THE EFFECTS OF COOLING AND CUTTING TOOL COATING ON TOOL WEAR DURING MILLING OF Ti6Al4V AND 40CrMnMo7

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ABSTRACT

In response to increasing climate change, the development and production of light weight structures in the aircraft- and automotive industry, has become a priority. This has increased machined component manufacture utilising various difficult-to-cut materials such as Ti6Al4V and 40CrMnMo7. In order to satisfy achieve business goals, there is a general urgency towards the reduction of machining time and -cost in the manufacturing industry. This has however led to demanding cutting parameters and higher process temperatures of the material during the machining process. In the pursuit for improved performance, there is a need to investigate alternative methods for effectively machining these materials. An important criterion during the processing of these materials is therefore their machinability.

This article investigates the high performance machining of Ti6Al4V and 40CrMnMo7. The properties that make the use of these materials advantageous in the aerospace- and automotive industry also make them difficult to cut and create various challenges. Ti6Al4V has a low thermal conductivity that causes heat to accumulate in the cutting zone. 40CrMnMo7, on the other hand, has a high stiffness which results in greater mechanical loading on the cutting edge. This has encouraged studies into cooling strategies and techniques to improve tool life and reduce the cost of machining of these materials.

This paper further investigates the application and effect of a coating (TiAlN) as well as various coating treatments under selected cooling conditions. A clear guideline is given for possible improvement and optimisation in milling operations, and creates a better point of departure for further studies.

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1 INTRODUCTION

Recent manufacturing technology developments in the machine tool-, aerospace- and automotive industries have increased the machining of components from difficult-to-cut materials, such as Ti6Al4V, and the new generation hardened steel 40CrMnMo7.

In general, the manufacturing industry endeavours to reduce machining time and machining cost, which has brought about higher cutting speeds, -feed rates, -cutting parameters and -process temperature during the machining process. This article investigates aspects of high performance machining (HPM) of Ti6Al4V alloy and 40CrMnMo7. Titanium's relative toughness, high strength and low modulus of elasticity (when compared to many steels) present demanding challenges in order to achieve a high material removal rate (MRR). The properties that make Ti6Al4V alloy and 40CrMnMo7 favourable for use in the tooling-, aerospace- and automotive industry also make them difficult to cut. When machining Ti6Al4V alloy, a large proportion of the heat is generated and concentrated on the tool’s cutting edge, which causes an increase of heat in the cutting zone. This is mainly caused due to Ti6Al4V alloy’s low thermal conductivity [1]. Therefore, the predominant problem during machining is caused by the direct or indirect heating of the cutting zone. It can therefore be deduced that the heat generated during the machining of these difficult-to-cut materials play a major role in determining the tool life.

It follows that cutting tools now require superior hardness, wear resistance, high strength, toughness and thermal stability when machining difficult-to-cut materials. Recent trends favour coated carbide systems [2]. Therefore, the overall aim is to optimise the machining process to establish how tool coating, coating treatment, and different cooling strategies or -techniques influence the cutting tool life during HPM of difficult-to-cut materials such as Ti6Al4V alloy and hardened steel 40CrMnMo7.

2 APPLICATION OF COOLING DURING MILLING

Thermal- and mechanical loading demands create fundamental challenges when difficult-to-cut materials are machined. The heat development in the cutting tool and workpiece, as well as the deformation zones in which the mechanical and the thermal demands develop are depicted in Figure 1 [3]. Machining difficult-to-cut materials produces excessive tool wear in the secondary deformation zone. In order to reduce wear, lower cutting speeds are used resulting in extended machining times and increased manufacturing costs [4].

The interrupted cutting process of milling intensifies the mechanical- and thermal loading on the cutting tool. The mechanical demands are largely influenced by the feed rate, whereas the thermal demands are proportional to and intensified by the cutting speed. These demands simultaneously apply load on the insert which intensifies the wear of the tool and introduces varying modes of tool failure [5,6,7,8].
Figure 1: The distribution and flow of heat and deformation in the cutting zone [3]

The initiation of tool failure can consist of one or a combination of wear modes. These modes lead to overloading or fatigue of the tool which can lead to catastrophic tool failure due to advanced stages of wear [5,9]. The modes of failure determine the mechanisms of wear and wear formations, which ultimately influence the cutting tool life. In the context of tool failure, the occurrences of these modes of failure are classified by temperature failure and fracture failure, which is depicted in Figure 2, below [10]. It should be noted that adhesion is an outcome of both thermal- and mechanical loading [11].

