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CO_2-assisted machining of biocompatible polymer materials

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Abstract

Efficient machining of biocompatible materials is key in the medical implant industry. Medical implants are components that have to be manufactured to tight tolerances with specific requirements regarding the surface quality and cleanliness of the components. The application of novel cooling methods has been the subject of active research in both academia and industry. Supercritical carbon dioxide ($scCO_2$) is one of the media that have been used to provide cooling in the cutting zone and assist in the evacuation of chips. This paper investigates the effect of $scCO_2$ in machining of polymer materials used as medical implants. The effect of cutting parameters and coolant medium application on the resulting surface roughness is investigated on Polyether ether ketone (PEEK) and Ultra High Molecular Weight Polyethylene (UHMWPE).

Keywords: Carbon dioxide, Polyether-ether-ketone, Turning, surface quality

1. Introduction

Similar to other manufacturing sectors, the medical implant manufacturing sector is characterized by demanding requirements regarding the quality of the manufactured components. The medical manufacturing sector has recorded high growth rates owing to the advances in the medical industry. As reported in literature, the annual growth of the sector is around 7-12% [1]. Implants are manufactured with high performance biocompatible materials including stainless steel, titanium, magnesium and cobalt based alloys as well as ceramic and polymer materials. These materials are used due to the ability to interact with human tissue or organs and ensure that compatibility and functionality of the implant is preserved. Manufacturing of these components is traditionally accomplished through subtractive machining using metal cutting machining centers. In particular, polymer materials are used as a load-bearing surface in conjunction with or without metal components [2-3]. A series of applications of polymer materials is presented in Fig 1.

One critical aspect of medical implants that is not encountered in other manufacturing sectors is the one of sterilization. A series of steps are performed on implants to ensure traces contaminants are removed from the components as they can lead to post operation complications [4].

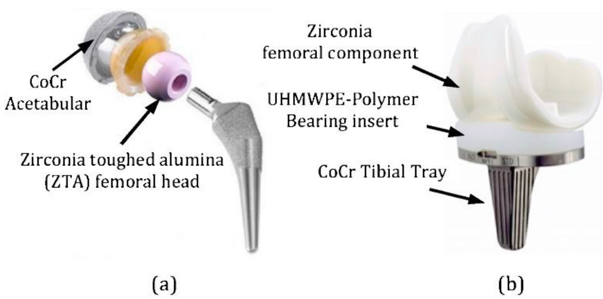

Figure 1 Applications of different biomaterials in (a) hip and (b) knee implants [1]

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The use of supercritical carbon dioxide ($scCO_2$) has been recently emerged as a potential alternative to traditional emulsion coolants for machining of materials relevant to the medical industry. In many cases, emulsion coolants are associated with skin conditions such as dermatitis due to the chemicals and bacterial that are contained in them. Unlike traditional emulsion coolants, $scCO_2$ is a clean alternative coolant as it is free of contaminating agents. In the medical industry, it is used as a sterilisation agent along with ethylene oxide, steam and gamma ray [5]. The mechanism through $scCO_2$ delivers the cooling effect in the cutting zone is fundamentally different to traditional coolants that are using heat convection to remove the heat from the cutting zone. $scCO_2$ is a liquid in the supercritical state, which gives properties of both liquid and gas phase to the medium. This state is encountered at temperatures and pressures above the critical point (Fig 2). In CO_2 that is at a pressure of 74 bar and a temperature of 31 ^oC. The mechanism through which $scCO_2$ provides the cooling action is through the Joule–Thomson effect. When $scCO_2$ is released from the nozzle of a tool the rapid drop in pressure leads in a phase transformation from liquid to gas and solid. This phase transformation attracts energy from the surrounding environment that in turn leads to a temperature drop that can reach -72 ^oC. A series of investigations have been performed on the use of CO_2 and $scCO_2$ in machining of metallic components primarily composed of Ti6Al4V [6-8].

