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Influence of supercritical CO_2 cooling on tool wear and cutting forces in the milling of Ti-6Al-4V

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Abstract

Ti-6Al-4V is known as a difficult-to-machine alloy due to its low thermal conductivity which limits the material's machinability causing rapid tool wear. Supercritical CO_2 is an environmentally friendly alternative cooling technique that can improve the machinability of Ti-6Al-4V enabling higher productivity. This study investigates the variation in tool life and cutting force coefficients when milling Ti-6Al-4V with scCO_2, scCO_2 combined with minimum quantity lubrication and flood coolant. Results from cutting trials carried out at 60 m/min have shown that when the chip load is controlled, substantial improvement in tool life can be obtained with scCO_2+MQL compared to flood coolant with no significant change in cutting force coefficients. However, it has been found that the capabilities of scCO_2 are limited outside the practical speed and feed range resulting in no additional benefit in tool life and sharp increase in cutting force coefficients due to higher thermal gradient and excessive tool wear.

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Keywords: Milling; Titanium; Supercritical Carbon Dioxide

1. Introduction

At present machining of hard materials using conventional techniques is rather uneconomical, as the machining process results in high tool wear and low material removal rates. This is mainly due to excessive heat generation in the cutting zone.

Ti-6Al-4V remains one of the most popular materials in demanding applications that requires high strength-to-weight ratio and service temperature [1]. However, it is considered as difficult-to-machine alloy due to its low thermal conductivity and the high strength. Its low thermal conductivity (6.6 W/m·K) results in poor heat dissipation from the cutting zone causing rapid tool wear. It has been reported [2] that the cutting speed to machine Ti-6Al-4V with carbide tools is limited to 60 m/min. Therefore, the implementation of effective coolant technique is crucial in order to improve the machinability of this alloy. A number of recent studies have looked at the effect of cryogenic cooling techniques to improve machinability of titanium alloys. In turning of Ti-6Al-4V, Bagherzadeh and Budak [3] showed that the combination of CO_2 and Minimum Quantity Lubrication (MQL) supplied separately to the cutting zone provides better heat dissipation and improves the tool life and surface finish. Similarly, Damir et al. [4] demonstrated that cryogenic cooling with liquid nitrogen (LN_2) has a significant positive impact on reducing cutting forces, tool wear and improving the surface integrity compared to flood coolant in turning of Ti-6Al-4V. Su et al. [5] carried out end milling at low radial engagement but very high speeds such as 400 m/min and managed to cool down and lubricate the cutting zone with a mixture of compressed nitrogen gas and oil mist. Tapoglou et al. [6] conducted a comparison study assessing the tool life in the low radial engagement shoulder milling with dry, liquid carbon dioxide (LCO_2), LCO_2+MQL, and flood coolant. They showed that LCO_2+MQL gives longer tool life at 80 m/min and 90 m/min compared to flood coolant. However, they

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found that when the speed increases up to 100 m/min, the ability of LCO_2+MQL providing both cooling and lubrication falls behind the flood coolant. Sadik et al. [7] reported that liquid CO_2 could give significantly longer tool life compared to flood in the face milling of Ti-6Al-4V using inserts with physically vapor deposited (PVD) coatings. They stated that the major tool deterioration mechanism was notch wear and also reported that increasing the flow rate of CO_2 extends the tool life.

In addition, there is a growing interest in advanced coolants and move towards Environmentally Sustainable Manufacturing (ESM) due to advances in high-speed cutting, concerns for the environment, and employee health awareness. One of the areas of interest in ESM are cutting fluids. Firstly, the majority of commonly used cutting fluids are soluble oil-based [8]. Secondly, whether delivered at high pressure or in the form of low pressure external flood, the machine tool and machined components need to be cleaned of any fluid residue after the operation and wet swarf must be disposed of accordingly. In addition, cutting fluids require continuous monitoring to check against contaminants and bacteria in order to extend their life. Thirdly, when fluids degrade and consequently their performance decrease, they have to be recycled and/or disposed of correctly. Lastly, fluids might be hazardous to machine operators and are a known cause of dermatitis due to toxicity or bacterial/fungal contamination in the fluid if safety procedures are not followed. These actions that need to be taken for correct management of cutting fluids are labour-intensive and may cause substantial overhead costs to manufacturers. Therefore, it is important to investigate environmentally friendly cooling techniques for clean and productive machining.

