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Investigation of the influence of CO_2 cryogenic coolant application on tool wear

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Abstract

The use of cryogenic coolants has emerged as an environmentally conscious alternative to emulsion coolant options. Cryogenic media can be delivered with a variety of methods to the cutting edge and they can be used in combination with other traditional coolant options such as Minimum Quantity Lubrication (MQL) and compressed air cooling in order to aid dissipation of heat generated in the cutting zone and maximize the lubrication of the cutting edge and thus prolong tool life. This study focuses on the investigation of tool life when milling aerospace grade titanium (Ti-6Al-4V) under different coolant delivery options. Tool wear progression was recorded for the following coolant options: cryogenic CO_2, emulsion flood cooling, dry machining, cryogenic CO_2 combined with air or MQL as well as MQL alone.

Keywords: Cryogenic machining, Tool wear, Milling, Carbon dioxide

1. Introduction

Cryogenic machining has in recent years emerged as an environmentally friendly alternative to traditional emulsion coolants. The process involves the application of a 'cold' medium in the cutting zone that reduces the heat generated through the cutting process on the tool, workpiece and chip. Although the term 'cryogenic' has no strictly defined temperature, -150°C is commonly considered to be the maximum temperature which may be considered cryogenic. In machining the most commonly used media for cryogenic methods include liquid nitrogen and carbon dioxide. The two media vary considerably both in terms of their boiling temperature and in terms of the cooling delivery mechanism. Liquid nitrogen boils at -197°C while carbon dioxide boils at a relatively warm -78°C. Both media are nontoxic but pose a series of safety issues that must be mitigated against prior to machining. The media are also present in abundance in the atmosphere. Although carbon dioxide is a greenhouse gas, industrial applications are based on carbon dioxide reclaimed from other processes as byproduct. In terms of storage of the two cryogenic media, liquid nitrogen remains in that state at atmospheric pressure but has to be kept at low temperatures in insulated containers.

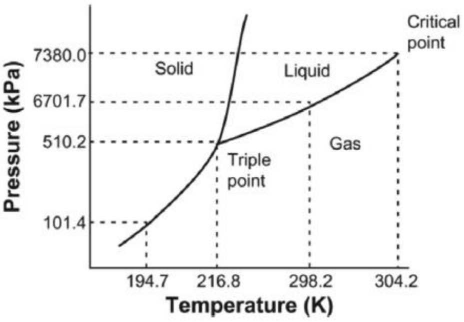

Figure 1. Carbon dioxide pressure-temperature phase diagram [1].

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Carbon dioxide on the other hand must be kept under high pressure (circa 50 bar) to remain in the liquid state but this can be done at room temperature without any special insulation needs. Fig. 1 illustrates the relationship between pressure and temperature in terms of state of matter for carbon dioxide. With regards to the cooling mechanism, liquid nitrogen delivers the cooling effect through the very low temperature of the medium, while in carbon dioxide the cooling effect is due to the rapid expansion of the carbon dioxide gas. As it exits the delivery nozzle, liquid carbon dioxide experiences a drop in pressure, resulting in a phase change from liquid to (60% solid & 40% gas) due to the Joule-Thompson effect [2], and delivering a cooling effect in the surrounding area. For this reason, the position and geometry of the exit nozzle is crucial in the success of the machining process.

The remainder of the paper is organized as follows: Section 2 presents the state of the art in the areas relevant to cryogenic machining. Section 3 presents the experimental setup and the structure of the machining trials. Section 4 presents the results of the machining trials. Finally, Section 5 presents the concluding remarks.

2. State of the Art

Cryogenic methods improve the machinability of various work materials in terms of tool wear and cutting forces. Work materials studied include Nickel alloys (such as Inconel 718), Titanium alloys (like Ti-6Al-4V), Steel alloys, Mg alloys, Co-Cr-Mo alloys, composites and elastomer materials [2–10].

A comprehensive review of the cryogenic machining area was presented by Jawahir et al. [11]. They focused on most applications of cryogenic machining, including milling, turning and drilling. They focused on both liquid nitrogen and carbon dioxide and reviewed a variety of materials.

Jerold and Kumar [12] focused on the influence of cryogenic coolant in machining Ti-6Al-4V material. They compared the performance of cryogenic coolants (CO_2 and LN_2) against flood emulsion coolant and dry machining. Based on their experiments cryogenic machining (CO_2 and LN_2) reduced cutting temperatures by 50% over the dry machining and about 15%–47% over the wet machining. Application of cryogenic CO_2 produced lower cutting forces than the cryogenic LN_2, wet, and dry machining environments.