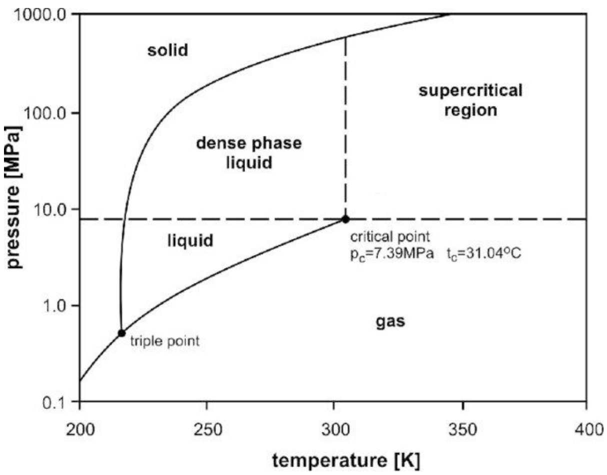

Figure 2 Phase diagram of CO_2 [9]

The present study focuses on the use of $scCO_2$ in the machining of PEEK and UHMWPE material using dry, $scCO_2$ and traditional emulsion coolant. The focus of the study is on the effect of the coolant medium on the resulting surface roughness and burr formation. The remainder of the paper is structured as follows; Section 2 presents the experimental set up for the machining trials. Section 3 presents the results for the machining trials for PEEK whereas section 4 for UHMWPE. Finally, section 5 presents the concluding remarks and future work.

2. Experimental setup

The machining trials were performed on a DMG Mori NLX2500/700 lathe equipped with a Fusion Pure-Cut+ system for the delivery of $scCO_2$. A Seco SCL CL 2525M09 JET toolholder with a CCGT09T308F-AL KX insert and a Jetstream inducer designed for use with $scCO_2$ was used throughout the trials. The insert is rhombic shaped with an 80 degree included angle, a length of 9 mm and a 0.8 mm corner radius. A sharp insert geometry was selected in order to assist with the separation of the chip and the workpiece following the work by [3]. The surface roughness of the machined surfaces was measured using a Mitutoyo SJ-210 roughness tester and the machined surfaces were examined through a USB microscope. The emulsion coolant used was a Blaser 7000 delivered external to the toolholder. The two materials investigated were Polyether ether ketone (PEEK) and Ultra high molecular weight polyethylene (UHMWPE) provided in a bar form with a diameter of 20.5 and 41 mm respectively. The experimental setup is presented in Fig. 3. The trials were split between the two materials. In each one, the trials were performed in a DoE (L9) style approach with the factors being the feed rate and the coolant type used. The DoE design is presented in Table 1.

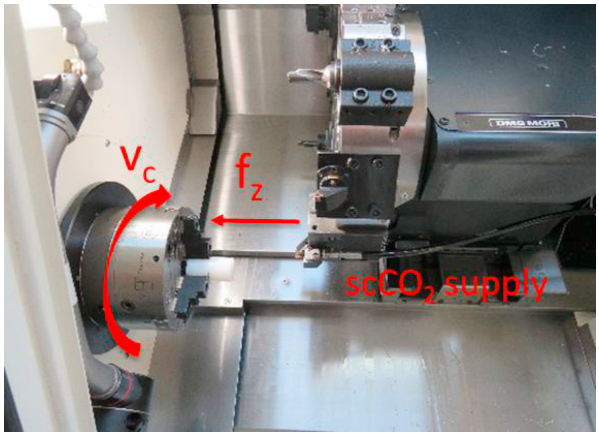

Figure 3 Experimental Setup

Table 1. Machining trials DoE

Trial ID	Cutting feed rate (mm/rev)	Coolant type
N1	0.1	Emulsion
N2	0.1	Dry
N3	0.1	$scCO_2$
N4	0.2	Emulsion
N5	0.2	Dry
N6	0.2	$scCO_2$
N7	0.3	Emulsion
N8	0.3	Dry
N9	0.3	$scCO_2$
N10	0.2	$scCO_2$
N11	0.2	$scCO_2$
N12	0.2	$scCO_2$

In the machining trials, the depth of cut was kept constant at 1 mm. For PEEK the cutting speed selected was 200 m/min whereas for the UHMWPE it was 200 and 400 m/min. For the later cutting speed in UHMWPE an additional set of trials were performed with parts having pre-drilled holes radially to investigate the effect of cooling media on the material flow and formation of burr during cutting.

