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Sustainable cooling method for machining titanium alloy

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Abstract. Hard to machine materials such as Titanium Alloy TI-6AI-4V Grade 5 are notoriously known to generate high temperatures and adverse reactions between the workpiece and the tool tip materials. These conditions all contribute to an increase in the wear mechanisms, reducing tool life. Titanium Alloy, for example always requires coolant to be used during machining. However, traditional flood cooling needs to be replaced due to environmental issues, and an alternative cooling method found that has minimum impact on the environment. For true sustainable cooling of the tool it is necessary to account for all energy used in the cooling process, including the energy involved in producing the coolant. Previous research has established that efficient cooling of the tool interface improves the tool life and cutting action. The objective of this research is to determine the most appropriate sustainable cooling method that can also reduce the rate of wear at the tool interface.

1. Introduction

Titanium Alloy has been widely used in the aerospace and automobile industries since the 1960s, and has been classified as a hard to machine material. During the intervening 50 year time period a number of tool tip materials have also been developed. These have reduced the effect of the chemical interaction and high thermal conductivity between the tool tip and the workpiece to help reduce tool wear [1, 2]. Common industrial practice for machining difficult titanium alloys is to select reasonable production rates of machining which can achieve an acceptable cost level. It is good practice not to allow tools to be cut to destruction, if production costs are not paramount i.e. the lower the tool wear the reduced number of used tool tips. Ideally, a tool tip should be used for as long as possible without risking damage to the tool or the workpiece, as long as the surface finish is maintained. A safe stopping point can typically be found by checking after a few cuts, by counting the workpieces produced and inspecting the surface finish and dimensions. By using these procedures it can be established how many acceptable parts can be produced before the tool tip fails. According to Sandvik, for the intermediate stage turning of titanium, the parameters should be DOC 0.5 to 3.00 mm, feed range o.15 to 0.25 mm/rev and cutting velocity of 50 to 70 m/min. According to the results from Nambi *et al* [3], the surface roughness improves by increasing the cutting speed when using a ceramic insert, which is the recommended tool tip material for titanium alloy TI-6AI-4V. However, it's found necessary to still use coolant to prolong tool life [4-6], and accuracy of the workpiece [7]. The reliance of copious amounts of cutting fluid to remove the heat from the tool interface is unsustainable and warrants further research to eliminate its use. Coolants used today have been refined to be used by specific materials such as titanium alloy TI-6AI-4V: the selected synthetic fluid combines chemical inertness and lubricating with cooling. Nevertheless, such coolants are still not sustainable as they become contaminated in the shop floor environment, and contribute 0.98kg-CO_2/L equivalent CO_2 emission of greenhouse gas during the life cycle of the liquid coolant, contributing to the environmental burden [8].

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Selecting the optimum machining parameters has proven difficult for titanium alloy TI-6AI-4V, as the generated heat at the tool tip is not effectively removed by the chips as per other metals. As a result, using the most effective cooling method is critical for high material removal rate (MRR) to increase tool life. In terms of economical and sustainable machining, the selection of the correct machining parameters with cooling method is critical for modern manufacturing. The challenge for the cooling method for TI-6AI-4V is to reduce the tool tip temperature while having minimum environmental impact [9]. A review of research has shown that there has been limited examination of the effectiveness of cooling methods for hard-to-machine material. The effectiveness of the cooling may be determined by improvements to the tool life and the surface finish. The challenge is how to discover the optimum sustainable cooling method to produce TI-6AI-4V workpiece at an economic cost [10, 11]. The following discussion will attempt to explain how this can be achieved.

2. Experimental cutting tests

The Design of Experiment (DOE) method was used to conduct experiments to establish the optimum cooling method for machining TI-6AI-4V material. This allowed the cutting speed and feed rate machining parameters to be robustly tested for each cooling method. A three level, three parameter array where 0, 1 and 2 represented the different levels of the three control levels is shown in Table 1. These given parameters resulted in a maximum test batch of 27 separate workpieces [12]. The test workpieces had a diameter of 60mm and length of 135mm to allow the workpiece to maintain its rigidity avoiding chatter. The length to diameter ratio of 8 was recommended by Lima *et al*. [13], and was used for the workpiece and cutting tool overhang. The depth of cut (DOC) for all tests remained constant at 1mm, as previous research has shown that the DOC has the least effect on the cutting process [14].

Table 1. Control parameters and their levels.

			Levels		
Control Parameters	Units	Symbol	Level 0	Level 1	Level 2
Cooling method		A	Cold Air	MQL	Cryogenic
Cutting speed	m/min	B	120	150	180
Feed rate	mm/rev	C	0.11	0.16	0.22

Selection of this insert was a compromise to tool wear, since this research was to determine the best cooling method with respect to wear. A tungsten carbide tool insert was selected for the machining tests, instead of the harder ceramic insert [15, 16]. The insert only needed to be able to machine the material for a limited time, allowing suitable benefits of cooling the insert to be observed. This insert, according to Sandvik [17], is suitable to machine cast iron and abrasive non-ferrous materials, not normally used for hard titanium' machining. Machining dry was used as the base tool life and environmental reference point.

