AN OVERVIEW OF ADVANCED COOLING TECHNIQUES FOR TITANIUM ALLOY MACHINING IN AEROSPACE

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ABSTRACT

Titanium is classified as a difficult to machine superalloy. Its low thermal conductivity causes a concentration of heat in the tool. It causes cutting tools to overheat during machining, that leads to increased machining cost. However, recent advances in cooling technology in aerospace manufacturing, specifically the combination of through spindle cooling and split tools, is claimed to yield improved Ti-6AL-4V machining productivity. The development was led by a tool supplier placing a premium on confidentiality. The result is as this technology has only recently been released into the market, rather little if any performance studies have been published in scientific literature.

The paper investigates the potential machining benefits of through spindle cooled split tools for Ti-6AL-4V milling. The geometry, coolant flow and operational characteristics of the split tools are described. The performance of other more conventional cooling methods such as a nozzle directed high pressure coolant stream is presented from literature. The investigation includes test results of split tools. In conclusion an application domain is discussed where the technology offers improvements over existing technologies.

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INTRODUCTION

The price of titanium can be up to 9 times more than steel due to a considerably more demanding process from ore to component [1]. Melting is done in either a vacuum or an inert atmosphere at nominally 1600 degrees Celsius compared to steel melting at nominally 1500 degrees Celsius in a normal atmosphere environment [2] [3] [4]. Similarly machining properties are also challenging, classifying titanium as a difficult to machine super alloy [5]. The machining of titanium alloy generates a large amount of heat, close to the cutting zone. This heat is the primary cause of tool failure, be it directly or indirectly. A number of cooling strategies have therefore been investigated by researchers [6].

The most common and extensively studied cooling strategies are dry cutting, flood cooling, high pressure cooling and through spindle high pressure cooling. The strategy and technique used depends on the material and parameters surrounding the machining process.

Recent advances in cooling technology for aerospace manufacturing, specifically the combination of through spindle cooling and split tools, is claimed to yield improved machining productivity for difficult-to-machine materials.

New advancements are highly specialized as they are usually made in-house by means of a partnership between the manufacturer and the tool supplier with a high premium on confidentiality. The cooling methods are designed for very specific applications within the production process and usually comprises a finely tuned hybrid between some of the aforementioned conventional cooling systems [7].

The result is that these technologies have only recently been released into the market, rather little if any performance studies have been published in scientific literature.

OVERVIEW OF CONVENTIONAL COOLING METHODS

2.1 Flood Cooling

Flood cooling using soluble oil is the most commonly used cooling method in industry. Flood cooling, best described as an uninterrupted flow of an abundant quantity of coolant, removes chips by a flushing action. With flood cooling, thermal shock on milling tools are minimized and the ignition of chips eliminated [8] [6].

![Figure 1: Extreme directional effects of flood cooling [6].](image)

This method is often a benchmark for experiments due to its extensive use in standard machining applications. Flood cooling is however insufficient in some cases, one of which is titanium machining.

Flood cooling is not based on the principle of precise directional application of the coolant stream. Two extreme cases are shown in Figure 1. In the most extreme case, where titanium’s short contact area between chip and tool is approximated, the chip prevents the
coolant from being applied to the tool chip interface (b). The cutting edge therefore experiences a large thermal load resulting in poor tool life [6].

2.2 High Pressure Cooling

High pressure cooling became the norm in industry as soon as flood cooling methods were found less effective for high speed machining of hard metals. During high speed machining the performance levels of modern machinery generate so much heat that normal flood cooling is unable to remove chips quick enough and pierce through the vapour barrier. As a result long, thick and unmanageable chips form [9].

The Leidenfrost phenomenon can be observed in cases where a vapour barrier is formed. In Figure 2, Bernardin and Mudawar’s time based graph for initial vapour barrier formation versus time [10] is depicted. This initial barrier “film boiling regime” prohibits the flood coolant to come into contact with the hot tool-chip interface as the vapour barrier persists [9] [10]. The only way in which to penetrate and remove the vapour barrier is to use high pressure (HP) nozzles to direct coolant at the hot surface. High pressure cooling also enables the formation of short chips. This prohibits the re-cutting of chips, increasing tool life [9].

