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Milling of aerospace alloys using supercritical CO_2 assisted machining

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Abstract

Novel "sub-zero" cooling methods are an emerging technology employed in machining of aerospace alloys that has been the focus of substantial ongoing research. A series of different cooling media have been used in an effort to decrease the friction and the amount of heat generated in the cutting zone. This study focused on the use of supercritical carbon dioxide ($scCO_2$) as a coolant in the face milling of titanium alloy Ti-6Al-4V. Traditional flood emulsion coolant was compared with through tool $scCO_2$ as well as $scCO_2$ with minimum quantity lubrication (MQL).

Keywords: Cryogenic machining; Milling; Wear

1. Main text

The use of cryogenic coolants as metalworking fluids has been gaining interest due to both environmental benefits and reduction in machining process costs, when compared to traditional emulsion coolants. Alternative cryogenic coolants, based on literature, have given benefits in terms of tool life, increased productivity, higher cooling capacity, and decreased contamination of the final surface [1-4]. In cryogenic assisted machining, emulsion coolant is substituted with a gas or liquid that decreases the temperature near the cutting zone. Traditionally liquid nitrogen (LN_2) and carbon dioxide (CO_2) have been used to reduce the temperature of the cutting zone. Researchers have focused on machining materials for the aerospace and medical industries owing to the high impact that increased productivity and cleanliness would have on the value chain of those industries. These materials include Titanium, Nickel and Magnesium alloys that are challenging to machine and would benefit from such an enhancement in their machinability. Titanium alloys, and primarily Ti-6Al-4V, are the one of the most commonly researched materials, with results from trials indicating increased tool life when using CO_2 as a coolant medium [5-6]. Sadik et al. [5-6] found that abrasion of the cutting tool was observed but the tool performance was limited because of chipping of the cutting edge due to the mechanical load of the cutting process. Gross et al. [7] investigated the effect of minimum quantity lubrication in solid carbide milling. Part of their research focused on the characterization of the flow of CO_2 when exiting the nozzle. The results suggested that decreasing the diameter of the output nozzle results in higher flow speeds and moves the front of low temperatures further from the output nozzle. Relating to the work that Gross performed, Pusavec et al [8] investigated the effect of cooling capacity of CO_2 and LN_2 against emulsion coolant. In their investigation they focused on the effect of flow rate and nozzle posture on the temperature of a heated element. The experimental trials showed that the cooling capacity of all media is increasing with the increase of media mass flow rate. The heat evacuation mechanism in cryogenic media was found to be due to phase transformation where as in emulsion coolant it was due to temperature difference.

Supercritical CO_2 is a phase of CO_2 (above 7.38 MPa pressure and 31.2 °C temperature) in which the substance has properties of both a liquid and a gas phase. Research on this

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subject is fairly limited compared to other cryogenic media. One of the first to investigate supercritical CO_2 as a metalworking fluid was Stephenson et al. [9], who investigated the use of $scCO_2$+MQL instead of water-based flood coolant in machining of Inconel 750. Their results indicated that $scCO_2$+MQL provided greater tool life than flood emulsion coolant, whilst also permitting an increase in material removal rate with equivalent tool life compared to aqueous flood coolant. Wika et al. [10] investigated the effect of using $scCO_2$ with the addition of MQL oil in machining of AISI 304L stainless steel. Based on their investigation the cryogenic medium provided equivalent results in surface roughness and residual stresses when compared to traditional emulsion coolant while providing a longer tool life at all cutting conditions tested.

On Ti-6Al-4V Litwa et al. [11] and Wika et al. [12] focused on profile milling of the material using elevated feed rates. A series of trials performed by the authors indicated that the surface roughness, residual stresses and micro hardness are not affected by the coolant medium. The variation of cutting parameters had the strongest effect on the residual stresses. The cutting forces recorded by the researchers indicated that the addition of MQL in the $scCO_2$ introduces a lubricating effect that assists the cutting process and reduces cutting forces.

In this paper the use of CO_2 in the supercritical fluid state as a metalworking fluid in machining of Ti-6Al-4V at elevated speeds and the effect on the surface condition is investigated. The remainder of the paper is organized as follows: Section 2 presents the experimental setup and the structure of the machining trials. Section 3 presents the results of the machining trials. Finally, Section 4 presents the concluding remarks.