Determining accurate temperatures at the tool interface during machining has always proved to be an onerous task, due to the difficulty in obtaining these temperatures. For this reason Cook's equation (1) was used.

$$\text{Tip temp } = \left(\frac{0.4U}{\rho C}\right)\left(\frac{Vt_c}{\mathrm{K}}\right)^{\frac{1}{3}} + ambienttemperature \qquad (1)$$

An extraction unit (as shown in Figure 1) was used to remove excess oil particles inside the working area to avoid possible ignition of the swarf during machining. Also, the extraction unit was reversed during cryogenic cooling to ensure adequate oxygen levels for additional safety of the operator.

Figure 1. Arrangement of the extraction duct.

The vortex tube (VT) supplying cold air to the tool tip used a customised fixture Figure 2, and a similar arrangement was used for providing MQL and liquid nitrogen (LN_2). The MQL was delivered from a Uni-max lubrication system distributing atomised coolube metalwork lubricant, adjusted to a minimum level to prevent fumes generated during the machining process. The output air pressure was 48kPa, and the tubes used to supply the coolube ran through the top of the CNC machine, which was similar for the compressed air supply to the VT inside the cabinet. For LN_2 the plastic tube was replaced by the flexible metal tube to prevent swarf damage causing leakage during the machining process.

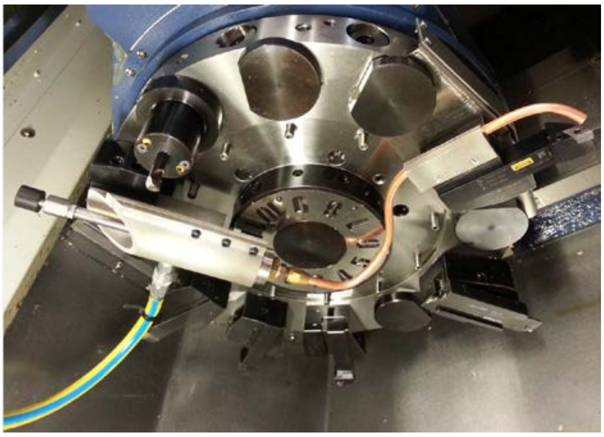


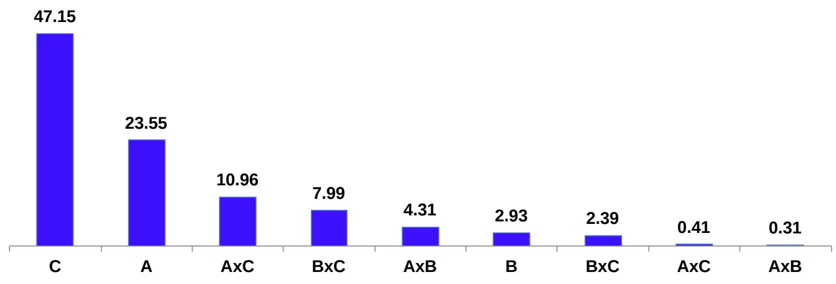
Figure 2. Machining setup for air cooling tests.

The machining power data was measured by a Yokogawa CW140 clamp type power analyzer and the surface finish was obtained by using a Mitutoyo SJ-201 surface roughness tester. The tool wear was examined using a Pro MicroScan 5908 microscope.

3. Results and analysis

To discover the results of the contribution of the interactions of the variables, a Pareto ANOVA analysis [18] was completed using the performance measures of temperature, tool life and surface roughness. By using the Pareto principle only 20% of the total machining configuration is needed to generate 80% of the benefit of completing all machining test configurations. The Pareto ANOVA identified which cooling method produced the optimum cutting processes, eliminating any effects that the different cutting speeds or feed rates may have on surface roughness, cutting force, cutting temperature, or tool life, and the results are presented in Tables 2 to 5. On examination of the surface roughness, the R_a value varies between 0.988µm (A0B2C0) and 6.98µm (A0B2C1) for cold air cooling, with MQL producing the lowest R_a value 0.596μm (A1B0C0). A response graph illustrating the influence of the machining parameters on the surface roughness is presented in Figure 3. This clearly shows that the feed rate parameter (C) has the most significant effect on surface roughness, followed by cooling method (A) and then cutting speed (B). The interaction between B x C from previous research has shown to be the major contributor to effect the machining process in producing the best surface finish [19]. In these tests the interaction of A x C was the optimum combination to achieve a low surface roughness. The combination to produce a low surface roughness was, therefore, A0B1C0 (i.e. cold air, cutting speed of 150 m/min, and feed rate of 0.11 mm/rev). The Pareto ANOVA for surface roughness given in Table 2 confirmed that the feed rate influences the mean surface roughness, at most 47.15% with the cooling contributing 23.55% to the surface finish. All other parameters, both individual and their interactions, had minimal effect on surface roughness.