Currently, there are several cooling techniques that could be used as environmentally friendly alternatives to conventional cutting fluids such as MQL, LN_2, LCO_2 and supercritical carbon dioxide ($scCO_2$) typically delivered through machine tool spindle for effective cooling and/or lubrication [9]. It has been shown in the literature [10] that these techniques have the potential to improve machinability of difficult-to-machine materials, reduce energy consumption and provide improved surface integrity.

The aim of this paper is to investigate the effect of supercritical CO_2, $scCO_2$ + MQL, and flood coolant on tool wear and cutting forces in the high radial engagement milling of Ti-6Al-4V.

2. Experimental Work

The experimental work consisted of two parts; the assessment of tool life and identification of cutting force coefficients. All work was carried out on a 4-axis Starrag Heckert HEC1800 horizontal milling machine tool with a maximum spindle speed of 4000 rpm and a torque of 2150 Nm. A $scCO_2$ unit manufactured by Fusion Coolant Systems was installed on the HEC1800 machine tool to provide a fine tuned stream of $scCO_2$.

The material used in the experiments was a Ø180 mm x 750 mm annealed Ti-6Al-4V bar. The chemical composition is given in Table 1. The bar used in the experiments was placed on two v-blocks securely fixed to a 500 mm x 500 mm custom-built Kistler 9366C dynamometer using end clamps. The dynamometer plate was then bolted down to the machine tool bed.

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

Elements [%]								
C	Al	Fe	H	N	O	V	Ti	Residual
0.008	6.26	0.21	0.0007	0.009	0.143	4.18	Remainder	<0.40

The cutting tool assembly consisted of a 42 mm diameter Sandvik 419-042C4-14M body, C4-390.410-100 holder, and three 419R-1405E-MM S40T grade high-feed milling inserts which are typically used in rough milling at significantly high feed rates. The tool body coolant delivery ports were specially modified to accommodate M4 0.15 mm and 0.25 mm diameter coolant nozzles for $scCO_2$ delivery. A fixed amount of 1 ml/min of soybean oil (NuCut Plus MQL lubricant with flash point at 282°C) was mixed with $scCO_2$ and delivered through the cutting tool to provide lubrication to the cutting zone. Details of coolant methods and their corresponding flow rates that were compared and contrasted in the experiments are listed in Table 2.

Table 2. Details of cooling methods used in all the experiments.

Coolant method	Flow rates [Pressure]
$scCO_2$	15 kg/h [138 bar]
$scCO_2$ + MQL	15 kg/h + 1 ml/min [138 bar]
$scCO_2$	40 kg/h [138 bar]
$scCO_2$ + MQL	40 kg/h + 1ml/min [138 bar]
Flood coolant	50 l/min [6 bar]

2.1. Assessment of tool life

It is common in academic literature as well as industrial practice, that tool life testing in milling is generally carried out along zig-zag type straight toolpath. One potential issue in using this interrupted cutting method is that the tool life tends to be reduced due to the high impact loads during the entry and the exit from the cut.

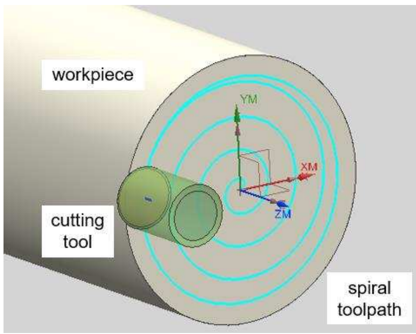

Fig. 1 – Spiral toolpath in tool life trials.

In this study, a spiral toolpath was used in order to obtain a more accurate representation of a continuous cutting scenario, especially in planar roughing operations and to also minimise the risk of random cutting edge chipping during the cut entry/exit. The spiral toolpath is shown in Fig. 1.