Application of cryogenic media in machining has been the focus of many researchers. Yuan et al. [13] investigated the effect of coolant in end milling of Ti-6Al-4V. The trials focused on different cooling methods including dry, wet (standard coolant), MQL, and MQL with cooling air. Of these variables, MQL with coolant air at a relatively warm -15°C (-30°C and -45°C were also used) was found to give the greatest tool life, at 22 minutes. The benefits of the cryogenic machining setup were indicated by some of the results. The worst performing sub-zero coolant method (MQL and -45°C air) gave superior tool life when compared to the best performing method at 0°C or above.

Sadik et al. [14] reported on the investigation of face milling of Ti-6Al-4V using CO_2 as a coolant medium. Using PVD coated inserts and a surface speed of 80 m/min, a doubling of tool life when compared to flood emulsion coolant was observed. They used three different nozzle diameters, the same for each coolant. Notch wear was usually the limiting factor, with wear profiles against time displaying the classic 'S' shape of high initial wear, followed by steady state conditions, before rising exponentially as a notch, acting as a stress concentration point, develops. Furthermore, it was clearly shown that CO_2 cooling offers much improved tool life over emulsion cooling.

Su et al. [15] present a similar comparison of coolant techniques to Yuan et al. [13]. By incorporating a sacrificial thermocouple into the surface to be cut, the temperature at the cutting zone during the high-speed machining of Ti-6Al-4V could be assessed. 'Cryogenic' MQL (CMQL) delivery (at -20°C) was by far the most effective medium in removing heat from the workpiece.

Other work in cryogenic milling includes that of Cordes et al. [16], who milled stainless steel using carbon dioxide and air and dry cutting on a Starrag LX051 and a new, bespoke tool and spindle design to allow through tool coolant delivery. Cryogenic machining offered a 63 % improvement in flank wear at a cutting speed of 320 m/min, and a material removal rate 72 % greater was also demonstrated.

The aim of this paper is the investigation of the effect of cryogenic CO_2 cooling in the development of wear when shoulder milling Ti-6Al-4V. Minimum Quantity Lubrication (MQL) and its combination with CO_2 cryogenic cooling is also included. The cryogenic options are compared with traditional coolant options including dry and MQL machining.

3. Experimental Setup

The machining trials were focused in shoulder milling of Ti-6Al-4V in the beta annealed condition. The shoulder milling trials were performed on a Starrag LX051, 5-axis horizontal machining center. The machine tool can deliver a variety of cooling including dry, flood emulsion cooling, through tool, MQL, compressed air, cryogenic CO_2, CO_2 plus compressed air and CO_2 plus MQL. The cutting tool used for the machining trials was an indexable, five insert end mill. Two variations of the tool of identical geometry were used for the trials. Each had an internal coolant delivery channel of a suitable diameter for the coolant delivery method for which it was designed, i.e. large for emulsion, small for MQL and CO_2. The cryogenic tool is presented in Fig. 3.

Figure 2. Machining trials set-up.

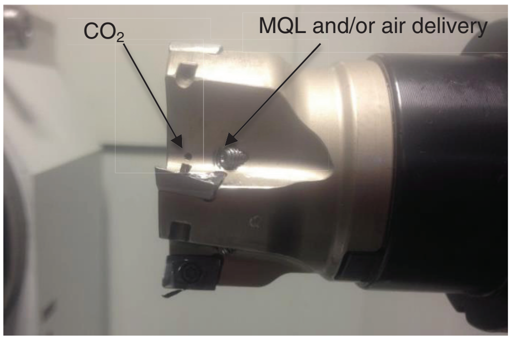

Figure 3. Tool used during the cryogenic trials.

The criterion for terminating the cutting trials was when the tools reached an average flank wear of 0.2 mm or experienced significant chipping. The set-up of the trials is presented in Fig. 2.

Tool wear measurements were taken periodically using a digital microscope. The workpiece used was a prismatic block of the following dimensions: 100x70x36 mm. The setup used is presented in Fig. 2. The cutting conditions used for the machining trials are presented in Table 1.

Table 1. Machining parameters used for the machining trials.

Parameter	Value
Radial Depth of Cut, ae (mm)	1
Axial Depth of Cut, ap (mm)	6
Feed per Tooth, fz (mm)	0.45
Surface Speed (Vc), (m/min)	70-100
Coolant	Flood emulsion, through tool, CO_2 and MQL, MQL, CO_2 and Air, CO_2, Dry

For the flood and medium pressure through tool coolant conditions a coolant emulsion with Hocut 795 at a concentration in the range 6-8% was used. The MQL fluid used was Aerosol Master lubricant, while the carbon dioxide used for the cryogenic option was delivered via a multi-cylinder pallet (MCP) at high pressure. Carbon dioxide was kept in a liquid state inside the bottles at room temperature and high pressure and was delivered directly to the tool nozzle at that state without any drop in pressure.

