High-speed milling of Ti6Al4V under a supercritical CO_2 + MQL hybrid cooling system

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Introduction

The effects of supercritical CO_2 cooling (Sc-CO_2) on the high-speed milling of titanium grade 5 (Ti6Al4V) using a Mikron MILL S 400 U® 5-axis milling machine, equipped with a StepTec 42k spindle, and a Fusion Coolant Systems Pure-Cut+® Sc-CO_2 delivery system was studied at various cutting parameters and compared with flood coolant milling using emulsion (Fig. 1). The effects on tool wear, achievable MRR, surface roughness and micro-hardness were evaluated.

This investigation revealed that the use of ScCO_2+MQL seems to improve productivity, machinability and cleanliness aspects when machining Titanium, and is likely to be especially useful when manufacturing implanted medical devices (orthopedic implants such as hips, knees, trauma plates – as well as casings for implanted devices such as pacemakers).

The experiments were divided into five steps with different cutting parameters (Table 1). A new tool was used continuously for each Sc-CO_2+MQL and flood cooling from step 1 up to step 4. The main aim of of the tests was to analyse the achievable material removal rate for both coolant systems. A high volume of the workpiece material (113,850 mm^3) was machined using new tools (for both Sc-CO_2+MQL and flood cooling) at step 5 to assess the tool life and machining performance in detail.

Table 1. Different machining steps conducted in current study

Machining steps	Axial Depth of Cut (a_p) (mm)	Radial Depth of Cut (a_e) (mm)	Cutting Speed (V_c) (m/min)	Feed (V_f) (mm/min)	Number of Passes
Step 1	5	2	110	225	15
Step 2	5	2	150	375	15
Step 3	5	2	175	557	15
Step 4	5	2	200	796	15
Step 5	5	2	200	796	45

Solid carbide end mills coated by TiAlN with internal cooling channels (6mm diameter, three flute GÜHRING series 6799) were used. The ScCO2+MQL coolant was applied through the internal channel of the milling tool, however, flood cooling (emulsion) was applied externally. Sc-CO_2 was supplied at 105 bars, and a MQL oil (HPM TEHCHNOLOGY, SURVOS, STANDARD) was added to the Sc-CO_2 at a constant rate of 2 ml/min.

Figure 1. High-speed side milling under Sc-CO_2+MQL (left) and flood cooling (right)

Experimental Results and discussion:

At the end of each test step, the tool wear progression was monitored; no significant differences could be detected up to the step 4 of the tests. However, after Step 4, the cutting edges and rake faces of the tools show significant differences (Fig. 2). The C1-Tool (images a – c) is severely damaged as chipping and small breakage has occurred. In contrast, the CO2-1-Tool (images d-f) cutting edges are not damaged as severely and the tool can still continue the cutting.