Cutting conditions in tool life tests are given in Table 3. Except the cutting speed and feed per tooth, they were selected within the range of tool manufacturer's recommendations. Cutting speed and feed per tooth were selected higher than recommended in order to find out whether $scCO_2$ would also perform beyond the upper limits of recommended values to increase productivity. The tool was run along the spiral toolpath at 75% engagement for multiple passes (planes) where each Ø180 mm diameter plane allowed one pass of 1.44 m length.

Table 3. Cutting conditions in tool life tests.

Cutting Conditions	Value
Cutting Speed (m/min)	50 / 60 / 80
Feed per Tooth (mm/tooth)	0.50 / 1.00
Axial depth of cut (mm)	1
Radial depth of cut (mm)	24.9

The flank wear was measured on each of three cutting inserts. The maximum flank wear (VB_{max}) of 300 µm was used as the end of tool life criterion. Each tool life trial was ended when at least one of the cutting edges exceeded the 300 µm threshold. The tool wear trials were conducted according to ISO 8688-1:1989 [11]. The flank wear on each insert was monitored using ShuttlePix P-400Rv portable microscope. The same setup was used for tool life trials and cutting force measurement in milling with the assistance of $scCO_2$ (with and without MQL) and flood coolant (Fig 2).

Fig. 2 – Tool life trials machine setup.

2.2. Identification of cutting force coefficients

It is a well-known relationship that the average cutting force in machining varies linearly with respect to the feed rate. This is expressed by the mechanistic cutting force model as

$$F_i = K_{ci} f_z + K_{ei} \quad i = \{x, y, z\} \tag{1}$$

where f_z is the feed per tooth, K_c and K_e are the cutting and edge force coefficients, which depend on the workpiece material and tool geometry. From the cutting mechanics, K_c is a scalar quantity that calibrates the chip thickness and chip width to the force acting on the rake face where the material is being sheared, whereas K_e is considered to quantify ploughing occurring over the tool's cutting edge.

Gradisek et al. [12] presented a mechanistic identification method to find out cutting force coefficients for a general milling tool geometry. This method equates Eq. (1), which is a linear regression of measured average cutting forces in feed, cross-feed and axial directions, to instantaneous cutting force expressions summed over radial and axial immersions and averaged over the pitch angle. Following the described method, cutting part of the coefficients in tangential, radial and axial directions are obtained as below.

$$K_{tc} = \frac{2\pi}{NA_1} \frac{C_3\overline{F}_{xc} - (C_2 - C_1)\overline{F}_{yc}}{C_3^2 + (C_2 - C_1)^2},$$

$$K_{rc} = -\frac{2\pi}{N(A_2^2 + A_3^2)} \left[\frac{A_2((C_2 - C_1)\overline{F}_{xc} + C_3\overline{F}_{yc})}{C_3^2 + (C_2 - C_1)^2} \quad \frac{A_3\overline{F}_{zc}}{C_5} \right],$$

$$K_{ac} = +\frac{2\pi}{N(A_2^2 + A_3^2)} \left[\frac{A_3((C_2 - C_1)\overline{F}_{xc} + C_3\overline{F}_{yc})}{C_3^2 + (C_2 - C_1)^2} \quad \frac{A_2\overline{F}_{zc}}{C_5} \right]. \tag{2}$$

Similarly, the edge part of the coefficients in three directions are described as follows.

$$K_{te} = +\frac{-2\pi}{NB_1} \frac{C_4\overline{F}_{xe} + C_5\overline{F}_{ye}}{C_4^2 + C_5^2} \quad \frac{A_2\overline{F}_{ze}}{C_5},$$

$$K_{re} = +\frac{2\pi}{N(B_2^2 + B_3^2)} \left[\frac{B_2(C_5\overline{F}_{xe} - C_4\overline{F}_{ye})}{C_4^2 + C_5^2} \quad \frac{B_3\overline{F}_{ze}}{2C_1} \right],$$

$$K_{ae} = -\frac{2\pi}{N(B_2^2 + B_3^2)} \left[\frac{B_3(C_5\overline{F}_{xe} - C_4\overline{F}_{ye})}{C_4^2 + C_5^2} \quad \frac{B_2\overline{F}_{ze}}{2C_1} \right]. \tag{3}$$

