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Cryogenic high speed machining of cobalt chromium alloy

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Abstract

Cobalt chromium (CoCr) alloys are extensively used in medical industries for a variety of applications. Due to their unique material properties, machining CoCr alloys are associated with short tool life, poor surface quality and low productivity. This paper presents one of the first studies on using various cooling methods in CNC milling of these alloys. A series of machining experiments were conducted at 200m/min cutting speed. Cryogenic cooling, minimum quantity lubricant (MQL) and flood cooling with water-based emulsion were investigated. The analysis clearly demonstrated that a 71% reduction in surface roughness Ra and a 96% reduction in flank wear can be achieved using cryogenic cooling when compared to conventional machining best practice.

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Keywords: Cryogenic machining; Machining; Milling; Wear

1. Introduction

Cobalt-chromium (CoCr) alloys together with stainless steel and titanium alloys are the major metals used in biomedical industry [1, 2] with CoCr alloys being the most extensively used material for total knee and hip implants [3]. These alloys have good corrosion resistance and high temperature strength making them suitable for aero engine and gas turbine applications [4, 5].

CoCr alloys have a high strain hardening tendency which together with poor thermal conductivity, high material strength and hardness results in poor machinability. Machining CoCr is commonly associated with short tool life and poor surface finish hence low productivity and high manufacturing costs [5].

Cryogenic cooling using liquid nitrogen as an alternative coolant is a novel method for improving machinability of difficult-to-machine materials [6, 7]. In this method, a controlled amount of liquid nitrogen at -197ºC is used to enhance heat dissipation and reduce the chemical reaction between cutting tool and workpiece material. Chetan et al. [8] performed a study on cryogenic machining of nimonic 90 in comparison with minimum quantity lubricant (MQL) and dry in turning. They reported that cryogenic cooling reduced the flank wear by 50% at 80m/min cutting speed as compared to dry machining. However, the flank wear in cryogenic machining at 80m/min was almost identical to that of MQL. In the experiments conducted by Chetan et al. [8] cryogenic cooling resulted in the highest surface roughness Ra in comparison with dry and MQL. Birmingham et al. [9] noted that cryogenic cooling can affect the frictional heat generation on the rake face of the cutting tool by reducing tool-chip contact area in turning titanium alloy. Pusavec et al. [10] studied the chatter in cryogenic turning AISI 1045 steel and reported that cryogenic cooling increases the stability of turning process. An earlier analysis of the published literature indicated that there is limited knowledge on the effects of cryogenic milling operations. Furthermore, the authors believe there is a research gap in the machining of CoCr alloys. This paper addresses this gap by investigating the effects of cryogenic cooling on the tool wear and surface roughness in CNC milling of biomedical grade CoCr alloy.

2. Methodology

The workpiece material used for this investigation was CopraBond K Cobalt Chromium alloy which consists of 61.0% cobalt, 27.9% chromium, 8.56% tungsten, 1.73% silicon, 0.23% manganese, 0.11% iron and 0.07% carbon. The alloy is specifically developed for denture implants by Whitepeaks Dental Solutions GmbH & Co. KG. The experimental investigation consisted of end milling using a solid carbide cutting tool. A Bridgeport VMC 610 CNC milling centre was used to conduct the machining experiments. Four machining environments of flood cooling, dry machining, minimum quantity lubrication (MQL) and cryogenic cooling where used. Other cutting parameters of cutting speed, feed rate and depth of cut where kept constant as shown in table 1. The cryogenic cooling system developed by authors in a previous study [11] was used for the cryogenic cooling experimentation. Liquid nitrogen at 1.5bar pressure and 20kg/hr flow rate was sprayed along the cutting tool into the cutting zone. This results in reducing the temperature of the cutting tool and workpiece at the point of cut. Neat oil at 70ml/hr flow rate was sprayed through a 5bar stream of pressurised air for the MQL system. Two nozzles at 45º angle to the workpiece surface were used for the MQL system. The nozzles were targeted towards the cutting zone.