Table 2. Pareto ANOVA analysis for surface finish.

<table>
<tr><th rowspan="2">Sum at factor level</th><th colspan="9">Factor and interaction</th></tr>
<tr><th>A</th><th>B</th><th>AxB</th><th>AxB</th><th>C</th><th>AxC</th><th>AxC</th><th>BxC</th><th>BxC</th></tr>
<tr><td>0</td><td>24.88</td><td>32.25</td><td>32.02</td><td>30.71</td><td>16.49</td><td>32.84</td><td>31.83</td><td>33.28</td><td>24.95</td></tr>
<tr><td>1</td><td>27.26</td><td>28.89</td><td>34.24</td><td>29.09</td><td>32.43</td><td>40.55</td><td>31.83</td><td>28.79</td><td>36.18</td></tr>
<tr><td>2</td><td>46.01</td><td>37.02</td><td>31.89</td><td>38.35</td><td>49.23</td><td>24.76</td><td>34.48</td><td>36.09</td><td>37.02</td></tr>
<tr><td>Sum of squares of difference (S)</td><td>803.26</td><td>100.09</td><td>10.52</td><td>146.91</td><td>1608.60</td><td>374.04</td><td>14.05</td><td>81.42</td><td>272.43</td></tr>
<tr><td>Contribution ratio (%)</td><td>23.55</td><td>2.93</td><td>0.31</td><td>4.31</td><td>47.15</td><td>10.96</td><td>0.41</td><td>2.39</td><td>7.99</td></tr>
<tr><td></td><td colspan="9">
</td></tr>
<tr><td>Cumulative contribution</td><td>47.15</td><td>70.70</td><td>81.67</td><td>89.65</td><td>93.96</td><td>96.89</td><td>99.28</td><td>99.69</td><td>100.00</td></tr>
<tr><td colspan="2">Check on significant interaction</td><td colspan="8">AXC two-way table</td></tr>
<tr><td colspan="2">Optimum combination of significant factor level</td><td colspan="8">A0B1C0</td></tr>
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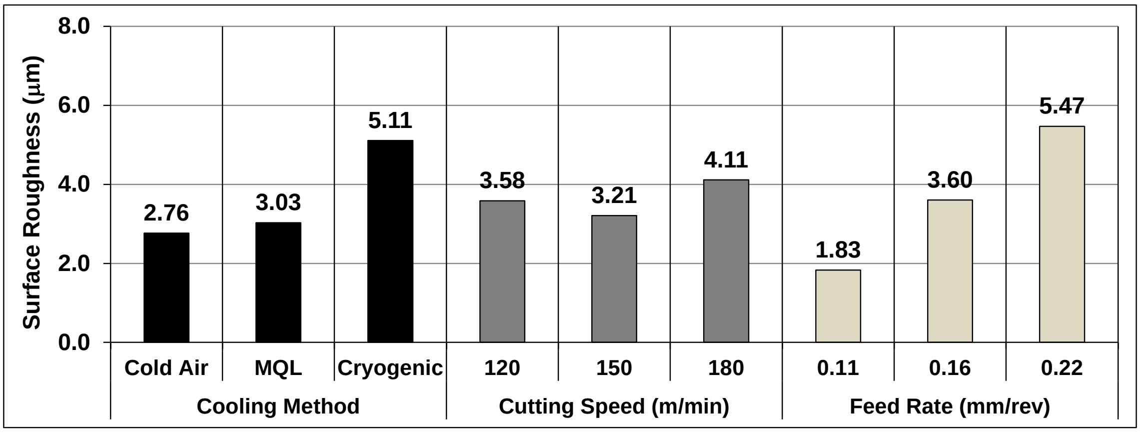
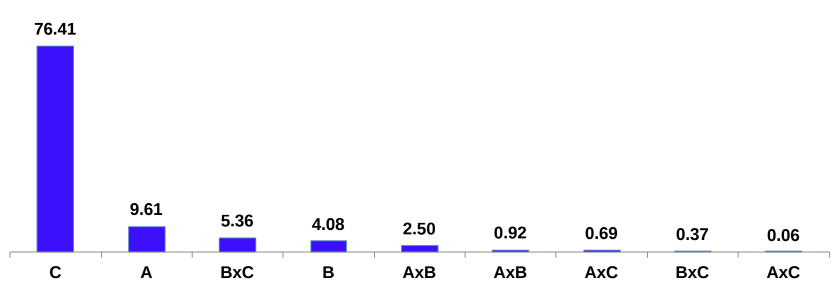


Figure 3. Effect of cutting parameters on surface finish.

