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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.

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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.

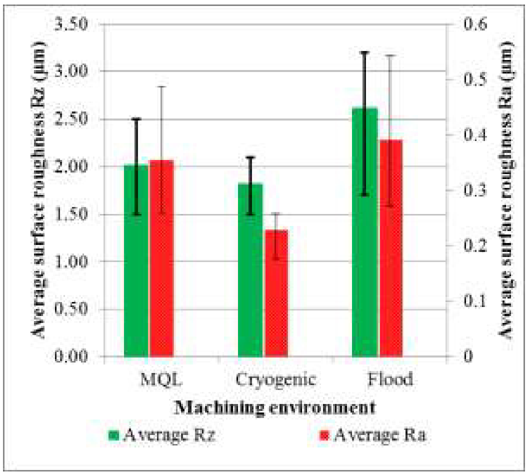

Fig. 1. Average surface roughness graph.

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.