Figure 2: Tool failure modes vs. cutting speed (adapted from [10])

2.1 Designated cooling strategies

One of the most practical and effective methods of raising productivity in the cutting process of Ti6Al4V alloy and 40CrMnMo7 is to dissipate heat as quickly as possible during cutting. This is accomplished by means of an efficient cooling strategy or technique, as any reduction in the cutting temperature will increase the tool life [12,13,14,15,16]. The cooling strategy forms the base of the cooling method and can be defined as the most basic process of applying coolant. The technique of application can be seen as a subdivision of the cooling strategy itself and supplies a method for a more specific application method of coolant.
Recent research by various institutes and researchers has determined the following cooling strategies or techniques:

- Flood cooling
- Forced air cooling (dry cutting)
- Minimal quantity lubrication (MQL)
- High pressure through spindle cooling (HPTSC)

2.2 Evaluation of cooling strategies

The cooling strategy or technique should simultaneously execute high efficiency cooling and effective chip removal [17]. The selected cooling strategies were evaluated in terms of heat removal, chip removal, lubrication and economic and environmental friendliness (E & EF), as illustrated in Table 1. Each cooling strategy or technique was graded as excellent, good, average, fair and poor.

Table 1: Selected cooling strategy evaluation criteria for machining hard-to-cut materials under HPM

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Cooling and Lubrication Strategies</th>
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<tbody>
<tr>
<td></td>
<td>FC</td>
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<tr>
<td>Heat removal</td>
<td></td>
</tr>
<tr>
<td>Chip removal</td>
<td></td>
</tr>
<tr>
<td>Lubrication</td>
<td></td>
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<tr>
<td>E&amp;EF</td>
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</table>

The heat removal indicates the potential of the cooling strategy or technique to remove the heat generated in the cutting zone. The chips that forms on the workpiece surface retain and remove a portion of the heat generated on the cutting zone, and the remaining heat is then conducted into the cutting tool and work piece. For this reason, chip removal is vital for the improvement of tool life. Finally, the economic and environmental friendliness of the cooling strategy relates to environmental problems, fluid disposal, toxicity, filterability, misting, staining and indirect costs incurred when using coolant during the machining process.

Flood cooling is the benchmark for all experiments in this article, as it is the most widely used cooling technique in standard machining processes. Dry cutting is also investigated, as it is an economic and environmental friendly cooling strategy. MQL has a good capability to transfer heat, but during HPM of Ti-6Al-4V it has been found that this proficiency is substantially reduced for this alloy. The SECO tool does not have the ability to apply through-spindle-cooling. Therefore MQL- and HPTS cooling have been omitted from this investigation.

In a study done by Li Anhai et al. [11] dry cutting was compared during varying cutting speeds and feeds. The insert was a 25 mm diameter tungsten carbide insert coated with CVD Ti(C, N)-Al2O3. Remarkable tool life was recorded at cutting speeds of 150 m/min when compared to speeds of 250 m/min and 300 m/min. The progressive flank wear over machining time is shown in Figure 3. Tool life at speeds of 150 m/min that exceed 90 min before 300 µm flank face wear is reached. After a certain period of time, chipping on the cutting edge was noticed and thereafter flank wear and chipping intensified until failure occurred [11].
Figure 3: Progression of average flank wear vs. machining time with varying cutting speed for coated carbide machining Ti6Al4V under dry cutting conditions [11]

Figure 4 shows the tool wear progression of varying feed rates over machining time. In applying higher feed rates, the wear development is substantially increased [11]. Therefore it can be seen from Figure 3 and Figure 4 that an increase in speed at a constant feed rate causes a drastic decrease in tool life. However, when the cutting speed is constant and the feed rate is increased the identical consequence is realised. It is therefore evident that an optimal cutting condition exists for machining difficult-to-cut materials with coated carbides under dry cutting.

Figure 4: Progression of average flank wear vs. machining time with varying feed rates for coated carbide machining Ti6Al4V under dry cutting [11]

The coating technique that was found to be most prevalent throughout the research literature was TiAlN [18]. Coated carbides show promise under dry cutting conditions. Additionally, coated carbides are cost-effective and readily available. With recent developments in coatings, coated carbides have been making advances in higher
temperature capabilities, force resistance and, in some cases, lubrication. The tools used in this paper were produced by SECO using their standard preparation techniques.

3 MACHINING OF DIFFICULT-TO-CUT MATERIALS

3.1 General considerations

The results are separated into two components comprising titanium and hardened steel. The experiments conducted, observes the wear on various coating treatments of carbide inserts mounted on the SECO tool holder that have been subjected to flood cooling and forced air cooling (dry cutting) conditions. The experiment evaluated the performance of the coating and coating treatments of the insert when subjected to different cooling strategies and techniques in terms of the machining time.