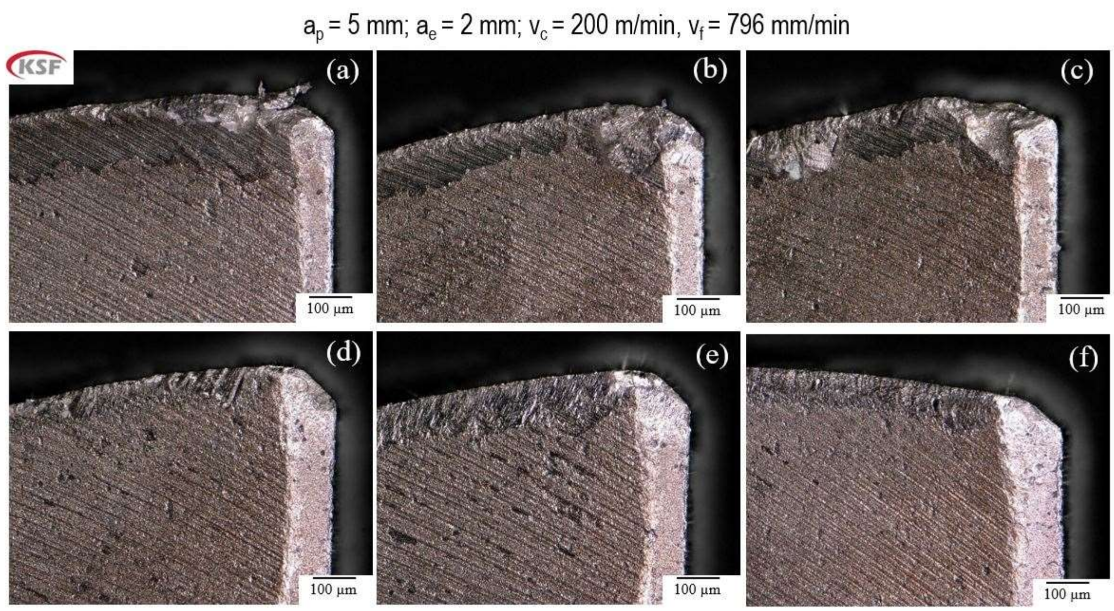

Figure 2. Optical microscopy images of the rake faces of the tools after step 4

Fig. 3 illustrates the cutting forces during the machining experiments untill step 4 of the experiments (Table 1). The results demonstrate that increasing the number of passes (removed material volume) and material removal rates causes a drastic rise in cutting force (up to 120% for C1-Tool and 45% for CO2-1-Tool).

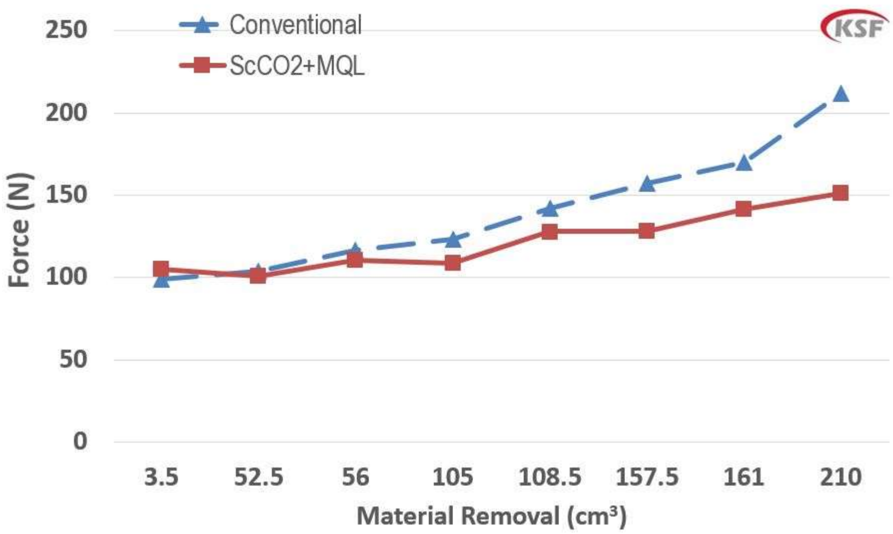

Figure 3. Cutting force (F_y) evaluation during steps 1 to 4 of the experiments

Fig. 4 represents the surface roughness in the parallel and perpendicular direction of the tool feed at the end of step 4 of the experiments. The Ra values in both conventional (emulsion) and $ScCO_2$+MQL cooling methods increased with the machining passes (material removed volume). Comparing the surface roughness values of workpieces machined, $ScCO_2$+MQL provides an enhanced surface quality (up to 70% reduction of Ra after 60 passes) in feed-perpendicular direction. The differences grow at higher material removed volumes (machining passes) due to lower wear of the CO2-1-Tool.

