Supercritical CO_2 milling of medical plastics

Overview

Ultra-high molecular weight polyethylene (UHMWPE) is a commonly used material in medical orthopedics, where its durable, low-friction surface is used as a spacer that ensures mobility for knee, hip and shoulder implants. However, machining this material with traditional milling results in the formation of burrs that are often manually removed in a secondary process. In addition, as the thermal expansion coefficient of UHMWPE is more than 12 times higher than that for steels, controlling heat in machining is essential to achieve the tight tolerances and high dimensional accuracies required for implants.

We investigated the effect of supercritical CO_2 cooling (sc-CO_2) on the milling process, using a Mikron MILL S 400 U® 5-axis milling machine equipped with a StepTec 42k spindle, a Fusion Coolant Systems Pure-Cut+® sc-CO_2 delivery system, and different milling tools (a 3 mm single blade end mill in slot cutting and a 6 mm ball nose end mill for the milling of a knee spacer) at various cutting parameters. The results point towards a significant reduction in burrs, improved work-piece accuracies, and better surface quality. These factors point toward a more reliable machining process that may greatly reduce, or even eliminate, manual deburring.

Dry slot milling

UHMWPE can be milled dry to avoid (especially in medical applications) the introduction of contaminants and moisture absorption. Slot machining was performed "dry" at a slot width of 3 mm and a depth of 6 mm. In Figure 1 below, we see the entrance and exit channel for semi-roughing cuts in dry milling, and the resulting burr formations.

Tool	End Mill (Gühring VHM 6793 – Ø3 mm, Single blade)
Workpiece	UHMWPE
Milling parameter	v_c = 100 m/min, f_z =0,12 mm/U, a_e = 3 mm, a_p = 6 mm
Coolant	Dry

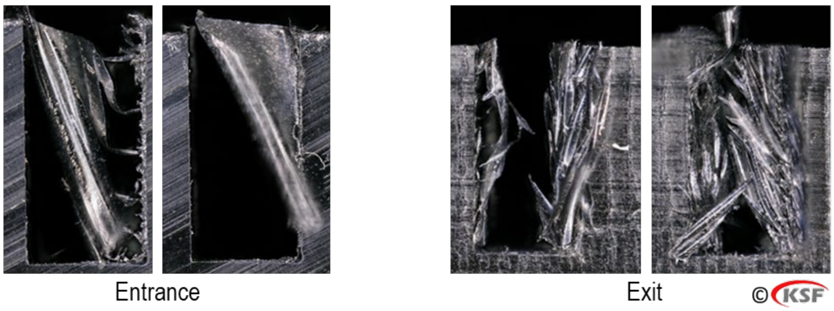

Figure 1: Excessive burr formation at the entrance and exit of the slot in dry milling

Supercritical CO_2 with MQL

A supercritical CO_2 delivery system from Fusion Coolant Systems was fully integrated with the Mikron MILL S machine. This system is capable of providing CO_2 up to 110 bar pressure and includes a Pure-Cut+® MQL (minimum quantity lubrication) delivery system. Supercritical CO_2 together with MQL is channeled through the spindle and, via small slots in the tool holder, rapidly expanding supercritical CO2 is directed towards the cutting edges of the mill. A medical-grade cutting fluid, SENTOS V-LR15® from HPM Technologie, was introduced to the supercritical CO_2 at a rate of 0.1 - 0.25 ml/hour. This particular lubricant is validated for use on medical products due to its ability to evaporate at room temperature without leaving any trace residue on the milled surface. We repeated the cut and observed that the burr formation is significantly reduced with supercritical CO_2 compared to the dry milling (see Figure 2).

Tool	End Mill (Gühring VHM 6793 – Ø3 mm, Single blade)
Workpiece	UHMWPE
Milling parameter	v_c = 100 m/min, f_z =0,12 mm/U, a_e = 3 mm, a_p = 6 mm
Coolant	Super Critical CO2 (80 Bar) with MQL = 0,25mL/min

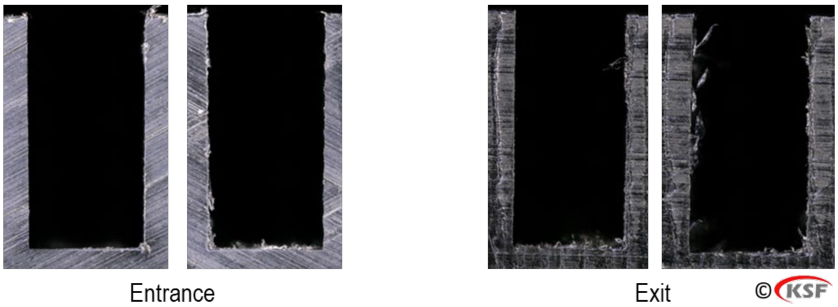

Figure 2: Minimal burr formation at the entrance and exit of the slot in SC-CO_2 milling

Results and preliminary analysis

Via an image processing software and taking the images from Figure 1 and Figure 2, the burr area was calculated and compared between dry and supercritical CO_2 milling (Figure 3).