Ezugwu et al. [11] found that high pressure cooling demonstrates the potential for improvements in tool life when machining Ti-6Al-4V with cemented carbide (coated and uncoated) tools at higher cutting speeds. Figure 3 illustrates notable tool life enhancement under high pressure, compared to flood cooling methods [11]. Particular attention to the greater potential of the high pressure over flood cooling should be noted, specifically at higher cutting speeds. Tool life usually increases with higher coolant pressures [11] as the cutting speed increases.
At a cutting speed of 110 m/min (Figure 3) the highest pressure of 203 bar yields approximately double the tool life compared to 110 bar pressure and an approximate three times increase in tool life compared to flood cooling. However, a cutting speed of 120 m/min has a variance in tool life of less than 5% between 203 bar and 110 bar cooling pressure, compared to 110 m/min [12], therefore making the supposed direct relationship between pressures and cooling effectiveness questionable.

2.3 Near Dry Machining with Oil based Lubricants

As industry moves toward greener manufacturing processes, the minimal quantity of lubricant technique (MQL) is being implemented in cases where the waste oil by-product of machining is undesirable [13] [14] [15]. The minimal quantity of lubricant technique employs a pressured air nozzle to deliver a small amount of oil mist to the cutting surface thereby substantially reducing the amount of cutting fluid required for machining operations.

In an attempt to improve the current minimal quantity of lubricant technique, Aoyama et al. [16] argues that it has two major disadvantages for consideration: Due to the absence of the hydraulic pressure of pressurized coolant, the chip removal ability of the minimal quantity of lubricant technique is limited. Furthermore, the minimal quantity of lubricant technique results in the work area being covered in oil due to the fine oil mist. It causes machine problems, slippage on affected surfaces and inhalation of hazardous oil mist [16].

Aoyama et al. [16] proposes an improved system: “Direct Oil Drop Supply system (DOS)”, to counteract the oil mist problem of the minimal quantity of lubricant technique. During the operation of this system, pressurized oil drops are supplied to the nozzle via a 0.4 MPa gear pump.
Compressed air is also exhausted from the circular slit surrounding the oil discharge hole in order to direct the oil mist to the cutting surface. The pressurized air serves both as chip removal mechanism and also contains the oil drops inside a high speed air barrier. During experimentation it was found that the nozzle in Figure 4 did not deliver oil to the entire cutting surface effectively and a second derivate nozzle was designed.

The subsequent design (Figure 5) comprises four small air flow pipes to deliver air flow to the cutting point more directly while still separating the oil and air. The oil delivery nozzle is located in the centre of the four surrounding air supply nozzles.

Figure 6 illustrates the measured temperatures at the cutting surface for Ti-6Al-4V with a 10mm Carbide square end mill. Cutting speed set at 150m/min, depth of cut 6mm and radial depth of cut at 0.5mm. Results indicate little difference in temperature between the minimal quantity of lubricant technique and the direct oil drop supply system. Aoyama et al. reported an 80% reduction in oil mist diffusion around the machine [16].

Yuan et al. [17] found that although the minimal quantity of lubricant technique significantly reduces cutting force, tool wear and surface roughness, it cannot produce evident effect on cutting performance. As a result flaking wear on the flank surface of the insert was found under certain experimental conditions.

Additionally, another major disadvantage of this experimental technology is the degree of customization that is required to install a minimal quantity of lubricant technique system or direct oil drop supply system. Machine modification setups can be complex and expensive.

2.4 Liquid Nitrogen Cooling

Liquid nitrogen (LN₂) as a coolant has been used in a number of studies. In certain cases, it has been conclusively proven that when utilized correctly; it improves tool life, surface finish and dimensional accuracy [18] [19].
Wang et al. [20] compared conventional cooling and LN$_2$ cooling during turning of Ti-6Al-4V for a cutting speed of 132m/min$^{-1}$, feed rate of 0.2 mm/rev$^{-1}$ and depth of cut of 1 mm. Experiment results indicated that with conventional cooling, flank wear was increased 5 times as compared to LN$_2$ cooling.

In contrast to this, Nandy and Paul (2008) [21] found that high pressure cooling outperformed cryogenic cooling by two fold when comparing tool wear. Further experiments by Bermingham et al. (2011) [22] supports Nandy and Paul’s finding.

Although both of the aforementioned papers found that high pressure cooling resulted in improved performance over cryogenic cooling, improvements are marginal. Turning of Ti-6Al-4V is used as comparison for all 3 experimental sets. The discrepancies between the respective findings can be attributed to differences in coolant delivery mechanisms.

![Figure 7: Flank and Nose wear during turning of Ti-6Al-4V [22].](image)

Birmingham et al. experimented with 4 different coolant delivery systems (Note D1-4 postfix for tests in Figure 7), that generated different results.