3. Polyether Ether Ketone (PEEK) machining trials

PEEK is a high hardness polymer material (Hardness Shore D 85) that is used in the manufacturing of spinal cages and intramedullary nails among other components. Based on the experimental setup presented above a series of trials were performed as per the DoE design using a cutting speed of 200 m/min. For each trial, a separate workpiece was used in order to retain the machined surfaces for further examination. Each part had the surface roughness accessed on the axial direction, which is also the feed direction. A set of five surface roughness measurements, equally spaced around the circumference of the part, were performed for each workpiece in order to get an accurate measurement of the quality of the part. The measurements were performed using a Mitutoyo SJ-210 in accordance with EN ISO 4288. Fig. 4 presents the results of the resulting surface quality of the parts machined. In principle for all coolants, the surface roughness showed an increase with an increase in feed rate. As it can be observed no significant difference in surface roughness values between the different coolant mediums for cutting feed 0.1 and 0.3 mm/rev. However, at 0.2 mm/rev cutting feed, the part which has been turned using $scCO_2$ has significantly lower roughness (1.4 µm) value compared to the parts which have been turned dry (2.24 µm) or using flood coolant (2.0 µm).

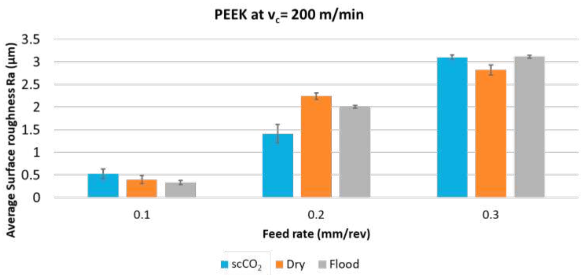

Figure 4 Surface roughness in PEEK machining

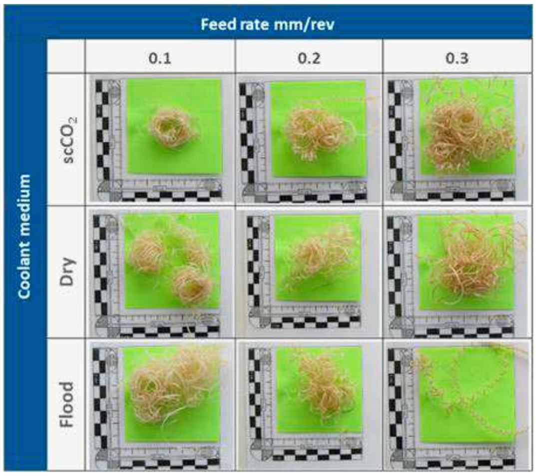

Figure 5 Chip samples during machining of PEEK material

Similar to material presented by Aldwell et al. [3] the machining trials created long continuous flow type chips in all cutting conditions with thickness of the chip increasing with the increase of feed rate. In many cases due to the large curl of the chips, they accumulated around the workpiece or the tool creating a bird nest type of chip that can lead in damage of the part. Some of the typical chips generated from the machining trials are presented in Fig. 5.

