Journal of Engineering and Applied Sciences 12 (4): 945-949, 2017
ISSN: 1816-949X

Effect of High Speed End Milling of Co-28Cr-6Mo Cobalt Chromium Molybdenum Alloy using Uncoated and Coated Carbide Tools

Hainol Akbar Zaman, Safian Sharif, Mohd Hasbullah Idris and Denni Kurniawan
Faculty of Mechanical Engineering,
Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia

Abstract: Cobalt chrome molybdenum alloys are advanced materials which are considered difficult to cut material due to their unique combination of high strength, high toughness, high wear resistance and poor thermal conductivity. High speed end milling was performed experimentally to access the machinability of Co-28Cr-6Mo alloy at different cutting speeds of 80 and 120 m min^{-1} using uncoated and coated carbide cutting tools. Tool wear, tool life and surface roughness were recorded analyzed accordingly. Results showed that higher cutting speed significantly reduces the tool life due to rapid tool wear. Uncoated carbide tool outperformed coated carbide with respect to tool life. It was also found that surface roughness at higher speed was slightly lower than at lower cutting speed for both coated and uncoated tools.

Key words: Cobalt chromium molybdenum alloys, machining, tool wear, tool life, surface roughness

INTRODUCTION

Under the advanced machining process, High Speed Machining (HSM) is considered a new technology for the 21st century which can increase the productivity and quality without increase in the production costs. Usually, the cutting speed in HSM is 5-10 time higher than the ordinary machining (Cui *et al*., 2014). Several advantages are evident when using HSM such as high material removal rates, short production times, low cutting forces, low cutting temperature, increased form and shape accuracy as well as better surface quality, reduced burr formation and reduced influence on the surface layer (Tönshoff *et al*., 1999; Khaimovich *et al*., 2014). High Speed Machining (HSM) is widely used for soft materials such as aluminum and magnesium to hard materials such as steels for dies and moulds, titanium, nickel and cobalt chromium alloys.

Cobalt-Chrome (Co-Cr) alloy of cobalt and chromium is categorised under the superalloys group material (Shokrani *et al*., 2012) and its applications are widely found in the field that requires wear, heat and corrosion resistance such as nuclear, aerospace and gas turbine industry (Bagci and Aykut, 2006). In the biomedical application, cobalt base alloys can be classified under metallic biomaterial besides titanium and stainless steel (Niinomi, 2002). Cobalt Chromium Molybdenum alloys (CoCrMo) were the common cobalt base alloy used in orthopedics implant such as knee and hip replacement due to their excellent properties such as high corrosion resistance, high strength, high hardness, high creep resistance, biocompatibility and greater wear resistance as compared to other metallic biomaterial (Shokrani *et al*., 2012; Niinomi, 2002; Patel *et al*., 2010).

The combination of properties such high strength, toughness, high wear resistance and poor thermal conductivity makes this material a very difficult to cut material (Milosev, 2012; Brazel *et al*., 2011). Machining studies on CoCrMo alloys are still lacking (Bruschi *et al*., 2013; Bordin *et al*., 2014a, b), especially in establishing suitable cutting tools and cutting parameters when dealing with these alloys compared to titanium, titanium alloys and stainless steel which so far have reached to an established level of machining studies.

Bruschi *et al*. (2013) performed an investigation on the influence of cutting conditions on tool wear, surface integrity and microstructure during turning operation of CoCrMo alloys under the semi-finishing operation. Song *et al*. (2010) compared the best turning method on CoCrMo alloys by using elliptical vibration cutting and ordinary cutting without tool vibration to evaluate the roughness and hardness of the finishing surface as well as the tool wear. Shao *et al*. (2013) studied the machinability of stellite alloys with uncoated and coated

Corresponding Author: Safian Sharif, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia

carbide tools in dry turning process. Ferreira *et al.* (2014) conducted a study on milling of Ti-6Al-4V and Co-28Cr-6Mo alloys to evaluate the effect of cutting speed on cutting temperature and cutting force. Bordin *et al.* (2014) presented the experimental results in terms of surface integrity when turning CoCrMo alloy under dry machining. Karpuschewski *et al.* (2014) investigated the effect of different cooling system on surface integrity using a ceramic cutting tool when turning CoCrMo alloys. Based on the majority of previous studies, it was observed that researches on CoCrMo alloys were mainly focused on machining at lower cutting speeds using turning operations (Bruschi *et al.*, 2013; Song *et al.*, 2010; Shao *et al.*, 2013; Bordin *et al.*, 2014a, b). This study was undertaken to investigate the machinability of CoCrMo alloys during HSEM operation using uncoated and coated carbides tools. Tool wear, tool life and surface roughness were assessed accordingly.