3.2 Experimental procedure

Machining was done using a SECO 220.13-12-0050-12 50 mm diameter milling tool holder fitted with a SECO SEAN1203AFTN-M14 insert. The inserts were coated with a TiAlN layer (2 µm thick) encased in a TiN layer (approximately 0.2 µm thick) and each insert had a different cutting edge treatment. The various coating edge treatments used were abrasive blasting (AB), abrasive flow machining (AFM), brushing (B), honing (H), laser machining (LM) and magneto-abrasive machining (MAM). Each experiment was conducted with a single insert mounted on the tool holder. The dimensions for both the Ti6Al4V and 40CrMnMo7 plates were both 330 x 253 x 48 mm.

Table 2: Experimental parameters for milling Ti6Al4V alloy and 40CrMnMo7

<table>
<thead>
<tr>
<th>Material</th>
<th>Cutting speed $v_c$ (m/min)</th>
<th>Feed per tooth $f_z$ (mm/z)</th>
<th>Axial depth of cut $a_p$ (mm)</th>
<th>Radial depth of cut $a_e$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti6Al4V</td>
<td>150</td>
<td>0.375</td>
<td>2</td>
<td>0.65</td>
</tr>
<tr>
<td>40CrMnMo7</td>
<td>250</td>
<td>0.485</td>
<td>3</td>
<td>4.7</td>
</tr>
</tbody>
</table>

The machining experiments were carried out in the type down milling operation along the shoulder of the workpiece material. The cutting parameters were derived from CIRP-Collaborative Project and complied with international standards and are assembled in Table 2 [19]. The experiment cooling strategies or techniques were the benchmark flood cooling, and forced air cooling (dry cutting). The flank face wear band width ($V_{fb}$) gave an indication of the effect of the chip contact and cooling effect on the cutting edge. For this reason the wear scar measurement was on the flank face of the insert. The tool flank wear was examined for clear wear mechanisms that contributed to tool failure. The tool rejection criteria were as follows:

- Average flank wear $V_{fb} = 200 \mu m$
- Maximum flank wear $V_{f_{max}} = 350 \mu m$
- Excessive chipping or catastrophic fracture of the cutting edge
3.3 Machining Ti6Al4V alloy

The tool life of various coating treatments under flood cooling and dry cutting are presented in Table 3. The average time taken to reach the tool wear criterion represents tool life/machining time.

<table>
<thead>
<tr>
<th>Cooling strategy</th>
<th>Type of coating treatment</th>
<th>Tool life (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U</td>
<td>AB</td>
</tr>
<tr>
<td>FC</td>
<td>10.7</td>
<td>9.6</td>
</tr>
<tr>
<td>FADC</td>
<td>119.9</td>
<td>125.2</td>
</tr>
</tbody>
</table>

Cooling strategy: Flood cooling: FC; Forced air cooling (dry cutting): FADC

Coating treatment: Untreated: U; Abrasive blasting: AB; Abrasive flow machining: AFM; Brushing: B; Honing: H; Laser machining: LM; Magneto- abrasive machining: MAM

The coating treatment which obtained the longest tool life under flood cooling was the Honing coating treatment. In the initial stages of machining, tool wear was relatively high until approximately 7 min machining time have elapsed. The flank wear progressed evenly over the cutting edge during this period, as can be seen in Figure 5. Hereafter, the wear stabilised, and increased gradually until 11 min machining time had elapsed. From there on the wear accelerated up to 200 μm flank wear at a tool life of 12.8 min. The formation of notch wear became significant after the initial stages of machining and was the reason for the accelerated wear.

![Wear after 4.2 min](image1)
![Wear after 8.9 min](image2)
![Wear after 12.8 min](image3)

Figure 5: Wear scar progression for honing coating treatment under flood cooling, machining Ti6Al4V

The coating treatment that performed the best under forced air cooling (dry cutting) was the MAM coating treatment. The wear development of MAM reached a constant linear wear rate in the initial stages and increased noticeably after 100 min machining time. The progression of the wear is shown in Figure 6, where the wear only starts to increase prominently after 114.6 min machining time, and accelerating until the 200 μm wear limit after 157.3 min machining time.

![Wear after 12.7 min](image4)
![Wear after 114.6 min](image5)
![Wear after 157.3 min](image6)

Figure 6: Wear scar progression for magneto-abrasive machining coating treatment under forced air cooling (dry cutting), machining Ti6Al4V
The overall tool life/machining time for the coating treatments under flood cooling and dry cutting conditions are compared in Figure 7. This gives clear indication that dry cutting Ti6Al4V with a MAM-coating treatment yields a favourable tool life/machining time under the given experimental conditions and cooling strategies.