4. Ultra high molecular weight polyethylene (UHMWPE)

UHMWPE is a polymer material that is composed of extremely long chains. The material has a low friction coefficient and resistance to abrasion. The material has a lower hardness compared to PEEK (Hardness Shore D 68). For this material two cutting speeds were tested. Figure 6 presents the results for the trials using v_c=200 m/min. As it can be observed this material showed a similar behavior to the results of the PEEK material. In 0.1 and 0.3 mm/rev, there was little difference between the different cooling media. When using a feedrate of 0.2 mm/rev the $scCO_2$ showed significantly lower surface roughness. When compared to the results of PEEK against the results in UHMWPE it can be observed that the surface roughness in PEEK was up to 75% lower when compared to the one measured in UHMWPE. This can be attributed to the difference of hardness between the two materials that leads in difference in the chip flow of characteristics during cutting with the possible presence of a side flow of material during the cutting process.

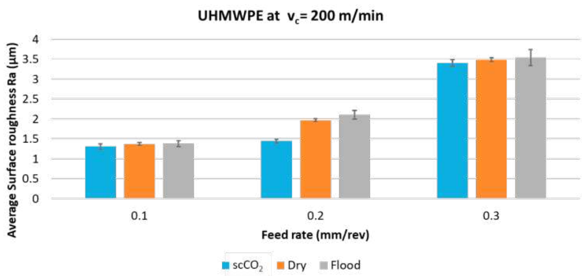

Figure 6 Surface roughness in machining UHMWPE at 200 m/min

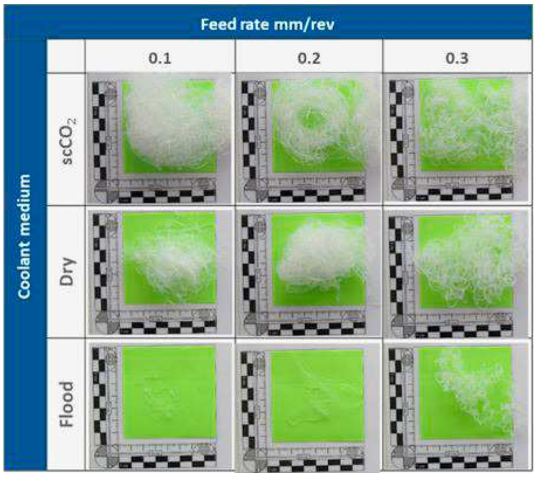

Figure 7 Chip samples during machining of UHMWPE material at 200 m/min

The chips that were collected during the machining trials showed that with increasing feed rate thicker chips are generated. Furthermore due to this higher thickness the curl of the chip is affected and thus its flow properties. As it can be seen in Fig 7, the chips at lower cutting feeds tend to create bigger bird nest type of structures.

The next set of trials performed on this material was using a cutting speed of 400 m/min. Figure 8 presents the results of the trials. As it can be observed, the trend that was observed in previous trials was not verified. Feed rate did not show to have a strong effect on the resulting surface quality. Another observation is that the cutting feed rate that provided the best result for the $scCO_2$ cooling at the cutting speed of 400 m/min was at 0.1 mm/rev. This is contrary to the results in the lower cutting speed of 200 m/min in which the biggest improvement in surface roughness was observed in a feed rate of 0.2 mm/rev. This can be attributed to the different direction of the chip flow due to the higher cutting speed and the increased heat generation during the cutting process. Another point worth noting is that the increase in cutting speed led to an improvement in the surface quality in the higher federate. On this cutting speed, the chips showed a big similarity to the ones observed in the 200 m/min trial. With a large curl of the chip appearing in all cases.