Cryogenic cooling reduces tool wear during higher speed turning operations (125m/min) while performing slightly inferior to high pressure cooling at lower machining speeds [20] [21] [22]. Evidence therefore suggests that there are high speed application possibilities for cryogenic cooling.
2.5 High Pressure through Spindle Cooling

High pressure through spindle cooling (HPTSC) has been a reality since 1994 when it was first patented by Du et al. [23]. This, nearly 20 year old technology has directly led to the removal of the external cooling pipe and nozzle in the design of modern high pressure cooling systems.

During high pressure through spindle cooling, coolant is delivered to the work surface by means of a channel inside the tool clamp and/or cutter body. The coolant is directed at the workpiece through tiny nozzles that are mounted close to the insert cutting edge [9].

![Figure 8: (a) CoroTurn HP - HPSTC system delivers coolant directly onto the cutting edge. (b) HPSTC application for Hyundai’s WIA drilling tool body.](image)

High pressure through spindle cooling seems complex and requiring high cost to implement. It is viewed superficially, but tool manufacturers maintain that it provides unrivalled advantages: Rapid tool changes, better chip control, increased tool life for difficult to machine materials, 50% increase in cutting capability at the same cutting parameters and 20% cutting speed increase for aerospace materials such as titanium and nickel alloys [9]. Although this method requires high pressure through spindle cooling capable machines, some tool manufacturers such as MAG provide through spindle cooling retrofit kits for certain machine models [24].

Dimitrov et al. [12] performed a number of milling experiments in order to compare high pressure cooling with high pressure through spindle cooling. During the experiments, single layer coated, multi-layer coated and uncoated inserts were compared for both cooling methods. It was found that when coated tungsten carbide cutting tools are used, improvements in flank wear under the concept of high pressure through spindle cooling are realised. Experiments indicated that the multi layered coating performance was the lowest and showed no benefit from pressurised cooling or high pressure through spindle cooling. Uncoated inserts showed clear benefit from high pressure through spindle cooling, yielding considerably lower values of uniform wear during the earlier part of the insert’s life.

2.6 Cutting Fluids

Cutting fluids in general serve two major roles in machining namely cooling and lubrication [25] [26]. The flow of cutting fluid also aids in the removal of chips, minimise thermal shock in milling operations and keeps chips from igniting. When high pressure cooling methods are used, chips are often small and discontinuous as shown in Figure 9.

Cutting fluids can be divided into three major categories: neat cutting oils, soluble oils and gaseous cooling. Each of these categories has their own characteristic application. Neat
cutting oils are mineral oils that may contain additives. They are primarily used when the pressures between the tool and chip are high and when lubrication is a primary concern. Water soluble coolants are suitable when cutting speeds are high and tool pressures are low. It has however been found that cutting fluids do not penetrate the tool-chip interface when cutting speeds are high [26]. Here gaseous coolants can be utilised to overcome coolant penetration difficulties. The high cost of gases does however limit their use.

![Figure 9: (a) Long continuous chips (b) Short and discontinuous chips.](image)

When a work piece is overcooled, it will become harder and tougher, resulting in reduced tool life [27]. Overcooling can also deteriorate the surface finish and dimensional accuracy of the work piece in severe cases.

Cutting fluids may cause environmental, health and logistical problems. Typical environmental problems are chemical breakdown resulting in water and soil contamination. Operators may experience dermatological ailments due to prolonged exposure. Government regulations are strict about disposal procedures. This results in high transportation costs to disposal sites [18]. Nitrogen composes approximately 78% of our earth’s atmosphere, and because liquid nitrogen evaporates to nitrogen gas when used, it is considered environmentally friendly [11] [18] [19]. No operator ailments have been reported with regard to nitrogen.

3 SPECIALIZED COOLING TECHNIQUES IN INDUSTRY

It is common to find manufacturers employing technologies that are on a more advanced level than those published in open, academic literature. This is due to the limitations on intellectual property within the industry. This especially the case with unique specialist applications.

3.1 Cryogenic Through Spindle, Through Tool Cooling (MQL)

During the production of titanium alloy components for the F-35 Lightning II fighter jet, through spindle cooling, using liquid nitrogen has resulted in a 10 times improvement in cutting tool life for Lockheed Martin [28]. Another example is of MAG machine tool and systems, which uses an internally developed through spindle liquid nitrogen cooling system in all machine shops. It has a positive effect on life cycle costs due to reduction in cycle times, total number of machines required and increases in tool life [7].
Marketing media may indicate what is being accomplished by these new technologies, but not how these processes precisely work. However, as is the case with MAG, these technologies are slowly making their way to the market [29].

Figure 10: Cryogenic minimum quantity lubrication & through spindle cooling system [29].