![Figure 7: Cooling strategy performance under various coating treatments, machining Ti6Al4V alloy](image)

### Table 4: Effect of various coating treatments on tool life during HPM 40CrMnMo7

<table>
<thead>
<tr>
<th>Cooling Strategy</th>
<th>Type of coating treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U</td>
</tr>
<tr>
<td>Tool life (min)</td>
<td></td>
</tr>
<tr>
<td>FC</td>
<td>13.7</td>
</tr>
<tr>
<td>FADC</td>
<td>27.6</td>
</tr>
</tbody>
</table>

Cooling strategy: Flood cooling : FC; Forced air cooling (dry cutting) : FADC

Coating treatment: Untreated : U; Abrasive blasting : AB; Abrasive flow machining : AFM; Brushing : B; Honing : H; Laser machining : LM; Magneto-abrasive machining : MAM

The wear progression for MAM-coating treatment under flood cooling is depicted in Figure 8. Thermal cracking was present after a machining time of 5.9 min and progressively formed along the cutting edge until failure occurred. Thermal cracking became prominent after a machining time of 14.8 min, which caused chipping and material removal from the cutting edge. The wear rate was almost linear throughout the machining under MAM-coating treatment.
Figure 8: Wear scar progression for magneto-abrasive machining coating treatment under flood cooling, machining 40CrMnMo7

The coating treatment that demonstrated the best tool life was a MAM-coating when subjected to forced air cooling (dry cutting). The wear progression of the MAM-coating treatment is shown in Figure 9. The machining time up to the failure criterion of 200 µm wear was 47.2 min and the initial wear after 5.9 min was distributed evenly along the cutting edge, and increased incrementally from that point up until 35.4 min machining time. Thereafter notch wear became evident at the maximum depth of cut, after which the notch wear increased substantially until finally failing after 47.2 min machining time.

Figure 9: Wear scar progression for magneto-abrasive machining coating treatment under forced air cooling (dry cutting), machining 40CrMnMo7

An overview of the outcomes for flood cooling and dry cutting is presented in Figure 10. It is therefore evident that MAM-coating treatment is preferred when machining hardened steel for both flood cooling and dry cutting. It however tends to yield more a favourable tool life under dry cutting conditions.
4 CONCLUSION AND OUTLOOK

From the results presented in this article, the following was determined for each cooling strategy or technique:

**Flood Cooling**

- When machining a titanium alloy as well as hardened steel, the cutting tools simultaneously experienced adhesion and abrasive wear, also known as attrition. This promoted oxidation as a result of the creation of new surfaces during the wear process, resulting in a reduction of tool life.
- Thermal fatigue was prominent over the entire cutting edge of the tool, that caused sections to break away, and further caused aggravated delamination of the coating layers. This exposed the cemented carbide substrate to the mechanical and thermal loading, resulting in chipping of the cutting edge.

**Forced air cooling (dry cutting)**

- The temperature experienced in the cutting zone made the deformation and shearing of the chip easier and did not harm the tool. This can be attributed to the coating that resisted the effect of high temperature.
- There was evidence of thermal fatigue at later stages of machining time, which induced the chipping and hammering effect on the cutting edge of the insert. The reduced thermal fatigue can be attributed to the coating that shielded the substrate from the bulk of the thermal loading.

From the experiments conducted it was evident that thermal fatigue and chipping formed the predominant wear mechanisms under flood cooling. This caused thermal loading on the cutting edge of the insert and resulted in the reduction in tool life. Therefore, the temperature fluctuations increased the phenomenon of thermal fatigue and accelerated the deterioration of the cutting edge.

In conclusion, it could be determined that, under the given cutting parameters and experimental setup, the cooling technique of forced air cooling (dry cutting) has the potential to improve the tool life during the HPM of titanium and hardened steel. The movement towards more environmentally friendly machining conditions encourages the reduced use of cooling fluids and harsh chemicals. This favours the use of dry cutting machining processes that are more environmentally friendly and cost efficient. It should therefore be noted that it is important to select the correct cutting tool material, cutting tool coating, coating treatment and cutting parameters. For this study and the results thereof, the recommended coating is TiAlN with MAM coating treatment under forced air cooling (dry cutting).

Further work is suggested in the following fields:
• Investigation into an optimised flow rate of the forced air cooling (dry cutting) and its impact on tool wear and surface quality. Closer attention should be paid to the mechanisms of tool failure and the impact it has on the coating and coating treatment, as well as the effect that an increase in temperature has on the microstructure of the work piece. From the results of this study, the recommended coating of the inserts should be TiAlN with a MAM coating treatment system when machining titanium and hardened steel.

• Investigation into the impact that different cooling liquids have on the machinability of Ti6Al4V

• Further investigation on effect of different flow patterns onto the cutting interface.

• Investigate the effects of cooling the air-stream, with the possible introduction of liquid nitrogen.

5 REFERENCES


