)

FIGURE 6. (a-c): Chipping, Attrition and Adhesive on the flank face of coated tool at cutting speed of 155, 140 and 125 m/min



(a) (b)

FIGURE 7.(a-b): Adhesive and cracks on the flank face of the uncoated tool at cutting speed of 155 and 140 m/min

CONCLUSIONS

The following conclusions are drawn during HSEM of CoCrMo alloy using coated and uncoated carbide tools under MQL condition, they are:

a) Flank wear, chipping and built-up-edge at the cutting edge were the dominant failure modes when using coated and uncoated carbide tools.
b) Coated carbide tool displayed the best tool life performance as compared to uncoated tools at cutting speed 125 m/min with feed rate 0.02 mm/tooth.
c) Adhesion, attrition and cracks were among the wear mechanisms operating during the HSEM process.

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