Inspection of the cutting force data presented in Figure 4 and Table 3 showed the influence of the machining parameters on the cutting power. It is clear again that the feed rate parameter (C) and the cooling method (A) are the dominant factors. The Pareto ANOVA for cutting force given in Table 3 confirmed that the feed rate accounts for 76.41%, with the coolant contributing a meagre 9.61% to the cutting process. All other parameters, both individual and their interactions, had minimal effect on the cutting power. The optimal combination to achieve lowest cutting force was, therefore, A2B1C0 (i.e. cryogenic cooling, cutting speed of 150m/min and feed rate of 0.11mm/rev).

Table 3. Pareto ANOVA Analysis for Cutting Force.

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	4121.33	4230.00	4353.33	3960.00	3034.67	4120.00	4234.67	4514.00	4226.00
1	4678.33	3908.00	4173.00	4396.33	4086.00	4156.00	4212.33	4238.00	4110.67
2	3815.00	4476.67	4088.33	4258.33	5494.00	4338.67	4167.67	3862.67	4278.00
Sum of squares of difference (S)	1149433.56	487910.22	109913.56	298433.56	9136086.22	82478.22	6982.89	641286.22	44006.22
Contribution ratio (%)	9.61	4.08	0.92	2.50	76.41	0.69	0.06	5.36	0.37
									
Cumulative contribution	76.41	86.02	91.39	95.47	97.96	98.88	99.57	99.94	100.00
Check on significant interaction		BXC two-way table							
Optimum combination of significant factor level		A2B1C0							

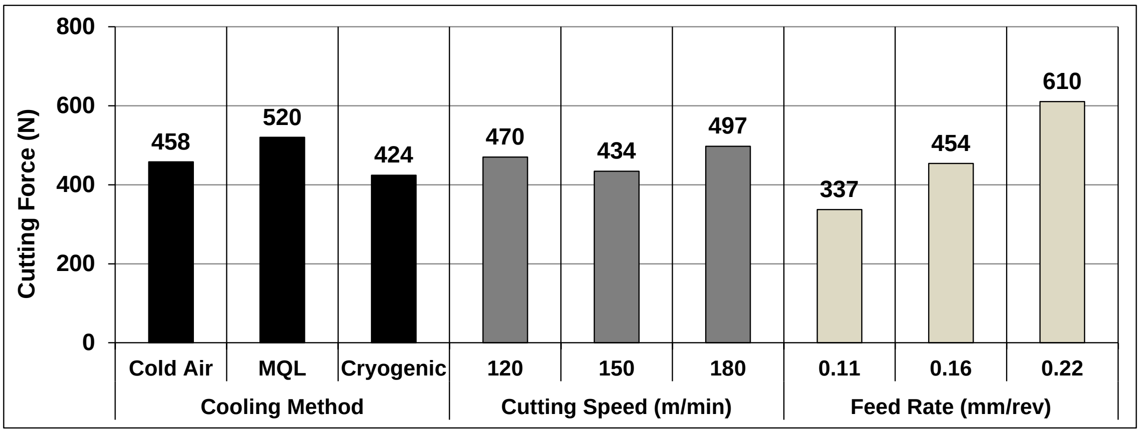
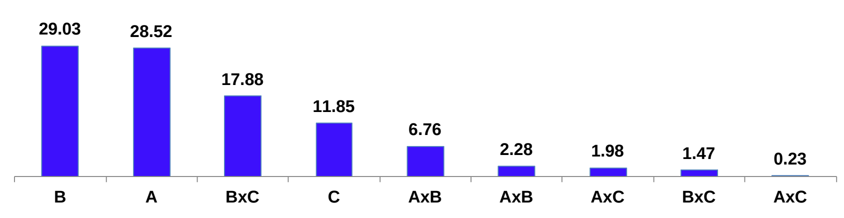


Figure 4. Effect of cutting parameters on cutting force.

The tool tip temperature data shown in Figure 5 illustrates that the influence of the feed rate has minimum effect on changing the temperature, with the feed rate only contributing 11.85% (C). The cutting speed (B) and cooling method (A) are near equal and are the main contributing factors for the tool tip temperature. The Pareto ANOVA for cutting temperature is given in Table 4 showing that the coolant contributes 28.52% to the cutting process, and the cutting speed contributes 29.03%. This identifies that the appropriate cooling method is relevant in obtaining a sustainable machining process. The optimal combination found to achieve lowest temperature was A2B1C0 (i.e. cryogenic cooling, cutting speed of 150m/min and feed rate of 0.11mm/rev).