In Eq. (2) and (3), F_{ic} and F_{ie} are the slope and intercepting point of the linear regression, which is carried out on measured cutting forces in feed, cross-feed and axial directions. Constants A and B are called geometric constants which take into account the effect of cutting edge geometry whereas constant C is called immersion constant which depends on the radial engagement. N is the number of flutes or inserts. The geometric and immersion constants are described as in Eq. (3),

$$A_1 = \int_{z1}^{z2} dz, \; A_2 = \int_{z1}^{z2} \sin\kappa(z)dz, \; A_3 \quad \int_{z1}^{z2} \cos\kappa(z)dz,$$

$$B_1 = \int_{z1}^{z2} dS(z), \; B_2 \quad \int_{z1}^{z2} \sin\kappa(z)dS(z),$$

$$B_3 = \int_{z1}^{z2} \cos\kappa(z)dS(z),$$

$$C_1 = \frac{1}{2}\phi\Big|_{\phi_{st}}^{\phi_{ex}}, C_2 = \frac{1}{4}\sin 2\phi\Big|_{\phi_{st}}^{\phi_{ex}}, C_4 = \sin\phi\Big|_{\phi_{st}}^{\phi_{ex}},$$
$$C_3 = -\frac{1}{4}\cos 2\phi\Big|_{\phi_{st}}^{\phi_{ex}}, C_5 \quad \cos\phi\Big|_{\phi_{st}}^{\phi_{ex}}. \tag{4}$$

where, dz is the differential elevation from the tool's tip at the centre, z_1 and z_2 are the upper and lower limits of the axial engagements, κ is the approach angle, dS is the differential cutting edge length, ϕ is the immersion angle.

For convenience, slot milling was chosen in the cutting force coefficient identification tests to reduce the number of variables in Eq. (2) and (3). Tests were conducted at two cutting speeds, 60 and 80 m/min, over three feed per tooth values i.e. 0.50, 0.75 and 1.00 mm/tooth and repeated for all cooling methods given in Table 2. The axial and radial depths of cut were kept constant in all tests at 1 mm and 33.2 mm, respectively. As shown in Fig. 3, each run consisted of four slot cuts, machined in random order.

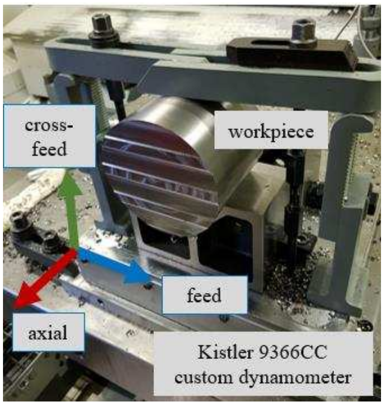

Fig. 3 – Machining setup for cutting force identification tests.

After each run, the bar was faced off to a clean surface and a new insert edge was used for the next experimental run: this was to minimise the effect of tool wear on the recorded force data. Cutting forces in three directions were measured with Kistler 9366CC custom dynamometer at a sampling frequency that would allow at least 120 data points to be captured for every full tool rotation. Portions of the measured forces in which the tool was fully engaged into cut were extracted out, low-pass filtered at three times the tooth-pass frequency and averaged over 20 tool rotations. Average forces in three directions were plotted with respect to feed per tooth values using Eq. (1) and each one's slope and intercepts were calculated through the least-squares method. After that, the sets of geometric and immersion constants were calculated using Eq. (2) as $A_1 = 1.000$, $A_2 = 0.326$, $A_3 = 0.946$, $B_1 = 3.110$, $B_2 = 1.013$, $B_3 = 2.940$, $C_1 = 1.571$, $C_2 = C_3 = C_4 = 0$ and $C_5 = -2$ where $z_1 = 0$, $z_2 = 1$, $\phi_{st} = 0$, $\phi_{ex} = 180$ and $\kappa = 19$ between z_1 and z_2. Finally, calculated slopes, intercepts, geometric and immersion constants were fed into Eq. (3) to calculate cutting and edge force coefficients in tangential, radial and axial directions.