2. Experimental setup

In order to evaluate the performance of supercritical CO_2 compared to traditional emulsion coolant in terms of tool life, a series of trials were performed. The workpiece material used was titanium alloy Ti-6Al-4V (grade 23) in the beta annealed condition. The chemical composition of the material is outlined in Table 1. The cutting trials were performed on a horizontal machining center Starrag Heckert HEC 1800 equipped with flood emulsion and supercritical CO2 capabilities. The $scCO_2$ was supplied through a Fusion Pure-Cut+™ system. The tool used for the trials was a 40 mm diameter button face mill 600 series from Sandvik with a HSK100 back end that used 12mm diameter button inserts. Single tooth milling was used in all the trials. The cutting trials were carried using the following cutting data: cutting speed Vc = 100 m/min, feed per tooth fz = 0.15 mm/tooth, axial depth of cut ap = 2 mm and radial depth of cut ae = 10 mm. With regards to the cooling used in the trials the following coolant regimes were used: Flood emulsion coolant externally applied (Hocut 795N), $scCO_2$ applied through the tool and $scCO_2$ plus minimum quantity lubrication (MQL) also applied through the tool. The cutting edge was examined throughout the trials with the use of a portable microscope. After the end on each trial the surface roughness of the final surface was measured using a Mitutoyo Surftest SJ-210 roughness measurement tester. For the cutting trials the failure criterion was VB = 0.25 mm for flank wear. Fig 1 depicts the experimental setup used for the trials.

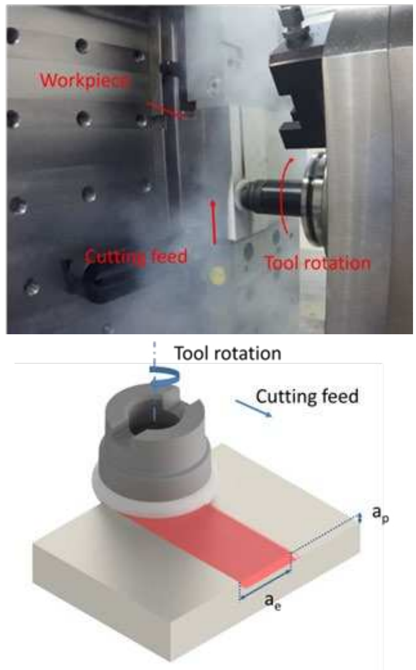

Figure 1 Experimental setup for the machining trials

Table 1. Chemical composition of Ti-6Al-4V used in the machining trials.

Element	% by Mass
Al	5.5-6.5
C	≤0.08
H	≤0.0125
Fe	≤0.25
N	≤0.03
O	≤0.13
V	3.5-4.5
Ti	Balance

3. Machining Trials Results

In order to understand and accurately measure tool life under different cooling conditions, the tool wear progression was monitored periodically using a portable microscope. The results of the trials with different coolant methods is presented on the top of Fig 2 while the bottom part of the figure presents the evolution of tool wear in each cooling condition. The flood emulsion coolant externally applied allowed the tool to reach 56 minutes of cutting before reaching the tool failure criterion. $ScCO_2$ gave a tool life of 18.5 minutes which is relatively low compared to flood emulsion coolant. Adding lubrication in the process by means of MQL to the $scCO_2$ aided the cutting process and helped in achieving a tool life of 150 minutes. This is in line with the results from Wika et al. [12] In terms of the tool wear progression, for $scCO_2$ it can be observed that the insert reached the vicinity of the tool wear limit and stayed below the limit briefly before moving over the tool wear limit. For the flood trial, it can be observed the initial flank tool wear was considerably less than the one observed in the $scCO_2$ trials. Tool wear progressed from the initial flank wear to the failure criterion in a steady gradient. This type of wear is more typical