Table 1. Cutting parameters used for experiments

Cutting parameter	Column A (*t*)
Cutting speed (m/min)	200
Spindle speed (rpm)	5305
Chip load (mm/tooth)	0.03
Feed rate (mm/min)	636.6
Axial depth of cut (mm)	1
Radial depth of cut (mm)	4

A new cutting tool was used for each machining experiment. The cutting tools were 12mm diameter TiSiN coated solid carbide with 4 flutes, 12º rake angle and 37º helix angle. Four blocks of nickel and beryllium free CoCr alloy, CopraBond K with the dimension of 70mm x 70mm x 25mm were prepared. The material hardness of the blocks was measured using an Armstrong Vickers hardness tester with 5kg load and repeated five times for each sample. The CoCr blocks used for this investigation had an average hardness of 466HV. In total, length of 1470mm was machined for each experiment which equates to 21 straight cuts of 70mm.

After the machining experiments, each cutting tool was analysed using a scanning electron microscope (SEM). Furthermore, surface roughness Ra and Rz of the samples was measured using a Taylor Hobson Surtronic S128 contact surface profiler with 5µm radius stylus. Instructions provided by [12], [13] and [14] were followed for surface roughness measurements. According to the instructions by BS EN ISO 4288:1998 [12], cut-off length of 0.08 and 5 cut-off samples were used for measurements.

3. Results and discussion

The surface roughness (Ra and Rz) was measured at 9 points for each machining sample and the average values for Ra and Rz were calculated. Fig. 1 illustrates the measurement results for surface roughness.

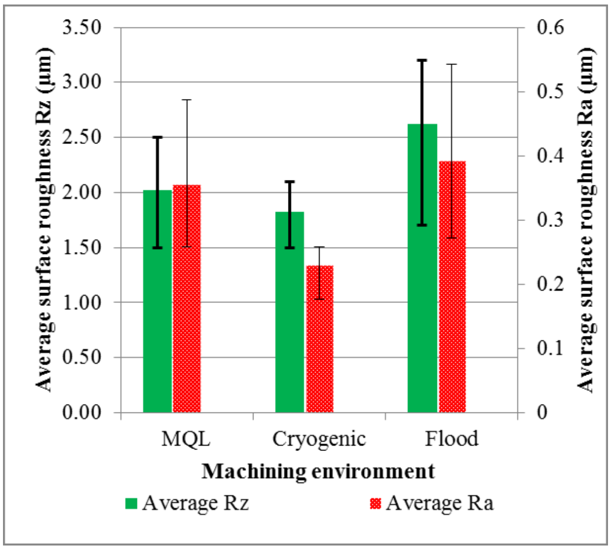

Fig. 1. Average surface roughness graph.

Comparison of the surface roughness results indicated that the lowest surface roughness Ra was produced under cryogenic cooling condition, followed by MQL. The average surface roughness Ra of the sample machined under cryogenic cooling condition was 0.23µm which was 35% and 42% lower than its counterparts machined using MQL and flood cooling, respectively. Furthermore, as shown in figure 1, the variations in measurements were significantly smaller for the cryogenic cooling sample. The standard deviation of the surface roughness Ra results for cryogenic machining was 66% and 71% smaller than that of MQL and flood cooling, respectively. Similar to the arithmetic surface roughness (Ra), the maximum height of profile (Rz) was lower for the cryogenic cooling sample. As shown in Fig. 1, the sample from the cryogenic cooling experiment had 10% and 30% less Rz than MQL and flood cooling.

SEM micrographs of the cutting tools indicated that cryogenic cooling has significantly reduced the extent of flank wear. As illustrated in Fig. 2, a comparison of cutting tools used under different machining environments demonstrated that at the cutting speed of 200m/min, cryogenic cooling and flood cooling perform considerably better when compared against the MQL environment. The tool wear in MQL and flood cooling environments were 26 and 17 times larger than that of cryogenic cooling. This denotes the importance of cooling in high speed machining of CoCr as opposed to the requirement for lubrication. Whilst the tools used in flood and MQL environments has passed their end of life after machining 21x70mm passes, the cutting tool used under cryogenic cooling demonstrated minimum flank wear. Abrasion and adhesion were prevalent on all tools.