Table 4. Pareto ANOVA analysis for cutting temperature.

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	4839.28	4691.49	5119.90	4665.48	4637.60	4810.19	5008.44	5375.99	4998.65
1	5539.12	4594.51	4920.91	5174.20	4901.81	4959.56	4915.41	4960.83	4816.70
2	4484.55	5576.94	4822.13	5023.26	5323.53	5093.19	4939.09	4526.12	5047.59
Sum of squares of difference (S)	1727712.92	1758581.84	138021.13	409585.50	718154.43	120263.45	14024.71	1083610.72	88815.70
Contribution ratio (%)	28.52	29.03	2.28	6.76	11.85	1.98	0.23	17.88	1.47
									
Cumulative contribution	29.03	57.54	75.43	87.28	94.04	96.32	98.30	99.77	100.00
Check on significant interaction			BXC two-way table						
Optimum combination of significant factor level			A2B1C0						

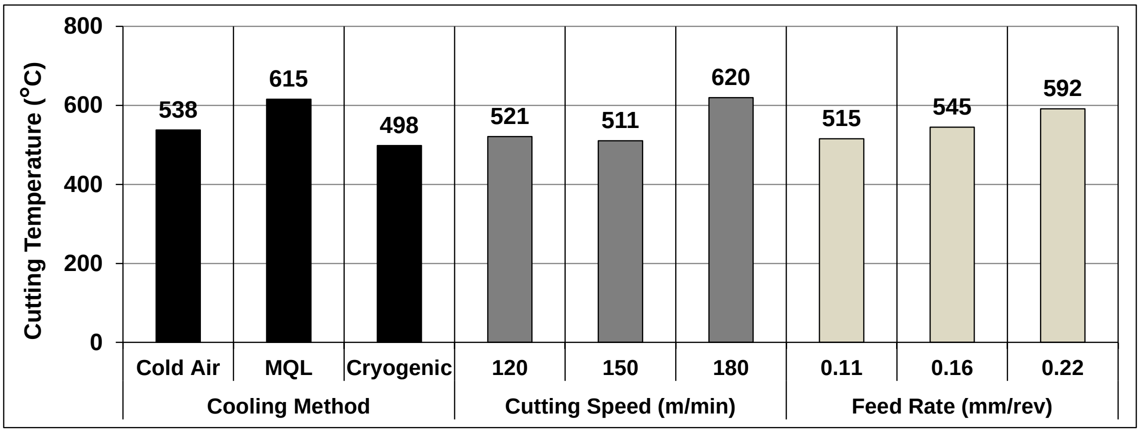
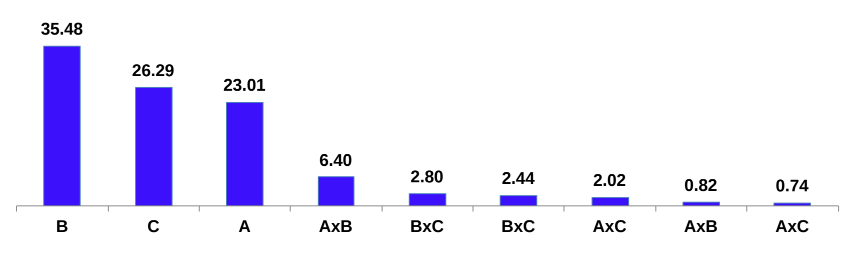


Figure 5. Effect of cutting parameters on tool tip temperature.

The data presented in Table 5 shows the influence all the machining parameters have on the tool life. Here all the cutting parameters have a contribution to make, with (C) the feed rate and temperature not being as dominant as previously shown, as in Table 2 and 3. Pareto analysis indicates that the feed rate (C) and (A) the cooling method, are near equal factors for tool life. The Pareto ANOVA for tool life given in Table 6 shows that the feed rate now only accounts for 26.29%, with the coolant contributing 23.01% and cutting speed contributing 35.48% to the cutting process. All other parameters, both individual and their interactions, had minimal effect on the tool life. The optimal combination to achieve longest tool life was, therefore, A2B0C0 (i.e. cryogenic cooling, cutting speed of 120m/min and feed rate of 0.11mm/rev).

Table 5. Pareto ANOVA analysis for tool life.