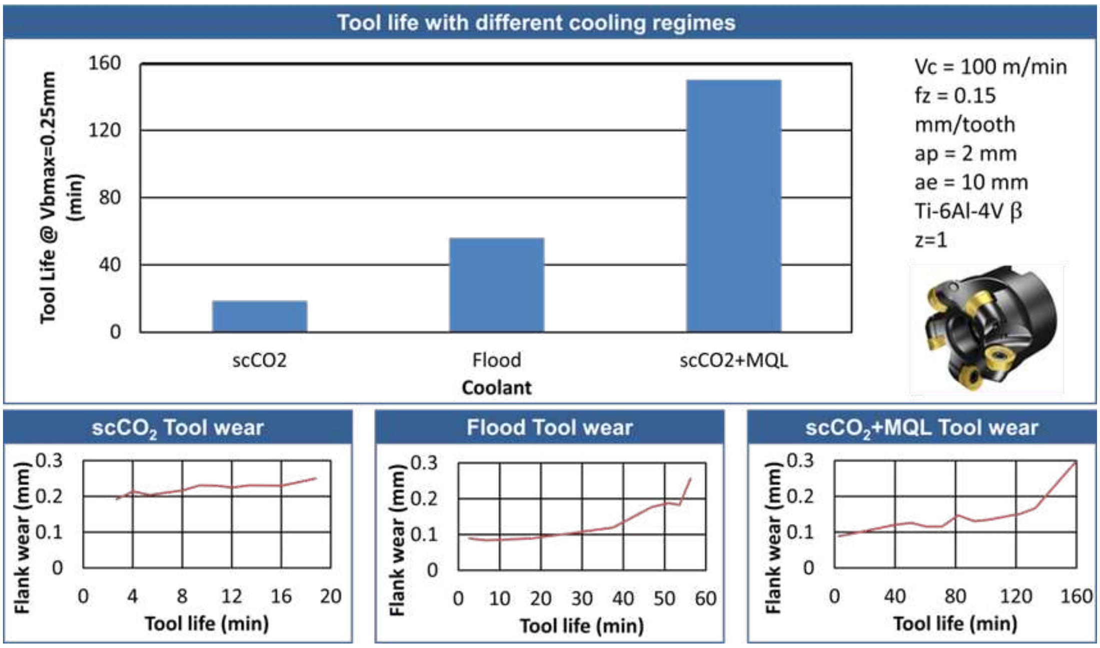

Figure 2 Tool life and wear progression in the machining trials

to an S-like curve observed in tool life trials and indicates a stable cutting process without any adverse effects due to high heat or load. For the $scCO_2$ plus MQL trials tool wear started with an initial flank wear of 89 µm and progressed steadily until the tool failure criterion was reached after approximately 150 minutes. The addition of MQL in $scCO_2$ assisted in the chip evacuation due to the lubricity it offers. The results thus indicate that highly productive cutting process can be realized with the use of $scCO_2$.

In terms of the condition of the cutting tool, Fig 3 presents the condition of the cutting tool at the time of failure. For the scCO2 trial, the damage mechanism appears to be rapid abrasive nature. In the case of flood emulsion coolant, tool wear was initially of an abrasive nature. Notches that appeared in the tool became magnified after 15 minutes of testing leading into tool failure.

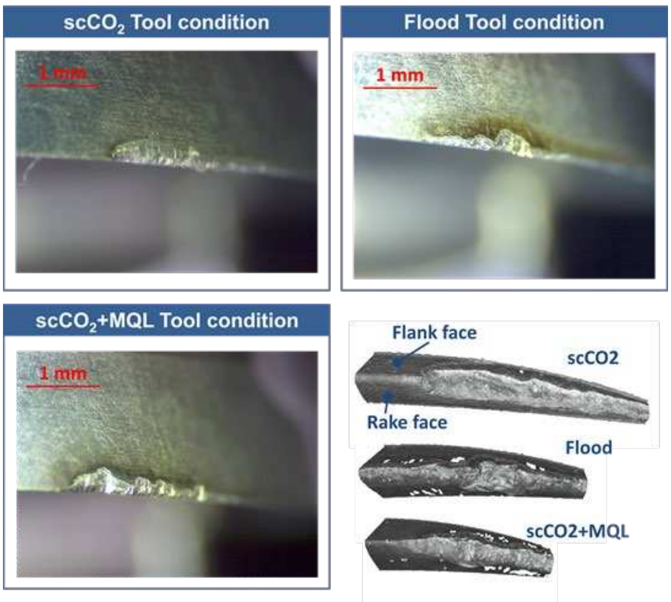

Figure 3 Tool condition for the life trials using $scCO_2$, food and $scCO_2$+MQL.

It is worth noting that there was a dark strip under the tool wear zone which existed throughout the trials. Finally, for the $scCO_2$+MQL trials it can be observed the damage mechanism the trial was abrasive flank wear with some amount of notching. Scans of the cutting tools with an Alicona system were also performed, right hand side of Fig. 3, to further understand the tool failure mechanism. As it can be seen in the $scCO_2$ trial the surface appears to be evenly deteriorating with an even wear throughout the edge which could be an indication of high temperature in the cutting edge. In the case of flood emulsion coolant and $scCO_2$+MQL this is not the case with the surface being un-even and areas of carbide missing from the cutting edge.

In terms of the resulting surface quality, the results from the different trials are summarized in Fig. 4. As it can be observed, small differences are observed between the different cooling methods. Overall there are small differences amongst the different cooling methods that are not statistically significant and in all cases the quality of the surface can be considered as very good as the average surface roughness is below 0.5 mm.