Tool	End Mill (Gühring VHM 6793 – Ø3 mm, Single blade)
Workpiece	UHMWPE
Milling parameter	v_c = 100 m/min, f_z =0,12 mm/U, a_e = 3 mm, a_p = 6 mm
Coolant	Dry and Super Critical CO2 (80 Bar) with MQL = 0,25mL/min

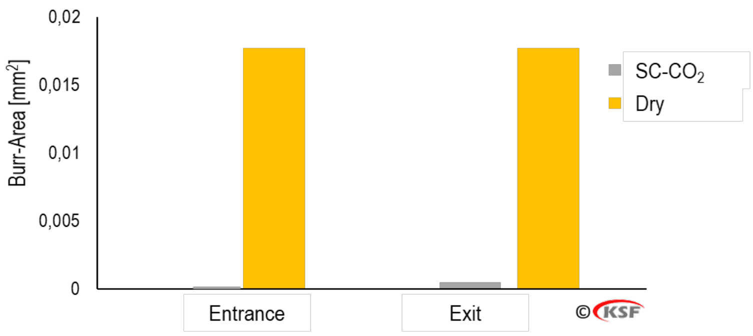

Figure 3: Burr area induced by dry and SC-CO_2 milling of UHMWPE

Comparing the burr area from both dry and CO2 machining we see a very significant reduction in burr formation of approximately 95%.

The study also considered surface roughness (Rz) of the slot walls. During the roughing operation, we observed less roughness in machining with supercritical CO2 than dry by approximately 30% as shown in Figure 4, with representative images demonstrating roughness reduction shown in Figure 5.

Tool	End Mill (Gühring VHM 6793 – Ø3 mm, Single blade)
Workpiece	UHMWPE
Milling parameter	v_c = 300 m/min, f_z =0,12 mm/U, a_e = 3 mm, a_p = 6 mm
Coolant	Dry and Super Critical CO2 (80 Bar) with MQL = 0,25mL/min

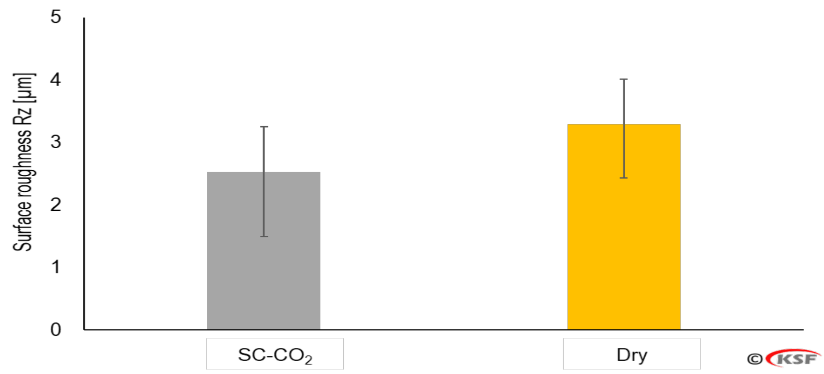

Figure 4: Surface roughness of the slot's wall in dry and SC-CO_2 milling of UHMWPE

Tool	End Mill (Gühring VHM 6793 – Ø3 mm, Single blade)
Workpiece	UHMWPE
Milling parameter	v_c = 100 m/min, f_z =0,12 mm/U, a_e = 3 mm, a_p = 6 mm
Coolant	Dry and Super Critical CO2 (80 Bar) with MQL = 0,1 mL/min

Figure 5: Comparison between surface quality of slots produced by dry and SC-CO_2 milling

5-axis milling

In the next step of the trial, a knee spacer was machined via 5-axis milling under both dry and SC-CO_2 conditions. The semi-roughing parameters utilized are listed in Figure 6. As can be seen from the figure, dry milling caused an excessive burr formation (likely due to material melting during the cutting process) and poor surface quality. However, very low burr formation and a clean work-piece surface with detailed milling contours are the results of SC-CO_2 milling.

Tool	HSS Ball-Nose Ø 6 mm, Cutting edge: 4
Workpiece	UHMWPE
Milling parameter	v_c = 100 m/min, f_z =0,12 mm/U, a_p = 1,5 mm
Coolant	Dry and Super Critical CO2 (80 Bar) with MQL = 0,25 mL/min

Figure 6: Comparison between burr formation and surface quality of knee spacers produced by 5-axis milling under dry and SC-CO_2 conditions

Potential applications and areas of further research

The use of UHMWPE in knee, shoulder and hip implants is extensive and, as the material cannot be molded using conventional technologies, most often they are milled. In most cases the milling process creates a significant number of burrs, the removal of which is done mostly by the use workers (manual process).

Further trials need to be done with specific tools adapted for use with CO2 – however, it would seem likely that this technology could allow for a stable, repeatable machining process for UHMWPE that results in a significantly finer surface finish and with dramatically fewer burrs. On future trials we would look to investigate the influence of different tool cutter geometries, as well as variations in rotational speed and feed rates, on surface roughness and burr formation.

For further information and for enquiries about collaboration on industrial projects, please contact:

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