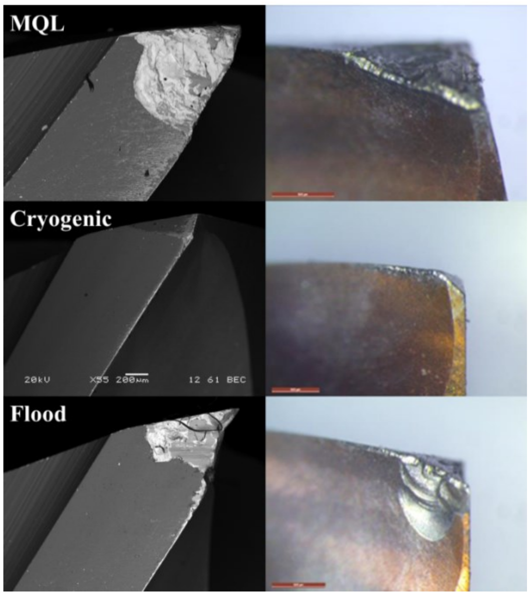

Fig. 2. SEM micrographs of the flank (left) and rake (right) faces of the cutting tools used for machining experiment.

It is reported [15] that cryogenic cooling increases the material hardness of the cutting tool and reduces the chemical affinity between the tool and workpiece material. This results in reduced abrasion and diffusion wear.

Microscopic images of the rake face of the cutting tools revealed that cryogenic cooling has effectively reduced the cutting temperature and chemical interaction between the cutting tool and cutting chips. Hong and Ding [16] reported that cryogenic cooling reduces the chemical affinity between cutting tool and workpiece resulting in reduced adhesion and diffusion wear. As shown in Fig. 2, minimum crater wear was observed on the cutting tool used for cryogenic machining.

Consequently large crater wear marks accompanied with flaking were noticed on the tool used in flood cooling. The comparison of the crater wear for various machining environments indicates that the tool-chip contact area is significantly reduced as a result of cryogenic cooling. Similar observations were reported by Birmingham et al. [9] in turning Ti-6Al-4V. The depth of crater wear for cryogenic cooling was 23µm compared to 305µm for flood cooling. Since the cutting edge of the tool from MQL experiment was worn, accurate measurement of the crater wear geometry was not practical. Through digital reconstruction of the tool, it appears that the depth of crater wear was in the region of 60-70µm.

Fig. 3 and 4 show the cutting edge of the tools used in cryogenic and flood cooling environments at 450x magnification. From these micrographs it is clear that the workpiece is smeared and welded over the cutting tool face by adhesion and diffusion. It was found that where the coating was removed and the cutting tool's substrate was exposed, the workpiece material was diffused into the carbide substrate. In MQL and flood environments, the coating was removed by chipping, flaking and abrasion. This has resulted in significant tool wear on the flank face of the cutting tools. In contrary, the coating was preserved for longer in cryogenic machining and diffusion only took place where the coating was worn.

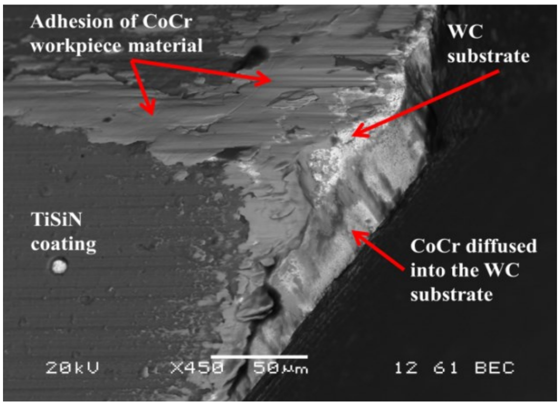

Fig. 3. Micrograph of the cutting edge of the tool used for cryogenic machining experiment depicting smearing and diffusion of workpiece material onto the cutting tool

Smearing of the workpiece material over the coating indicated lack of lubrication in cryogenic machining.