MAG’s technology combines liquid nitrogen cooling with through spindle cooling for machining of difficult-to-machine materials (Figure 10). Such is the case with their MQL liquid nitrogen system that is said to provide a 60% speed increase in the milling of compacted graphite iron with carbide and four times using Polycrystalline Diamond tooling [30]. Full commercialization of the technology is due. The benefits for cryogenic machining aren’t only economic or operational. In terms of environmental friendliness, there is no mist collection, filtration, wet chips, contaminated workpieces or disposal cost and less energy consumption without all the pumps, fans and drives that go into handling coolant [30].

Figure 11 graphically depicts the warmest and coldest areas on the tool/workpiece interface the temperature scale is indicated on the left. The measured temperature for the cutter is -32 °C, while the hottest area is measured to be 82 °C. MAG’s cryogenic cooling technique is able to concentrate the cooling in die body of the cutter. Early experimental tests indicate that through tool cooling provides the most efficient heat transfer model and consumes the least amount of liquid nitrogen.

Figure 11: Infrared thermograph of spindle and workpiece temperature gradients [29].

MAG expects 4 times increase in processing speed for milling compacted graphite iron with Polycrystalline Diamond inserts. In addition, the cryogenic through tool cooling is claimed to provide twice the tool life, compared to minimum quantity lubrication.
3.2 Through Spindle Cooling with Split Tool Inserts

The Kennametal Company pioneered through spindle cooling with split tools inserts in 2010 (Beyond Blast). This came as a result of Boeing’s pre 2010 market research that indicated that there would not be enough titanium alloy machining capacity in the world during peak requirement for the new 787’s as 80 to 90 percent of the material needs to be machined away for aerospace parts [31].

Kennametal’s Beyond Blast split tool technology is similar to MAG’s through tool cooling, with the exception being the type of coolant that is utilized. This method, dubbed Precision Coolant Technology (PCT) differs slightly from MAG’s system in that it employs high pressure coolant to flow through the cutter body and eject from the split tool inserts instead of cryogenic coolant (Figure 12).

Beyond Blast Precision Coolant Technology is available for milling and turning operations. Kennametal claims that it offers a cost reduction over conventional high pressure cooling methods, due to the insert that directs the coolant precisely where it is needed.

Figure 12: Kennametal's Beyond Blast technology delivers high pressure coolant through split tool inserts for both milling (a) and turning (b) operations [32].

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Figure 13: Infrared representation of tool-chip interface for turning with typical cooling (a) vs. through insert cooling (b).
Cooling applications often miss the highest heat concentration location, generated at the shearing point (Figure 13). Impacting chips after they have formed proves typical cooling applications can even force chips back into the cut, accelerating tool wear. Part of the challenge is that the coolant-delivering nozzle is located relatively far from the workpiece.

With a split tool delivery system (Figure 13 (b)), coolant is delivered through the insert, at the cutting interface. Coolant is therefore delivered much closer to the shear point, causing pressure to remain stable. Delivery is therefore more reliable and controlled, significantly reducing temperatures at the point of the cut [32] [33].

Kennametal’s KSRM tools for face milling applications are specifically aimed at large material removal rates. The KSRM tools employ round insert split tool technology with high pressure through spindle cooling. The cutter bodies for KSRM have up to 8 positions for indexable inserts. The inserts are channelled to precisely (Figure 14) direct the flow of coolant into the cutting interface, where it helps with chip lifting, chip removal, lubrication, and increased heat transfer.

Round insert cutters have a continuously variable entering angle, depending upon the cutting depth and causes a chip-thinning effect, suitable for machining difficult-to-machine materials [34]. Modern insert geometry developments have made the round insert milling cutters more widely suitable because of the smoother cutting action, requiring less power and stability from the machine tool. Today, it is not a specialized cutter anymore and should be regarded as an efficient roughing cutter, capable of high material removal rates [34].

Figure 14: KSRM features and benefits [32].