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	652.40	1877.60	1114.40	806.40	1786.00	1031.20	968.60	1280.20	1348.40
1	1023.60	1042.20	1052.20	1262.40	1026.80	1167.00	1157.60	1224.60	1008.80
2	1748.20	504.40	1257.60	1355.40	611.40	1226.00	1298.00	919.40	1067.00
Sum of squares of difference (S)	1863612.24	2872800.24	66564.24	517986.00	2128626.96	59869.68	163937.52	226415.04	197901.36
Contribution ratio (%)	23.01	35.48	0.82	6.40	26.29	0.74	2.02	2.80	2.44
									
Cumulative contribution	35.48	61.76	84.78	91.17	93.97	96.41	98.44	99.26	100.00
Check on significant interaction			AXB two-way table						
Optimum combination of significant factor level			A2B0C0						

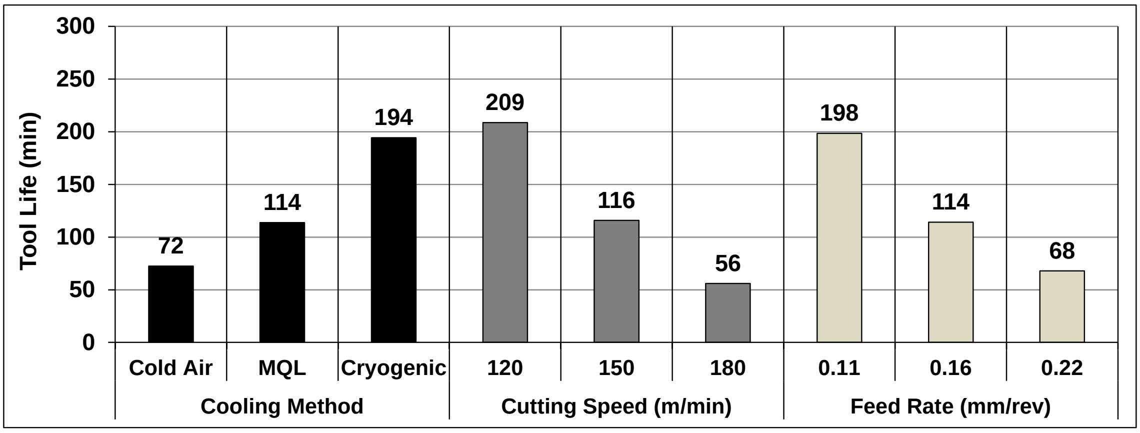


Figure 6. Effect of cutting parameters on tool life.

4. Discussion

Experimental investigations by S.M. Yuan *et al.* [20] of air cooling when machining Ti–6Al–4V alloy found that the addition of a small amount of oil has led to better surface finish and tool life compared to dry, wet or MQL.

The wear mechanism specific to titanium alloys, is called “chemical crater wear”. Chemical crater wear is caused by the chemical affinity between the carbide of the cutting tool and the titanium workpiece [21]. This chemical reaction weakens and eventually damages the carbide tip at higher temperatures. In addition, the low thermal conductivity accelerates the temperature rise at the cutting zone, as will any increase in the cutting speed. These wear reactions make efficient cooling of the tool essential to prolong tool life.

The energy consumption during the machining process is important, due to the fact that the lower the power consumed in the manufacturing process, the smaller the carbon foot print of the product. Figure 8 is typical of the graphs for power usage during the machining tests for the different feed rates used. The trend identified from the power data was as expected, i.e. the higher the feed rate the more power is needed. This confirmed the relationship for the cutting force (due to the cutting speed and feed rate) and power for these cutting tests. From Table 3 the cooling method (A) accounted for 9.61% contribution, effecting a reduction on the cutting force, indicating that the colder the tool interface, the less power is required. From a sustainability point of view, power consumption is the main concern in the manufacturing industry. This will gain even more importance when countries implement carbon tax in the future.

The compressed air supply to the VT and MQL was measured at 198 SLPM which accounts for 761W of energy used by the compressor. For simplicity it was assumed that the LN_2 evaporated linearly with time resulting in an average of 0.24kg of LN_2 evaporating per minute during the testing. The energy consumed for its production can be estimated at 0.5 kW hr/kg taken from C. Knowlen. *et al.* [22]. This has been based on suppling LN_2 from a large production facility. For 10 minutes of cutting the energy consumed would be 720W, and the cost of suppling LN_2 from BOC was AU$1.53 / litre in (August 2015).