Energy dispersive X-ray analysis (EDAX) was performed on the cutting tools used for machining experiments. Applying the analysis on the worn surfaces indicated high concentration of chromium on the worn surfaces of all cutting tools. This was more prevalent in areas where no Ti (indicator of coating) was identified. In Fig.4, the workpiece material appears brighter than the cutting tool in the back scattered SEM micrographs of the tools.

The EDAX graphs of the worn surfaces are provided in figure 5 for the tools used in cryogenic (top) and flood cooling (bottom) experiments. As can be seen, cobalt and chromium elements were prevalent on the tools' surfaces indicating smearing and diffusion of workpiece material onto the cutting tool surface. Silicon and titanium exhibited the presence of coating whilst carbon and tungsten were from the tungsten carbide cutting tools' substrate.

4. Conclusions

A series of machining experiments were conducted to investigate and compare the effects of various machining environments, namely flood, MQL and cryogenic in CNC milling of CoCr alloy at 200m/min cutting speed. The following conclusions were identified:

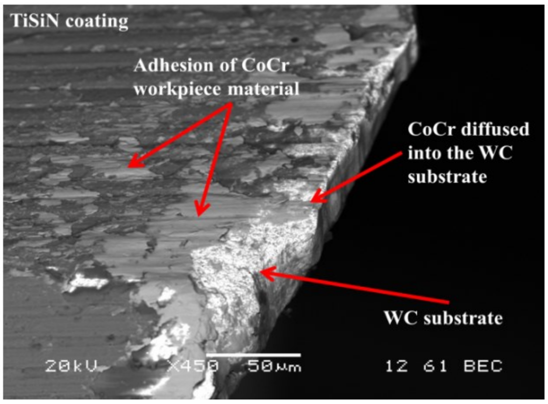

Fig. 4. Micrograph of the tool used for flood cooling experiment showing workpiece material diffused into the exposed tungsten carbide and smeared over TiSiN coating

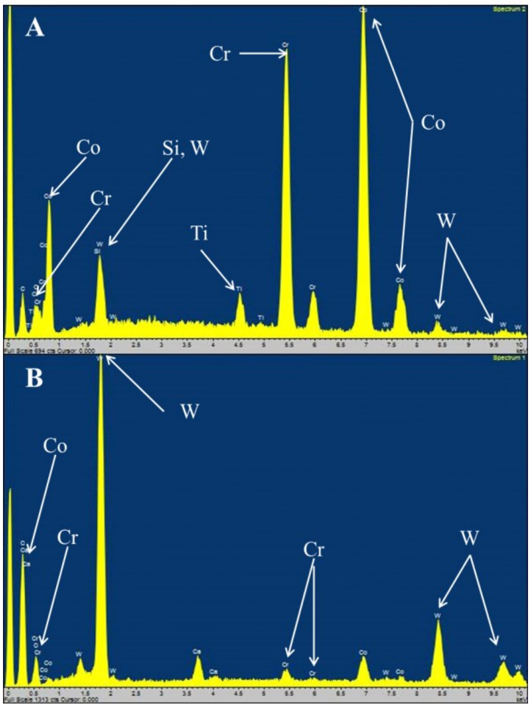

Fig. 5. Micrograph of the tool used for flood cooling experiment showing workpiece material diffused into the exposed tungsten carbide and smeared over TiSiN coating

- Cryogenic cooling has resulted in a 35% and 42% reduction in surface roughness Ra as compared to MQL and flood conditions.
- Significant reduction in tool flank wear was achieved using the cryogenic cooling approach. The flank wear was 26 and 17 times larger for MQL and flood cooling environments when compared to cryogenic cooling.
- Diffusion and abrasive wear were dominant irrespective of the machining environment. However, microscopic images of the cutting tools indicated that cryogenic cooling has effectively controlled the extent of tool wear where minimum crater wear was observed.

This study has demonstrated that the novel method of cryogenic cooling can significantly improve the machinability of CoCr by enabling higher cutting speeds to be used, potentially resulting in increased productivity in various industrial sectors and specifically medical industry.

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