MATERIALS AND METHODS

Workpiece material: A Cobalt Chromium Molybdenum (CoCrMo) alloy was selected as the workpiece material. The chemical compositions and mechanical properties of the CoCrMo alloy are shown in Table 1-2, respectively. A rectangular block of 400 mm in length, 40 mm in width and 80 mm in height was used in the High Speed End Milling (HSEM) experiments.

Cutting Tools and Cutting Parameters: Uncoated and coated inserts of similar geometry supplied by SECO Inc. were used in the HSEM experiment. Table 3 describes the detail of the tooling system. The cutting parameters used in this study were: feed fz = 0.04 mm/tooth, cutting speed (Vc = 120 and 80 m min^{-1}), axial depth of cut a_p = 4 mm and radial depth of cut is a_e = 1.5 mm.

For the HSEM trials, a CNC MAHO 700S machining center was used for the side cutting process under dry cutting environment with down milling mode. A handysurf E-35 surface roughness tester was used to obtain the surface Roughness (Ra) value of the machined surface with an average of four readings was considered as the final surface roughness value. Tool wear was measured using a tool maker's microscope at specific machining interval. 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. Tool rejection or failure was based on the following criteria: average flank wear, Vb_{ave} = 0.20 mm; maximum flank wear, Vb_{max} = 0.5 mm; excessive chipping/flaking or catastrophic fracture of the cutting edge. Experiment trial was stopped when any one of the above criteria is reached.

Table 1: Chemical composition of CoCrMo alloys

Chemical Composition (wt.%)	
Element	Weight
Cr	26-30
Mo	5-7
Fe	0.75
Mn	1.0
Si	1.0
C	0.15-0.35
N	1.0
Ni	0.25
Co	Bal

Table 2: Mechanical properties of CoCrMo alloy

Parameters	Values
Mechanical properties	
Young's modulus (Gpa)	235-247
Tensile strength (Mpa)	1290-1420
Yield strength (Mpa)	760-839
Elongation (%)	25-29
Hardness (HV)	363-402

Table 3: Cutting tool details

Items	Description
Tool holder	R217.69-1612.3-09-1AN with shank diameter 16 mm
Cutting tool material	a) PVD coated (F40M, TiAlN+TiN) b) uncoated (H25)
Tool diameter	12 mm
Cutting edge length	9.9 mm
Width	6.35 mm
Thickness	3.65 mm
Corner radius	0.8 mm
Rake angle	24°
Major cutting edge angle	90°

RESULTS AND DISCUSSION

Tool wear and tool failure mode: Result on tool wear of coated and uncoated tools was observed to follow the normal wear curve as shown in Fig. 1. In the initial wear stage for the new cutting edge, the small contact area and high contact pressure resulted in a high wear rate. As cutting progresses and due to the relative motion between the tool and workpiece, various wear modes become active and the tool starts to deteriorate. After the initial stage, the wear gradually increases into a stable wear stage until it reaches the maximum level of tool wear. At the final stage, the flank wear increases drastically due to increase in cutting force and higher cutting temperature as a result of a worn cutting edge which finally leads to the failure of the cutting edge.

Figure 2a and b show a slight built-up-edge was observed as the main failure mode when HSEM CoCrMo alloy using uncoated and coated cutting tools at the lower cutting condition Vc = 80 m min^{-1} with feed of 0.04 mm/tooth.

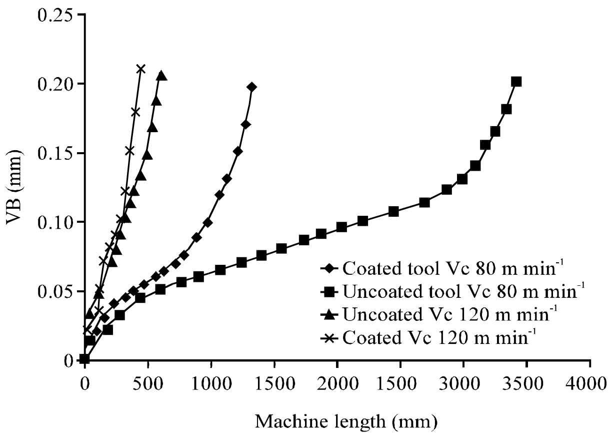

Fig. 1: Tool wear versus machined length when HSEM under dry cutting with uncoated and coated tool at cutting speeds of 80 and 120 m min^{-1}