4. Machining Trial Results

The machining trials were divided in three parts. Initially single insert trials were conducted to evaluate the performance of all the coolant options available. From the results of the first part of the trials, the best performing cryogenic option was selected along with the conventional cooling options for a series of tool life tests using all five cutting edges of the tool, in part two. Part three of the trials focused on finding a set of parameters that would give an acceptable tool life.

The results of the first part of the trials are presented in Fig. 4. It is clearly illustrated that the greatest performance in terms of tool wear at 100 m/min is achieved using flood emulsion coolant, which presents a slow, steady wear rate resulting in a tool life in excess of 30 minutes. Medium pressure through-tool delivery also followed a steady progressive wear pattern, exceeding the wear limit after approximately 28 minutes.

All other coolant delivery methods, by contrast, show a shortened steady wear period followed by an exponential increase, indicative of a different wear mechanism becoming dominant as tools became worn. The best performing cryogenic method was CO_2 plus MQL. It showed a significant improvement in tool life over MQL alone, which itself was superior to CO_2 and CO_2 plus air (and dry machining). Therefore, the cryogenic method qualifying for the second part of the trials was CO_2 plus MQL. In addition to that coolant option flood emulsion, medium pressure through-tool and MQL alone were tested as benchmark options.

The second part of the machining trials focused on trials using five inserts using the above-mentioned coolant options. Tool wear curves from trials using five inserts are presented in Fig. 5. As was observed in the single insert trials at 100 m/min the slowest wear rate and greatest tool life is achieved using emulsion coolant delivered via flood. The test was stopped at 30 minutes as the wear was much lower than the established criteria (average flank wear below 0.2 mm). This was followed by medium pressure through tool delivery of emulsion coolant, again following the trend seen in single insert testing. MQL and CO_2 plus MQL gave much shorter

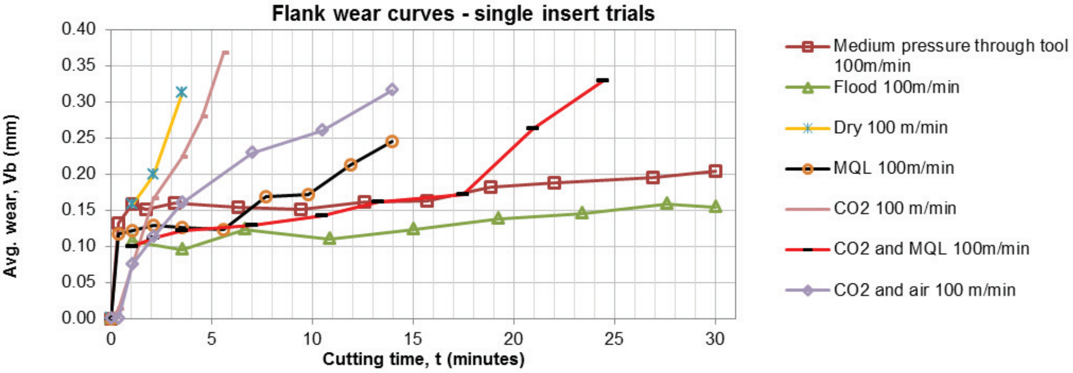

Figure 4. Tool wear progression of single insert trials.

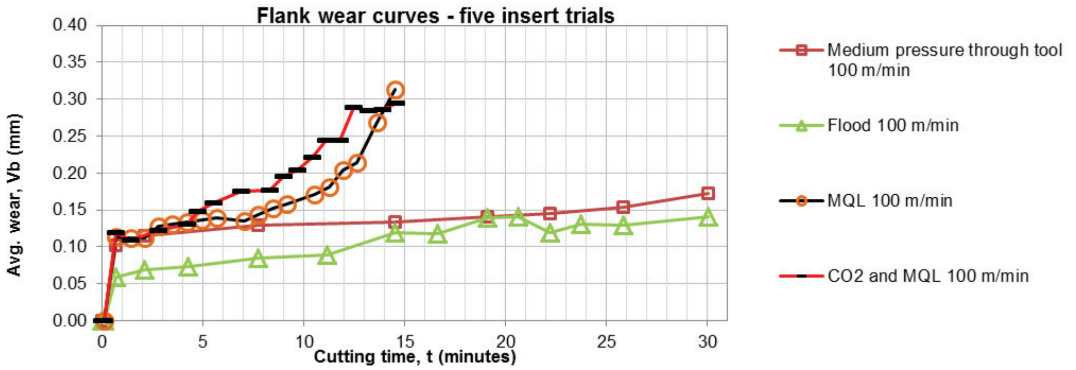

Figure 5. Tool wear progression of five insert trials.

tool life. Collectively, this confirmed the general trends seen in the single insert testing were transferable to machining with five inserts.