3. Results and discussion

3.1. Comparison of tool life

Fig. 4 summarises the results from the tool life trials. Shokrani et al. [2] indicated that excessive tool wear is seen above certain speed-feed combination regardless of the cooling method being used. From Fig. 4a, this can be observed at the most aggressive cutting conditions, i.e. cutting speed (V_c) of 80 m/min and feed per tooth (f_z) of 1.00 mm/tooth. Premature tool failure occurred at this condition in all cases, due to poor thermal conductivity of titanium alloy and inefficient heat dissipation through a coolant media. It resulted in a maximum tool life of less than 2 minutes. At V_c = 80 m/min, decreasing feed per tooth from 1.00 mm/tooth to 0.50 mm/tooth does not seem to have contributed to extending tool life as much as expected as the maximum obtained was ~10 minutes for flood coolant and 15 kg/h sCO_2+MQL. Similar results were obtained for V_c = 60 m/min and f_z = 1.00 mm/tooth where 15 kg/h $scCO_2$+MQL yielded the longest tool life of ~10 minutes. At this condition, although there is not much difference between 15 kg/h $scCO_2$+MQL and 40 kg/h $scCO_2$+MQL, the results indicate that higher flow rate of $scCO_2$ does not necessarily assure longer tool life as its effectiveness seems to be limited beyond certain level of V_c and f_z. This observation is more evident at V_c = 50 m/min in which 15 kg/h $scCO_2$+MQL again yields the longest tool life of approximately 35 minutes whereas 40 kg/h $scCO_2$+MQL appears to last only 30 minutes. Although the chip load is quite high at this testing point, the cutting speed is well in the practical range and combined delivery of $scCO_2$+MQL gives significantly longer tool life at both flow rates in comparison to flood coolant. At the least aggressive cutting condition in these trials, i.e. V_c = 60 m/min and f_z = 0.5 mm/tooth, a significant improvement in tool life was observed under all $scCO_2$ and $scCO_2$+MQL combinations in comparison to flood coolant. The progression of the flank wear is shown in Fig. 4b. While the tool life with flood coolant was only 63 minutes, 15 kg/h $scCO_2$ resulted in ~145 minutes cutting time. The addition of MQL to 15 kg/h $scCO_2$ increased the tool life to ~154 minutes. With an increase in $scCO_2$ flow rate from 15 kg/h to 40 kg/h the tool life was further extended to ~167 minutes. However, the addition of 1ml/min of MQL oil to 40 kg/h of $scCO_2$ did not provide any further increase in tool life.

3.2. Comparison of cutting force coefficients

Fig. 5 shows the results from cutting force identification tests in the form of resultant cutting forces which were calculated as the vector sum of measured forces in three directions. It can be seen from both figures that the linearity in the variation of cutting force with respect to the feed per tooth is satisfactory for the estimation of the coefficients. In Fig. 5a, at V_c = 60 m/min, there is no significant difference between the forces under different cooling media regardless of the chip loads, however flood coolant appears to be the one generating the least force among all. This difference between the flood and other cooling methods is more prominent at 1.00 mm/tooth. There is no clear trend between $scCO_2$ and

$scCO_2$+MQL, so it is difficult to argue whether the addition of MQL contributed to decreasing the magnitude of cutting forces. It is believed that more repeated tests are necessary to meet a certain level of statistical significance to clarify this relation. In Fig. 5b, it is apparent that there is a significant difference in average forces between all cooling media at V_c = 80 /min. Similar to the previous case, flood coolant seems to generate less force compared to $scCO_2$ and $scCO_2$+MQL. However, the addition of MQL appears to have a positive effect on decreasing the forces. This effect is visible at both flow rates, 15 kg/h and 40kg/h, but its magnitude is much higher at 40 kg/h. Higher cutting forces for $scCO_2$ and $scCO_2$+MQL compared to flood coolant can most likely be attributed to the magnitude of the thermal gradient in the cutting zone. Ti-6Al-4V is a two phase, $\alpha+\beta$ alloy, with microstructure and therefore mechanical properties changing with respect to the cooling rate.

Multiple studies [13,14] reported that a faster cooling rate can raise the intensity of martensitic α' particles in the microstructure of Ti-6Al-4V which in turn increases the hardness of the material. However, the rate of increase in cutting forces is relatively high, especially with 40 kg/h $scCO_2$ and $scCO_2$+MQL, which means that phase transformation cannot be the only factor. Considering the results from tool life trials at 80 m/min, rapid progression of tool wear is also believed to contribute to the drastic increase in cutting forces.