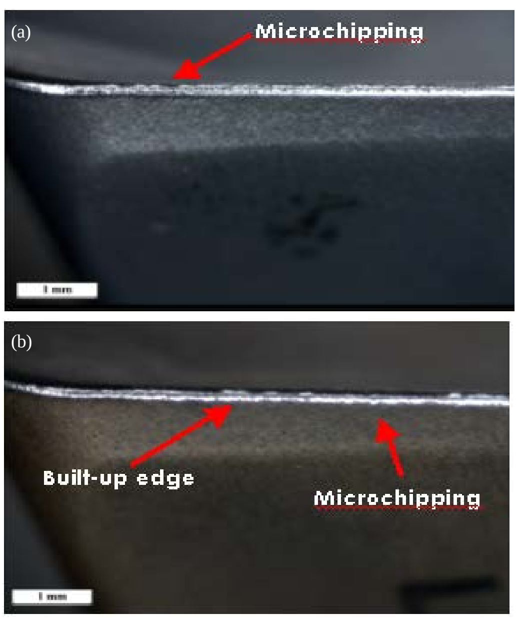

Fig. 2: a) Micro chippings were observed when using uncoated tool at Vc = 120 m min^{-1} and b) Built-up-edge was observed when using coated tool at Vc = 80 m min^{-1}

Simultaneously, micro chipping also occurred at the edge of the flank at high cutting speed of Vc = 120 m min^{-1}. It was observed that the wearing out of the coating after prolonged machining contributes to the occurrence of the micro chipping. It was evident that both failure modes started to appear at the stable region and final wear stage. The coated tool also demonstrated rapid failure due to the excessive wearing out of the coatings at higher cutting speed.

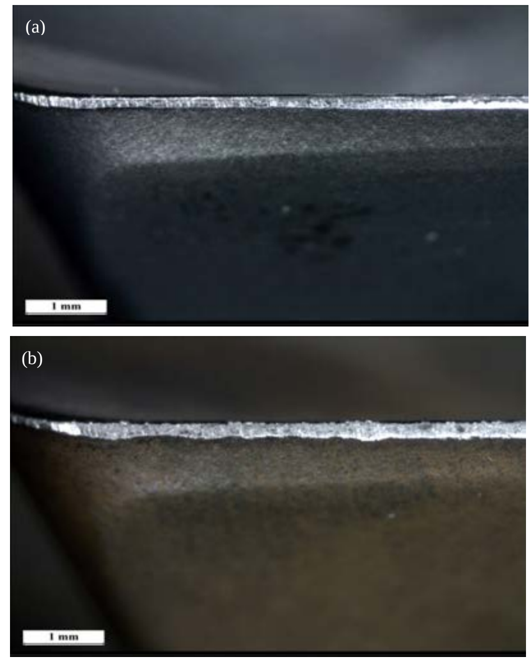

Fig. 3: Uniform flank wear for both uncoated: a) and coated and b) carbides cutting tools at the final stage of cutting at all cutting speeds

Figure 3a and b reveal that uniform wear at the flank face was found to dominate the tool failure mode at the final stage for all cutting speeds when HSEM CoCrMo alloy with coated and uncoated carbide tools. At high speed machining, since these alloys retain their strength and hardness at elevated temperatures, their machining remains difficult. In addition, low thermal conductivity, high strain hardening, high hardness at elevated temperature and high wear resistance (Ferreira *et al*., 2014) of CoCrMo alloys are amongst the reasons of increasing tool wear and short tool life due to the large heat transmitted into the cutting edge during the cutting process.

Tool life: Based on the tool wear curves in Fig. 1, the tool life data can be summarized graphically in Fig. 4 with respect to cutting speed and tool type. Rapid increase in flank wear was observed at higher cutting speed of 120 m min^{-1} when using both uncoated and coated tools whereby shorter tool life of 4.75 and 3.3 min, respectively were recorded. At lower cutting speed of 80 min both tools recorded higher tool life of 36.25 min (uncoated tool) and 16.66 min (coated tool) with increment of 663 and 405% of tool life for uncoated and coated tools, respectively. In general, uncoated carbide tool outperformed coated tool at both cutting speeds of 80 and 120 m min^{-1} with huge percentage of