Kennametal benchmarked the Daisy Beyond Blast cutter body (split tooling) with T114526 and T117470 inserts, specifically designed for heavy roughing of Ti-6Al-4V and other difficult-to-machine materials. The cutting conditions for the experiments were:
Table 1: Kennametal Experimental Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpiece Material</td>
<td>Ti-6Al-4V</td>
</tr>
<tr>
<td>Number of inserts</td>
<td>5</td>
</tr>
<tr>
<td>Hardness</td>
<td>42-46 HRC</td>
</tr>
<tr>
<td>Length of Pass</td>
<td>245 mm</td>
</tr>
<tr>
<td>Cutting Fluid</td>
<td>Water based synthetic</td>
</tr>
<tr>
<td>Coolant Pressure</td>
<td>1000 Psi (~70 Bar)</td>
</tr>
<tr>
<td>Cutting Speed</td>
<td>46 m/min and 58 m/min respectively</td>
</tr>
<tr>
<td>Chip Load (fz)</td>
<td>0.25 mm per tooth</td>
</tr>
<tr>
<td>Axial Depth of Cut (ap)</td>
<td>3.8 mm</td>
</tr>
<tr>
<td>Radial Depth of Cut (ae)</td>
<td>51 mm</td>
</tr>
</tbody>
</table>

Table 2: Experimental Results

<table>
<thead>
<tr>
<th>Material Removal Rate at 46 m/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table Feed</td>
</tr>
<tr>
<td>Vf = 183.03 m/min</td>
</tr>
<tr>
<td>Vc = 46.00 m/min</td>
</tr>
<tr>
<td>Fz = 0.25 mm</td>
</tr>
<tr>
<td>D = 100.00 mm</td>
</tr>
<tr>
<td>Z = 5.00 teeth</td>
</tr>
<tr>
<td>N = 146.42 RPM</td>
</tr>
<tr>
<td>MRR = 35.47 cm³</td>
</tr>
<tr>
<td>A0 = 3.80 mm</td>
</tr>
<tr>
<td>Ap = 51.00 mm</td>
</tr>
<tr>
<td>N = 146.42 RPM</td>
</tr>
<tr>
<td>Vf = 183.03 m/min</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material Removal Rate at 58 m/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table Feed</td>
</tr>
<tr>
<td>Vf = 230.77 m/min</td>
</tr>
<tr>
<td>Vc = 58.00 m/min</td>
</tr>
<tr>
<td>Fz = 0.25 mm</td>
</tr>
<tr>
<td>D = 100.00 mm</td>
</tr>
<tr>
<td>Z = 5.00 teeth</td>
</tr>
<tr>
<td>N = 184.62 RPM</td>
</tr>
<tr>
<td>MRR = 44.72 cm³</td>
</tr>
<tr>
<td>A0 = 3.80 mm</td>
</tr>
<tr>
<td>Ap = 51.00 mm</td>
</tr>
<tr>
<td>N = 184.62 RPM</td>
</tr>
<tr>
<td>Vf = 230.77 m/min</td>
</tr>
</tbody>
</table>

Figure 15: Beyond Blast Daisy round inserts vs. standard through spindle cooling.

Kennametal’s experiment results indicate that round insert split tooling delivers high material removal rates for Ti-6Al-4V roughing at 35.37 cm³/min and 44.72 cm³/min. Kennametal also reported (Figure 15) a 2.5 times tool life benefit over conventional through spindle cooling.
4 DISCUSSION

High pressure cooling provides better chip removal and penetration than flood cooling. In addition it breaks the vapour barrier and successfully cools hot work pieces during high speed machining. Experimentation shows that increased coolant pressure doesn’t result in increased performance in all aspects. There is a trade-off between coolant pressure and tool-life.

The direct oil drop supply system is an improvement on the minimal quantity of lubricant technique due to its use of water jets to reduce oil mist by 80%. Operational improvements are however incremental. The machining temperature of the direct oil drop supply system shows 4% improvement over dry machining and during experimentation flaking wear on the flank surface was observed. Minimal quantity of lubricant systems are cumbersome and relatively costly to install.

Liquid nitrogen holds potential for high speed machining applications. The effectiveness of this cooling method is dependent on the delivery system. As a result, more research and development from private companies has yielded products such as MAG’s cryogenic through tool cooling. The technology offers a 60% speed increase with 10 times increase in tool life due to the extraordinary low temperatures maintained at the tool and work piece (-32°C and 86°C respectively). However, this type of cryogenic machining is currently specialized, relatively costly and therefore more suitable for high volume production.

Kennametal’s round insert split tools (Beyond Blast) provide aggressive material removal rates for rough and semi smoothing face milling. Pocket milling tools are also available for intricate profile machining. During experimentation material removal rates of 35.37 cm³/min and 44.72 cm³/min at cutting speeds of 46 m/min and 58 m/min were observed. The use of round inserts causes a chip thinning effect that reduces cutting force and temperature. Round inserts in combination with the split tool cooling extends tool life by 2.5 times over other through spindle cooling applications. Kennametal’s choice to implement water based cooling with round insert split tools permits wider industry adoption. The cutter bodies are designed so that it is compatible with all milling machines that are capable of through spindle cooling.

5 REFERENCES