The third part of the trials focused on the comparison of CO_2 plus MQL with MQL alone across different cutting speeds. The results of the trials are summarized in Fig. 6. The trials at 70 m/min and 80 m/min, showed that the addition of CO_2 resulted in a significant improvement in tool life (although this was reversed at 100 m/min in five insert testing). This is illustrated in Fig 6. At 70 m/min, adding CO_2 increased tool life by 29 % over MQL alone; at 80 m/min tool life improved by 32 %. At 100 m/min, a decrease of 19 % was exhibited This highlights the dual purpose of any coolant medium: it must both cool and lubricate the cutting zone, in order to dissipate the heat produced by the machining process and prolong tool life.

Over the course of the trials a series of observations can be made. The most obvious observation is that the greatest tool life was demonstrated using conventional emulsion coolant. Both flood emulsion coolant and through tool gave significantly lower wear rates than any other method. This was repeated consistently across both stages of trials (single and five insert) and surface speeds (70-100 m/min).

The wear curves indicate emulsion coolant conditions resulted in a different wear mechanism when compared with dry, MQL and cryogenic methods. Comparing the insert condition at the start and end of the emulsion wear tests, indicated a consistent progressive wear pattern; a gradual rounding of the insert edge. By contrast, the exponential wear rates displayed by dry, CO_2, CO_2 plus air, MQL and CO_2 plus MQL suggest significant removal of material volume from the insert flank under these conditions.

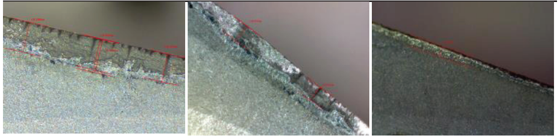
MQL CO$_2$+MQL Flood

Figure 6. Comparison of tool damage at the end of tool life in cutting speed 100m/min

Micro-notches (dark 'tiger stripe' cracks perpendicular to the cutting edge) indicative of heat-induced damage are apparent in several cases (particularly MQL), while significant cratering, indicative of adhesion and plucking is displayed in others (especially under dry conditions). This suggests that the temperature at the tool tip is too high to promote viable tool wear rates.

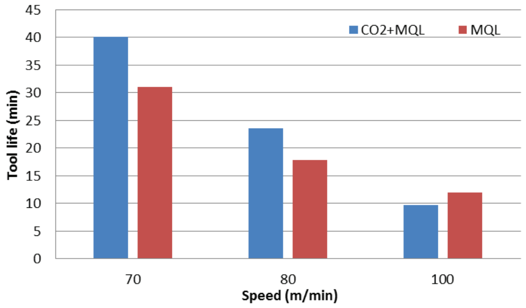

Figure 7. Comparison of tool life achieved using MQL versus CO2 plus MQL during five insert machining trials, 70-100 m/min.

5. Conclusions

This paper focused on the investigation of wear progression during cryogenic milling of Ti-6Al-4V in the beta annealed condition.

A literature review of material from academic and industrial sources has established that while significant variation in results exist, cryogenic machining has the potential to improve tool life, surface finish, productivity and surface integrity when compared with conventional coolant methods.

Tool life trials used the cooling options dry, flood emulsion, through tool emulsion, MQL, CO_2, CO_2 plus air and CO_2 plus MQL. The best performance at 100 m/min was achieved using flood emulsion coolant, which easily achieved a tool life of 30 minutes. The best performing cryogenic method was CO_2 plus MQL which achieved a tool life of 18.5 minutes in equivalent testing. The successful performance of cryogenic machining is dependent on a number of factors, including workpiece material and machining process details. Further, within cryogenic coolant methods, the dual mechanism of cooling and lubrication have been shown to be equally important in improving tool life as in conventional emulsion coolant techniques. This is evidenced by the improvement in tool life of both CO_2 alone and MQL alone by combining the two media together (hence the best results being achieved with CO_2 plus MQL). However, there is a limit to this effect, as indicated by MQL alone contradicting CO_2 plus MQL in five insert testing at 100 m/min. Again, this limit (in surface speed), is also dependent on the specific details of the machining process being studied.

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