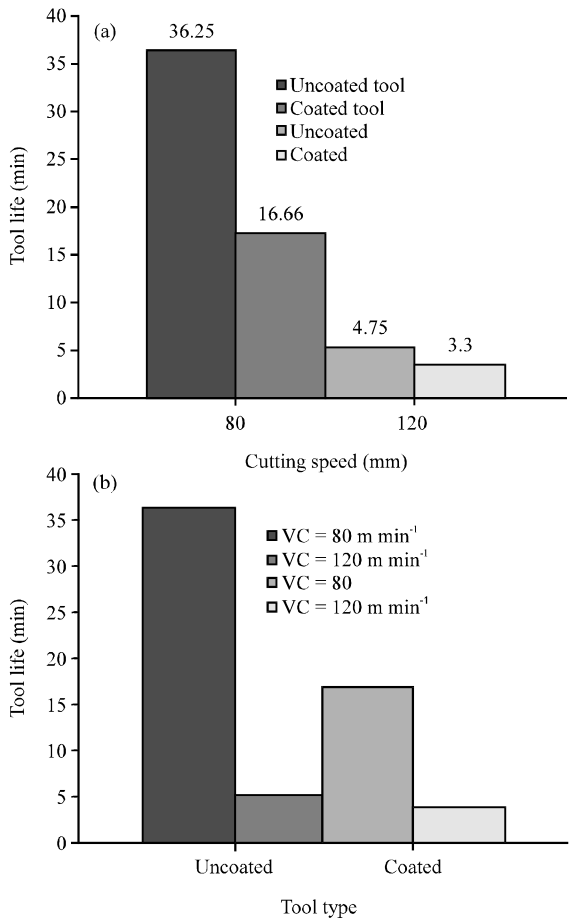

Fig. 4: The effects on tool life when HSEM CoCrMo alloy at feed rates 0.04 mm/tooth with different: a) cutting speed and b) cutting tools

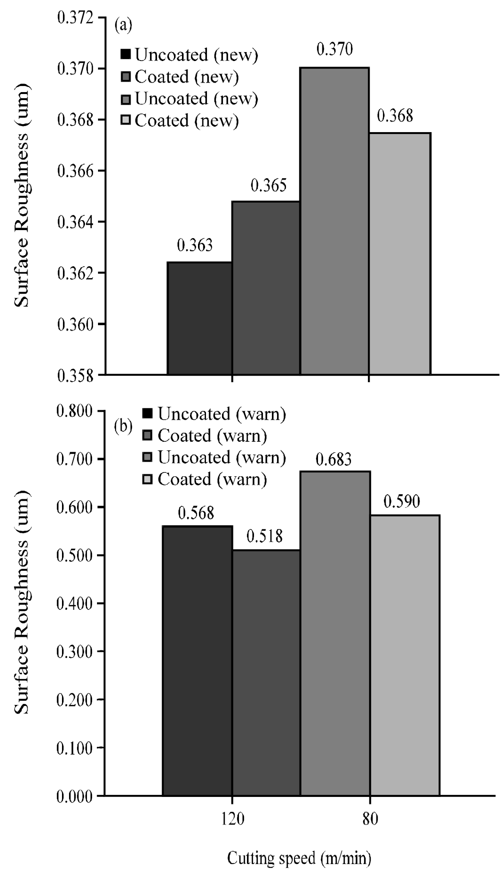

Fig. 5: The surface roughness using the coated and uncoated tools when HSEM CoCrMo alloy under various cutting speed for: a) new tools and b) worn tools

improvement in tool life when HSEM CoCrMo alloy under dry condition. An increment of 118% of tool life was recorded when HSEM at cutting speed at 80 m min^{-1} using uncoated carbide tool. It was evident that the increase in wear rate at high cutting speed adversely affects the tool life due to significant increase in cutting temperature and thermo mechanical stresses at the cutting zone. The variation in cobalt content and WC grain size between the two carbide tools may contribute to the better performance of the uncoated tool against the coated tool especially when high speed machining. Similar grade of carbide tools were used by the researchers in machining titanium alloys and similar result was revealed when uncoated carbide tool out performed coated carbide tool (Safari *et al*., 2014).

Surface roughness: The surface roughness of the machined surface of CoCrMo alloys when HSEM using new tools and worn tools at various cutting speeds is presented graphically in Fig. 5a and b, respectively.

Cutting speed was found to have a direct influence on the surface roughness of the machined surface. Result showed that surface roughness values for both cutting tools tend to improve when HSEM at higher cutting speed of 120 m min^{-1}. At the initial cutting stage (new tool) under all cutting speeds, surface roughness values were relatively low due to the sharp edge of the cutting edge and insignificant tool wear (Fig. 5a). The roughness values increased with prolonged machining due to the rounded cutting edge considerably after complete failure of the cutting edge (Fig. 5b). Under most circumstances, a significant increase of surface roughness values of the machined surface was observed at the end of the HSEM CoCrMo alloy which can be attributed to the severe flank wear, built-up edge and chipping of the tools. In general, coated carbide tool produced better surface roughness when compared to uncoated carbide tool at all cutting speeds.

CONCLUSION

The following conclusions are drawn during HSEM of cobalt chromium molybdenum alloys using uncoated and coated carbide tools under dry condition. They are:

- Flank wear, micro chippings at the cutting edge and built-up-edge were the dominant failure modes when high speed end milling CoCrMo alloy for both uncoated and coated carbide tools
- Uncoated carbide tool display the best tool life performance as compared to coated tool at cutting speed 80 m min^{-1} with feed rate 0.04 mm/tooth
- The best surface roughness was achieved using coated carbide when high speed end milling at the high cutting speed of 120 m min^{-1} with feed 0.04 mm/tooth

ACKNOWLEDGEMENTS

The researchers wish to thank Ministry of higher education, malaysia and universiti teknologi Malaysia for the financial support in conducting this research through the research university grant No. Q.J130000.2510.06H89.

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