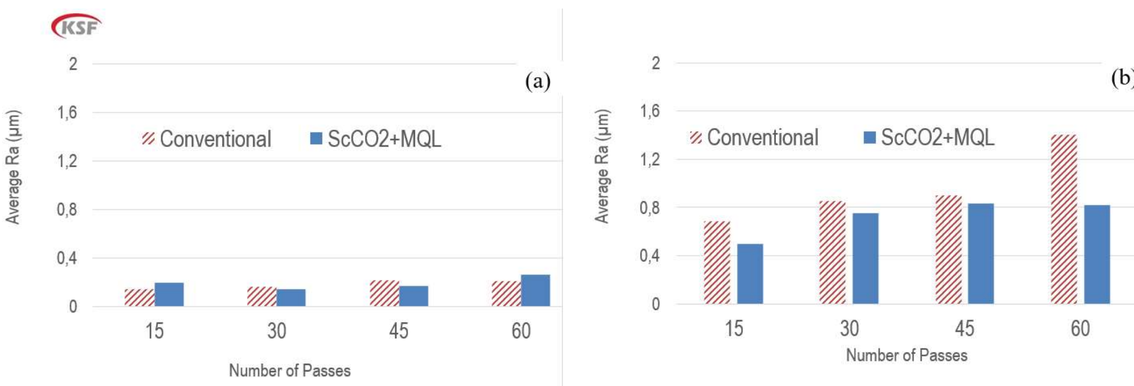

Figure 4. Measured surface roughness a) feed-parallel and b) feed-perpendicular directions

In the second series of the experiments (step 5), a high volume of material (113,850 mm^3) was machined under the highest achieved material removal rate using new tools (for both Sc-CO_2+MQL and flood cooling). Fig. 5 illustrates the cutting edges and rake faces of the tools after 45 passes of the milling process. The severe damages on the cutting edges of C2-Tool are detectable in Fig. 5 (a-c). A large portion of the cutting edges of the C2-Tool is broken owing to the excessive cutting forces and heat concentration during the machining process. However, the Sc-CO_2-2-Tool (d-f) xhibited reliable performance.

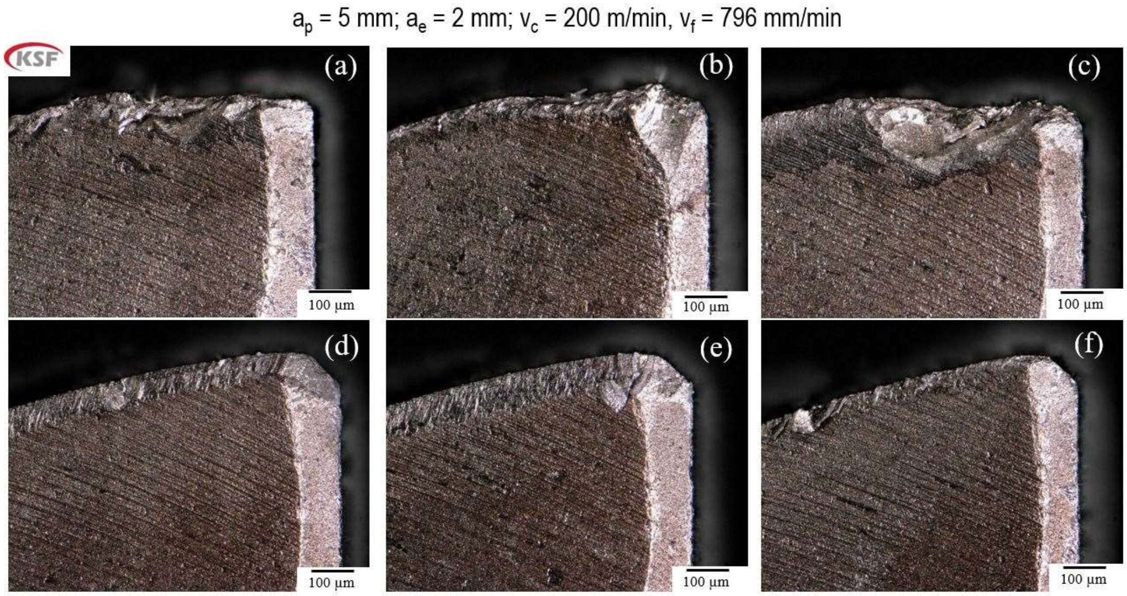

Figure 5. Rake faces of the (a-c) C2-Tool and (d-f) Sc-CO_2-2-Tool after step 5

Fig. 6 depicts the microstructure of the workpieces machined using conventional and ScCO_2+MQL coolants. Comparing these images demonstrate that the grain sizes in the zones near the machined surface for the sample machined under ScCo_2+MQL is smaller than those of the specimen machined using conventional coolants.