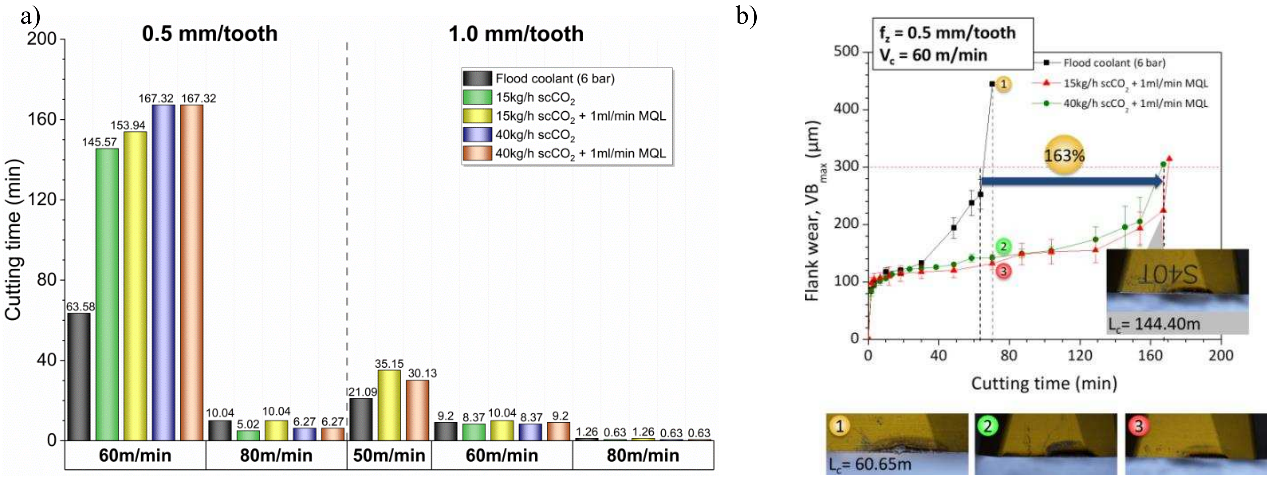

Fig. 4 - Various combinations of cutting conditions and cooling methods and their resulting a) cutting time, (b) flank wear.

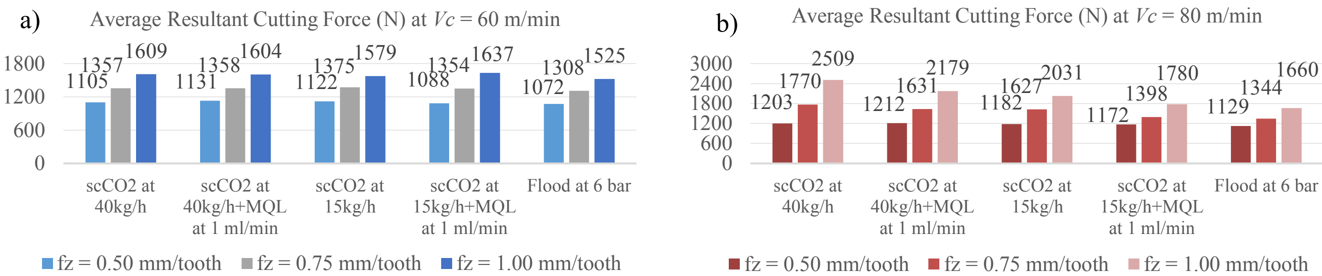

Fig. 5 – Results of cutting force identification tests carried out at (a) V_c = 60 m/min and (b) V_c = 80 m/min.