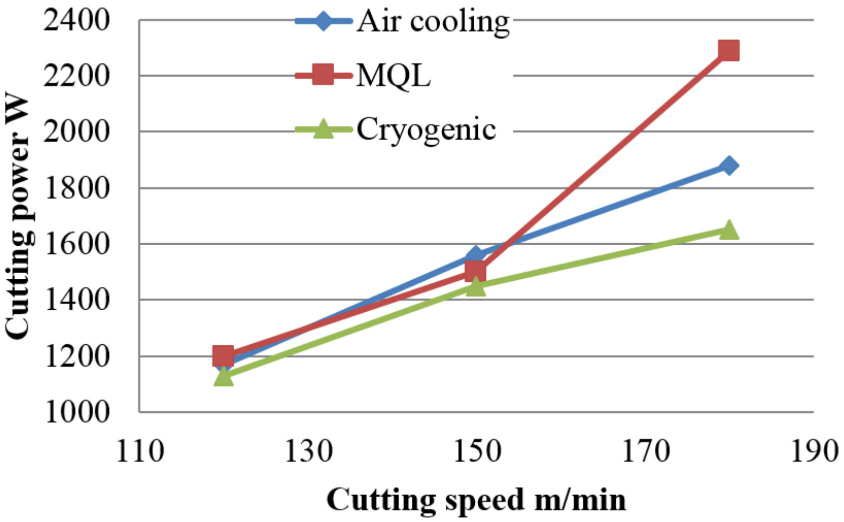


Figure 8. Measured cutting power at a feed rate of 0.22 mm/rev

It is now obvious from the power data recorded during the cutting tests that the optimum cutting parameters are important to reduce the power foot print of machining titanium alloy. However, it is apparent that removing traditional coolant is the best option since it would provide the largest reduction in carbon foot print, as changes to the other parameters are limited.

Finding the optimum cooling method and reducing the power consumption will greatly reduce the manufacturing cost. It is apparent that the higher the cutting speed, the more power is required for machining. The highest power is when using MQL. It was observed that the cutting power consumed in air cooling is nearly as low as in the cryogenic cooling method. In air cooling the power consumption is only 2-7% higher than cryogenic cooling. Contrasting using MQL with air cooling shows a reduction in the power consumption by nearly 26%, at the cutting speed of 120m/min (B0), with a feed rate of 0.16mm/rev (C1) and 0.22mm/rev (C2). Therefore, from the cutting power consumption point of view, implementing air cooling at the feed rate of 0.11mm/rev (C0) is highly recommended.

4.1. Effect on chip formation

Chip formation allows a comparison to be made of the cooling methods for the same cutting parameters by observation. The length of the chips can show how effective the chip breaking is for different cutting conditions while machining. Figure 8 shows the overall length of the chips generated for air cooling, MQL and cryogenic cutting condition. The length of the chips generated by air cooling and cryogenic cooling conditions were similar, but the air cooled chip produced a coiled spring like shape. This suggests that the temperature and plasticity of the chips is higher than when being cooled by LN_2. For all the cooling methods the effectiveness of the chip breaker was inadequate, as shown by the chips.

Figure 8. Chip formation for varying cutting speeds and cooling methods.

Chips generated when using MQL cooling become crinkly and roll into a ball, with the overall length of the chips, if unwound, being significantly longer than that of air cooling or cryogenic cooled chips. This indicates high plasticity and a higher temperature, with the chip shear force not being large enough to break the chip. The difference of the overall length of the chips generated from air cooling and cryogenic cutting condition is more noticeable as the cutting speed increases. The overall length of the cutting chips from air cooling was 11% longer than that of cryogenic cooling. The shortest overall chip length was obtained while machining the titanium alloy under cryogenic cooling. The chip breaking effect is completely lost with MQL cooling (as shown in Figure 9) where a metal like wire ball is formed. This was caused by the high cutting speed leading to plastic deformation at the shear zone, caused by the large amount of heat produced, with poor cooling. In contrast, the chips generated in air cooling or cryogenic cooling were shorter, as the heat at the cutting zone was dissipated more efficiently. The overall length of the cutting chips from air cooling cutting conditions were 32% longer than that in cryogenic cooling. The chip breaking of the cutting chips while machining titanium alloy is very important. Machining titanium alloy using MQL cooling, at high cutting speed adds to the fire hazard, since fire can occur at the cutting zone, causing the ball like metal swarf to ignite. This danger is always present, with fine cuttings and high cutting temperature as the chips retain the heat. Unlike the lower temperature produced by air cooling or cryogenic cooling which made the cutting chips become brittle and easy to break due to chip stress.

Figure 9. MQL cooling encouraging poor chip breaking at higher cutting speed.

4.2. Cooling effect on tool wear

This research found the formation of built up edges affects the surface quality of the machined component at lower cutting speeds. At higher cutting speeds the effect of the formation of built up edge is not noticed. The flank wear and tool crater depth for different cutting parameters and cooling conditions are shown in Figure 10. The level of flank wear under air cooling and cryogenic cooling was very similar. It was apparent that the flank wear was significantly increased using MQL at the cutting speed of 120 m/min and comparing it with cold air and LN_2. There was slight discolouration on the tool insert after machining, with air cooling at a cutting speed of 150m/min. Discolouration affected MQL cooling most, while there was little or no discolouration on the tool insert when cryogenic cooling was used. This indicated that the heat dissipation by cryogenic cutting condition was better than that of air cooling condition. MQL cooling, the heat generated in the machining operation was dissipated inefficiently.