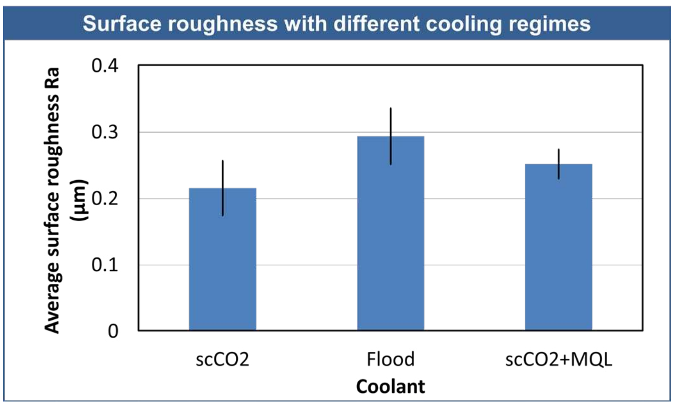

Figure 4 Resulting surface roughness when machining with $scCO_2$, flood and $scCO_2$+MQL as coolant

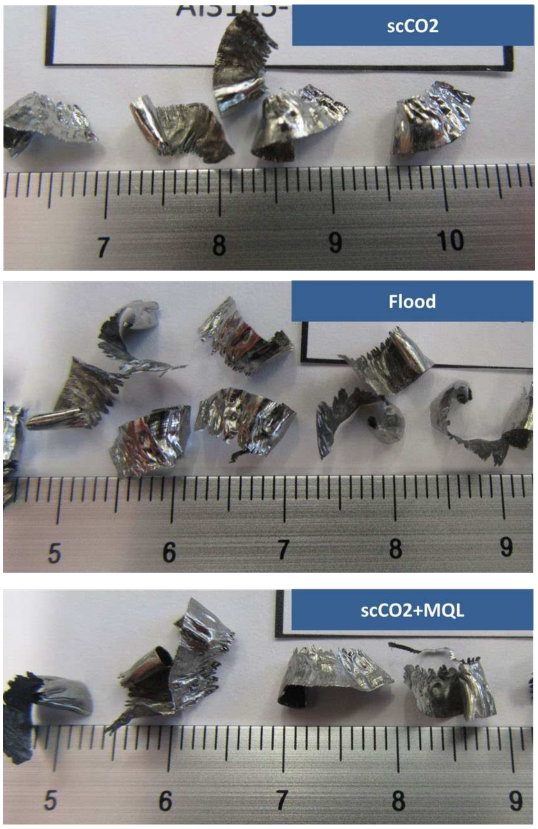

Figure 5 Swarf images collected after cutting trials using $scCO_2$, Flood coolant, and $scCO_2$ + MQL coolant.

Chips form each cutting trial were collected in order to investigate if there is any effect of the coolant on the characteristics of the chips. As it can be seen in Fig 5 the samples are similar in shape size and color. In all cutting trials discontinuous, chips of a similar color were produced.

An additional trial was performed at the best performing coolant to investigate the effect of elevated cutting speed in the tool wear progression. A tool life trial at 140m/min cutting speed resulted in rapid tool wear due to what appears to be excessive mechanical load on the cutting edge. The tool life was limited to 8 minutes. A view of the tool condition at the end of the trial is presented in Fig. 6. It was observed the cutting edge shows elements of chipping. The tool wear progression is rapid and can be compared to the tool wear progression observed with $scCO_2$ at a cutting speed of 100m/min. in terms of the surface roughness of the resulting surface it was comparable to the one measured in the cutting speed of 100m/min.

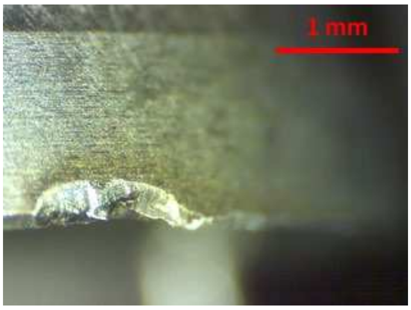

Figure 6 View of the cutting edge at the end of the life trial using $scCO_2$ + MQL at Vc=140m/min

4. Conclusions

The present study focused on the investigation of $scCO_2$ as a coolant in machining of aerospace grade Ti-6Al-4V on a face milling configuration. Flood emulsion coolant, scCO2 and $scCO_2$+MQL were evaluated in terms of tool wear performance in machining Ti-6Al-4V on the beta annealed condition. Based on the machining trials performed, $scCO_2$+MQL provided a tool life which was up to 2.6 times that of emulsion, at the conditions tested. The additional cooling provided by the MQL solution improved the tool life against $scCO_2$ cooling alone up to 8 times. In terms of tool wear mechanisms, in all cases evidence of abrasive wear was present on the micrographs. No noticeable difference was observed in terms of surface roughness. Further research on the subject could include verifying the results using all the inserts of the tool, performing trials in a variety of cutting speed and feed combination and expanding the machining trials in other cutting processes.

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