Fig. 6 shows the cutting part of the cutting force coefficients estimated through the experimental procedure described in Section 2. At 60 m/min, similar to the results shown in Fig. 6a, there was no consistent change in tangential and radial cutting coefficients among the flood coolant, $scCO_2$ and $scCO_2$+MQL. However, at 80 m/min, it can be seen from Fig. 6b that there is an increasing trend in both coefficients from flood coolant to 40 kg/h $scCO_2$. The addition of MQL seemed to limit this trend to a certain extent. It is interesting to see that, at 80 m/min, the rate of increase in radial cutting coefficient is more than the tangential, in all cases. Radial cutting coefficient appeared to be even higher than the tangential in 40 kg/h $scCO_2$ and 40 kg/h $scCO_2$+MQL. For both cases, it is mainly caused by the escalation of the slopes in axial forces while slopes in feed and cross-feed directions are very similar. Results from edge coefficient estimations are presented in Fig. 7. In comparison to Fig. 6a, lubricating effect of MQL at 60 m/min is more apparent in edge coefficient results given in Fig. 7a. $scCO_2$+MQL at 15 kg/h was the most effective cooling method in decreasing the edge force coefficient at 60 m/min. However, as seen in Fig. 7b, the one yielding the lowest edge coefficient was $scCO_2$+MQL at 40 kg/h. The addition of MQL to 15 kg/h $scCO_2$ increased the edge force coefficients at 80 m/min which is in contradiction to decreasing trend of edge coefficients with MQL in Fig. 6a. Nevertheless, the flood coolant is the one having the highest edge coefficients at both speeds.

4. Conclusions

The cooling efficiency of $scCO_2$ in the milling of Ti-6Al-4V is best exploited in a certain range of cutting conditions:

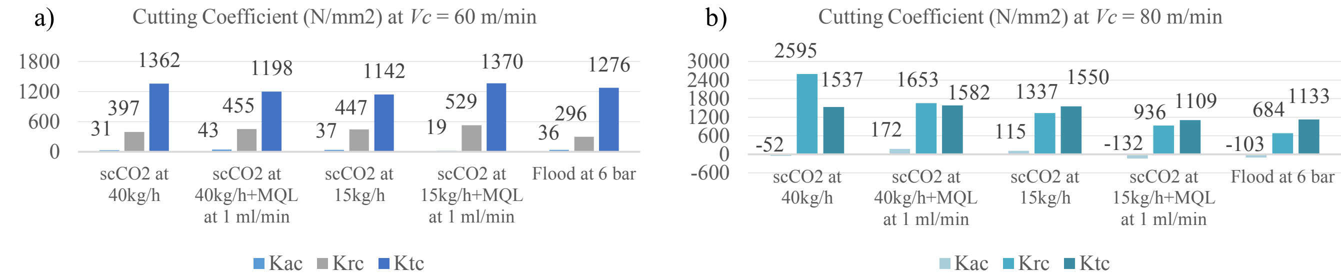

Fig. 6 – Estimated cutting coefficients in tangential (K_{tc}), radial (K_{rc}) and axial (K_{ac}) directions at (a) V_c = 60 m/min and (b) V_c = 80 m/min.

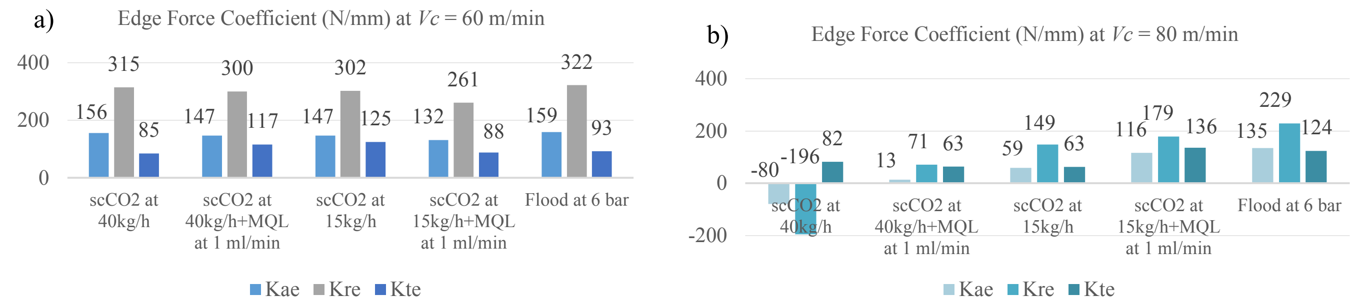

Fig. 7 – Estimated edge coefficients in tangential (K_{te}), radial (K_{re}) and axial (K_{ae}) directions at (a) V_c = 60 m/min and (b) V_c = 80 m/min.