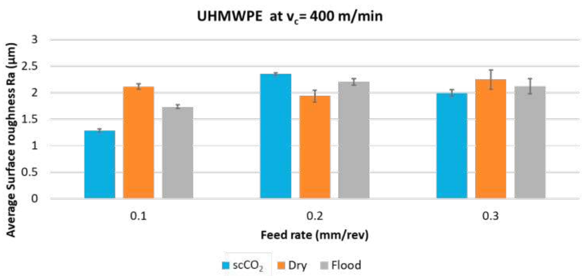

Figure 8 Surface roughness in machining UHMWPE at 400 m/min

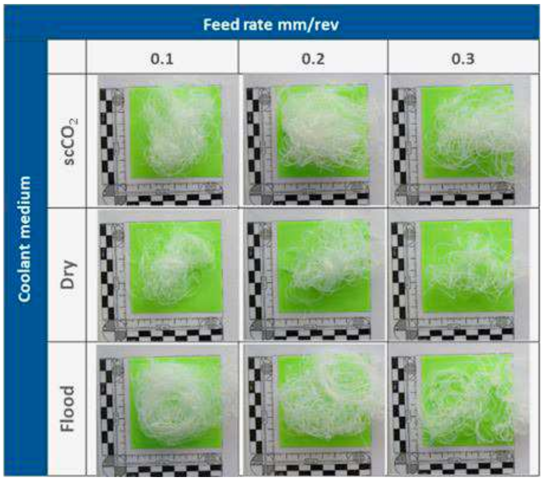

Figure 9 Chip samples during machining of UHMWPE material at 400m/min

The final part of the machining trials investigated the effect of the cutting action on material transfer and the creation of burr. The investigation was performed at the most aggressive cutting parameters (v_c=400 m/min, f_z=0.3 mm/rev). A series of 3 holes were drilled radially on the components at an axial distance of 10, 15 and 20 mm from the face of the component. The 2 mm holes were separated by a 120 degrees rotation between them. Figure 10 presents the material transfer over the hole when machining with different cutting media. The material transfer was measured at the center of the hole along the direction of the cutting speed. As it can be seen, the lowest material transfer was observed in the case of the $scCO_2$ cooling.

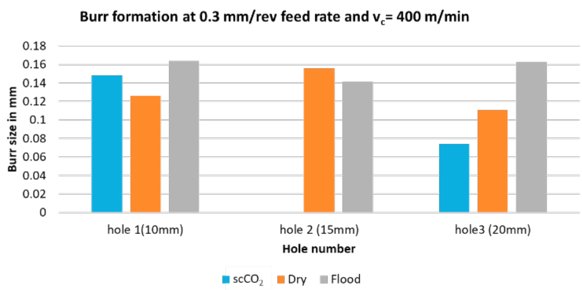

Figure 10 Burr formation in the pre-drilled specimens.

5. Conclusion

The present study investigated the effect of cooling medium on the resulting surface quality in machining of polymer materials relevant to the medical industry. Based on the work performed a series of conclusions can be drawn.

- On Polyether ether ketone when machining at 200 m/min federate had a direct effect on the resulting surface quality with an increase in surface roughness following an increase in feed rate. No significant changes were observed between the different media in machining at 0.1 and 0.3 mm/rev. In 0.2 mm/rev $scCO_2$ yielded the best results.

- On Ultra high molecular weight polyethylene, use of increased cutting speeds from 200 m/min to 400 m/min at 0.3 mm/rev, leads to lower surface roughness for most coolant media and parameters. The machining trials on the third stage showed that the minimum size of burr is observed under the $scCO_2$ conditions.
- No tool wear was observed in any of the tests.
- Chips in all the trials appeared to be of a continuous flow nature.
- Machining with $scCO_2$ has been demonstrated to provide equivalent or better results in all parameters tested when compared to flood coolant and dry machining while keeping the part clean and free of contaminants.
- Overall cost of making the part can be reduced by using $scCO_2$ assisted machining, as there is reduced power requirements from the machine tool.

In practical terms the selection of the selection of the most appropriate cooling method goes hand in hand with the requirements for the part quality, the equipment available and throughput required. Based on the results of the trials performed in this project when using PEEK the recommended parameter set would be $scCO_2$ cooling at v_c=200 m/min and f_z=0.2 mm/rev. On UHMWPE the most appropriate cutting parameter set $scCO_2$ cooling at v_c=400 m/min and f_z=0.1 mm/rev.

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