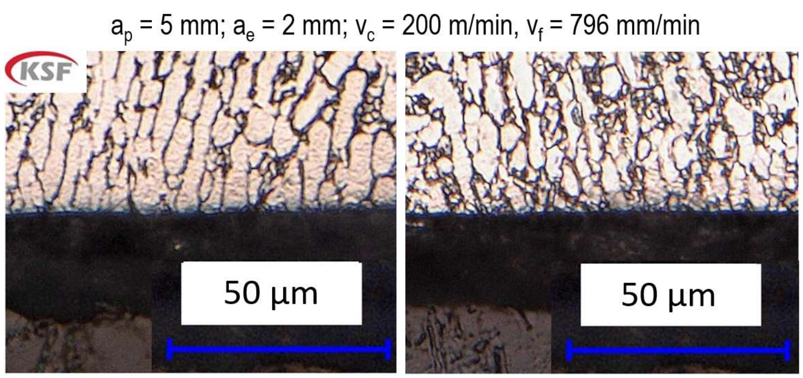

Figure 6. Cross sections using left) flood cooling and right) ScCo_2+MQL coolant

The microhardness values of the base material (prior to milling) and machined surface in the workpieces machined using flood cooling and ScCO2+MQL coolant were measured after step 5 of the experiments and are represented in Fig. 7. The microhardness values of the workpiece machined under ScCO2+MQL coolant showed a measurable increase compared to that of flood cooling (up to 15%). The main reason for this behaviour could be the lower heat generation in the machining zone in the case of ScCO2+MQL cooling, which intensifies the work hardening.

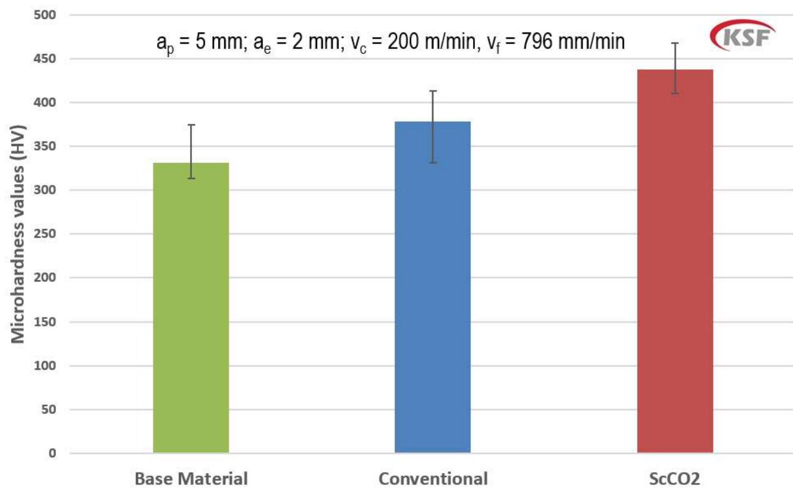

Figure 7. The microhardness values (base and after machining)

Conclusions and Future Research

The results of the tests conducted showed that, as compared to flood coolant milling, the use of Sc-CO_2 milling led to;

- reliable machining at higher Material Removal Rates
- significantly increased tool life
- significantly lower cutting forces (up to 50%)
- increased surface microhardness (up to 30%)
- reduced surface roughness (up to 50%)

We believe this technology has the potential to improve machining efficiency, reduce the pollution and energy consumption (through reduction or elimination of washing to remove emulsion), improve mechanical properties of the machined material, and reduce the risk to patients (through the reduced risk of contamination from residual cutting fluids). The authors of this study would want to continue the research by testing speeds, efficiencies, and to carry out a full cost – benefit analysis for finishing cuts on orthopedic implants, and are actively seeking industrial partners interested to fund such a program.

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

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