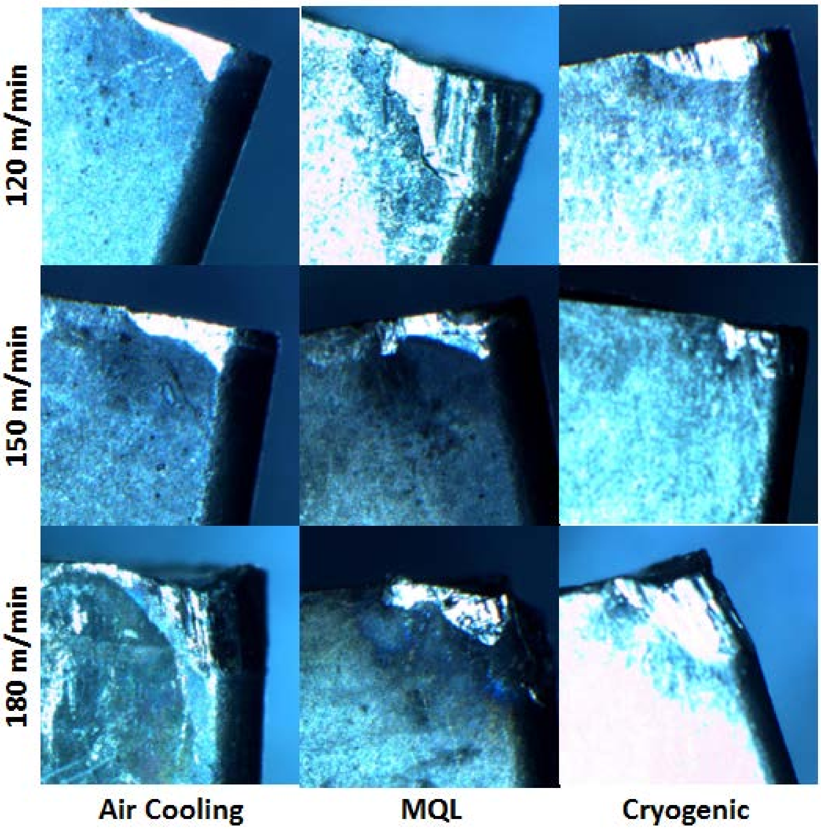


Figure 10. Tool wear for varying cutting speeds and cooling methods.

Machining titanium alloy at a high cutting speed of 180m/min caused substantial crater and flank wear to the tool tip with air cooling and MQL cooling. Crater wear on the tool tips caused by the chemical affinity between the carbide tool tip and the titanium workpiece was observed to be higher when MQL was used. The chemical reaction which weakens and eventually damages the carbide tip is shown to react faster as the temperature at the cutting zone becomes higher.

4.3. Future of sustainable machining of titanium alloys

Reviewing the current practices of machining titanium alloys has revealed that this material, although considered a hard to machine material, can be machined quite efficiently when the correct machining parameters are used. In most cases has been found by trial and error. Future research investigates what the best machining parameters are with respect to sustainable machining practices. This fundamentally means the removal of the traditional cutting fluid and replacement with an environmentally friendly method. The research in this paper discussed three distinct methods where no traditional coolant was used, each providing different performances. Cold air is the best practical option to use, as it provides the necessary cold with no undue safety requirement and minimum cost axillary equipment. Future research needs to investigate the most optimum energy efficient method of providing sustainable cold air.

5. Conclusion

The main environmental burden for machining is due to the energy consumption of the machine tool which is unavoidable [23]. This means the only option available is to reduce the energy foot print of the cutting parameters, with the liquid coolant being the only applicable parameter. The flood fluid parameter was also identified in its own right as a major environmental burden and needs to be eliminated where possible. Cold air was found to provide the best surface finish for most of the cutting speeds compared to cryogenic cooling or MQL. Since the surface roughness is a critical priority for TI-6AI-4V workpieces, this would suggest air cooling to be the best option. Unfortunately, cold air provides the shortest tool life, with MQL cooling having a 37% increase over air cooling, and cryogenic cooling resulting in an increase of 63% over cold air. Obviously LN_2 is most likely the best cooling method if tool life alone is the criteria used. Tool life for cold air would have been improved in these tests if colder air had been produced from the vortex tube, air as cold as -50^0C is possible when a suitable air pressure is available. The cutting tests showed that even though air cooling temperatures were not as low as LN_2, the cutting performance was not significantly different. Taking into account environmental considerations, LN_2 is no longer the winner, as the cost of producing LN_2 is significantly higher than providing compressed air. Cryogenic cooling is more difficult to use than cold air and cold air generation also has a smaller carbon footprint than LN_2. Therefore, for sustainable machining, the recommendation for the TI-6AI-4V workpiece is to implement cold air cooling at a cutting speed of 150 m/min with DOC of 1mm, and feed rate of 0.22 mm/rev as the optimum cutting conditions (A0B1C0).

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