- 163% improvement in tool life was obtained with the use of $scCO_2$+MQL at V_c = 60 m/min and f_z = 0.5 mm/tooth. However, at unconventionally higher speeds such as V_c = 80 m/min, none of the tested combinations provided sufficient cooling and lubrication effect resulting in premature tool failure.
- The use of $scCO_2$ in combination with MQL tends to yield marginally longer tool life at practical cutting speeds below V_c = 60 m/min.
- At higher speeds than V_c = 60 m/min, increasing the flow rate above 15 kg/h of $scCO_2$ does not provide any additional benefit in improving the tool life.
- At V_c = 60 m/min, the variation of cutting force coefficients with respect to tested cooling method is negligible.
- At V_c = 80 m/min, $scCO_2$ without MQL yields drastically higher cutting force coefficients due to lack of lubrication. Increasing flow rate of $scCO_2$ also causes coefficients to escalate. This is most likely attributed to the effect caused by the heating-cooling cycle. The more $scCO_2$ is delivered to the cutting zone per unit time, the faster the cooling is causing an increase in the material hardness.

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References

[1] K. Busch, C. Hochmuth, B. Pause, A. Stoll, R. Wertheim, Investigation of cooling and lubrication strategies for machining high-temperature alloys, Procedia CIRP 41 (2016) 835-840.
[2] A. Shokrani, V. Dhokia, S.T. Newman, Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids, International Journal of Machine Tools & Manufacture 57 (2012) 83-101.
[3] A. Bagherzadeh, E. Budak, Investigation of machinability in turning of difficult-to-cut materials using a new cryogenic cooling approach, Tribology International 119 (2018) 510-520.
[4] A. Damir, A. Sadek, H. Attia, Characterization of machinability and environmental impact of cryogenic turning of Ti-6Al-4V, Procedia CIRP 69 (2018) 893-898.
[5] Y. Su, N. He, L. Li, X. Li, An experimental investigation of effects of cooling/lubrication conditions on tool wear in high-speed end milling of Ti-6Al-4V, Wear 760-766 (2006) 261(7-8)
[6] N. Tapoglou, I. M. Lopez, I. Cook, C. M. Taylor, Investigation of the Influence of CO 2 Cryogenic Coolant Application on Tool Wear, Procedia CIRP (2017) 63 745-749
[7] M. Sadik, S. Isakson, A. Malakizadi, L. Nyborg, Influence of coolant flow rate on tool life and wear development in cryogenic and wet milling of Ti-6Al-4V, Procedia CIRP 46 (2016) 91-91.
[8] Y. Yildiz, M. Nalbant, A review of cryogenic cooling in machining processes, International Journal of Machine Tools & Manufacture 48 (2008) 947-964.
[9] I.S. Jawahir, H. Attia, D. Biermann, J. Duflou, F. Klocke, D. Meyer, S.T. Newman, F. Pusavec, M. Putz, J. Rech, V. Schulze, D. Umbrello, Cryogenic manufacturing process, CIRP Annals – Manufacturing Technology 65 (2016) 713-736.
[10] E. Benedicto, D. Carou, E.M. Rubio, Technical, economic and environmental review of the lubrication/cooling systems used in machining processes, Procedia Engineering 184 (2017) 99-116.
[11] ISO 8688-1:1989, Tool life testing in milling Part 1 – face milling, International Organisation for Standardisation, Geneva, (1989).
[12] J. Gradišek, M. Kalveram, K. Weinert, Mechanistic identification of specific force coefficients for a general end mill, International Journal of Machine Tools and Manufacture, 44(4) (2004) 401–414.
[13] M. Jovanović, S. Tadić, S. Zec, z. Mišković, and I. Bobić, The effect of annealing temperatures and cooling rates on microstructure and mechanical properties of investment cast Ti–6Al–4V alloy, Materials & Design, 27(3) (2004) 192-199.
[14] D.Y. Kim, D.M. Kim, H.W. Park, Predictive cutting force model for a cryogenic machining process incorporating the phase transformation of Ti-6Al-4V, The International Journal of Advanced Manufacturing Technology (2018).