INVESTIGATING THE EFFECT OF TOOL WEAR AND SURFACE INTEGRITY ON ENERGY EFFICIENCY DURING THE MACHINING OF TI-ALLOYS

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ABSTRACT

Manufacturing processes carried out on modern machine tools are still energy and resource intensive. In order to comply with future sustainability legislations and standards these processes should become more energy and resource efficient. The strategic objective of companies still remains to increase the production throughput rate, reduce the inventory and operating costs while keeping the products within the quality constraints of the voice of the customer. Increasing the material removal rates (MRR) will influence the energy efficiency, tool failure rate and the work piece's surface integrity. Thus, a better understanding of the effects cutting mechanisms have on energy efficiency during high speed machining (HSM) are gaining interest. In this research study the effect of various cutting conditions on surface integrity, tool wear and energy efficiency were investigated. Cutting speed and feed rate were varied while the depth of cut was kept constant during the turning of Ti6Al4V under flood lubrication. Tool wear and surface roughness both deteriorated with an increase in the material removal rate. It was also found that worn cutting tools produced a higher work piece surface hardness than a new tool. The energy usage for a specific cutting distance also decreased with an increase in material removal rate. Future work is also outlined.
1 INTRODUCTION

The growing demand for increased production of Titanium (Ti) alloy components imply that machining processes need to be carried out at higher cutting velocities ($v_c$) and feed rates ($f_a$) [1]. At the same time, this increase in MRR reduces the work piece’s dimensional accuracy and surface integrity and mostly reduces tool life. Managing energy and resource efficiency have also become a key strategy for most production plants. Thus, manufacturers have to balance energy efficiency management programs with the overall cost implications due to quality and downtime issues. Guo et al [2] argue that reducing energy consumption during production is one of the main practices for promoting environmental friendly manufacturing. Research [3] found that most of the energy consumption of machining processes is taken through driving the machine auxiliary functions and that the actual cutting processes take very minimal energy. Up to 35% of the total energy is used by the spindle. It was also found during an environmental examination [4] of machining processes that for the total energy consumed by the machine tool, very little amount of energy is required for cutting. Still, it remains critical to understand the effects of increasing the material removal rate on tool wear and surface integrity at the cutting interface to ensure the balance with energy efficiency. Machining also remains one of the most frequently used manufacturing activities it is estimated that approximately 15% of all manufactured components are produced using machining operations [5].

Titanium alloys have high strength-to-weight ratio, good bio-compatibility characteristics and high temperature toughness. These factors make titanium alloys desirable for industries like the aerospace, chemical processing, biomedical applications, automotive, missile development and nuclear installations [6, 7, 8]. Due to titanium alloys’ good corrosion resistance the material is also gaining ground in application in the marine industry [9]. These very same relative superior qualities makes Ti-alloys also difficult to machine. The material has a very low thermal conductivity and Young’s modulus (114 GPa) [8]. Most cutting tool materials lose their hardness at elevated temperatures resulting in the weakening of the inter-particle bond strength and consequent acceleration of tool wear, [10]. Possible surface and subsurface alterations may appear as plastic deformation or take the form of micro-cracks, phase transformations and heat-affected zones. It also produces segmented chips during machining operations that causes micro-vibrations [11]. This forced vibration from the cutting action, due to the process of shear localization, can lead to catastrophic tool failure. The temperature generated within the primary, secondary and tertiary shear zones of the cutting process also affect the tool wear rate and high cutting temperatures can result in severe tool wear [12, 13]. There are different types of tool wear mechanisms that can influence the tool wear and subsequently the tool life during machining Ti-alloys [13]. Under normal machining conditions flank wear predominate crater wear and defines the failure criteria for cutting tools [14]. Tool wear types include adhesion, abrasion, delamination, diffusion, micro-chipping and plastic deformation [15, 16]. The flank wear criterion for cutting tools according to the ISO Standard 3685-1977 (E) [17, 18, 17] and industrial practice is where $V_p=300 \, \mu m$.

In this research study the effect of different cutting parameters on tool wear, surface integrity and energy efficiency were studied. The objective is to understand the effect of cutting speed ($v_c$) and feed rate ($f_a$) on tool wear, surface integrity and energy efficiency during the machining of Ti-alloys.

2 EXPERIMENTAL SETUP AND DESIGN

Turning experiments were performed on an Efamatic CNC lathe (model: RT-20 S, Maximum spindle speed 6000 RPM). A Kistler, Model 9625B, 3-axis dynamometer along with Type 9441 B Charge Amplifiers and a National Instruments multi-channel data acquisition system were used. This dynamometer was used to measure the three components of the cutting force: $F_x$ (radial force), $F_t$ (tangential and main cutting force) and $F_z$ (axial feed force).
Labview Signal Express software data acquisition system was used to output the data to a windows based personal computer. A solid carbide tipped tool (CNMX 12 04 A2-SM with coating) mounted on a Sandvik tool holder (DCLNL 2525 M12) was used for turning Ti6Al4V with conventional flood cooling. Ti6Al4V (Grade 5) titanium alloy was supplied in annealed condition at 36 HRC as a solid round bar ($\phi=75.4$ mm x 250 mm long). The work piece chemical composition and mechanical strength characteristics (as per the material certificate) are presented in Tables 1 and 2 respectively. The experimental set-up is shown in Figure 1.

### Table 1 Chemical Composition of the Titanium Alloy Material used

<table>
<thead>
<tr>
<th>Element</th>
<th>% Content</th>
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</thead>
<tbody>
<tr>
<td>Al</td>
<td>6.0</td>
</tr>
<tr>
<td>V</td>
<td>4.1</td>
</tr>
<tr>
<td>C</td>
<td>0.02</td>
</tr>
<tr>
<td>Fe</td>
<td>0.14</td>
</tr>
<tr>
<td>N</td>
<td>0.01</td>
</tr>
<tr>
<td>O</td>
<td>0.16</td>
</tr>
<tr>
<td>H</td>
<td>0.001</td>
</tr>
<tr>
<td>Others</td>
<td>0.5</td>
</tr>
<tr>
<td>Ti</td>
<td>89.069</td>
</tr>
</tbody>
</table>

### Table 2: Mechanical Properties of Ti6Al4V

<table>
<thead>
<tr>
<th>Mechanical Characteristic</th>
<th>Treatment Condition</th>
<th>Tensile Strength (MPa)</th>
<th>Yield Strength (MPa)</th>
<th>Elongation (%)</th>
<th>Reduction of Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>State/Value</td>
<td>Annealed</td>
<td>969</td>
<td>847</td>
<td>13</td>
<td>28</td>
</tr>
</tbody>
</table>

![Experimental set-up](image)

Figure 1: Experimental set-up (a) Cutting forces measurements and (b) Surface roughness measurements

Table 3 below summarises the machining conditions used during the experiments. Tool wear was observed and measured using a Mitutoyo Optical tool maker’s microscope model 176-801D. Power measurements were taken using a KYORITSU ELECTRICAL 3 PHASE DIGITAL POWER METER MODEL 6300 with the KEW POWER PLUS2 power signal recordings captured.

### Table 3: Turning parameters of Ti6Al4V under flood Coolant

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting Speed, $v_c$</td>
<td>mm/min</td>
<td>150, 200, 250</td>
</tr>
<tr>
<td>Feed Rate, $f_n$</td>
<td>mm/z</td>
<td>0.1, 0.2, 0.3</td>
</tr>
</tbody>
</table>
and read off an Acer Aspire 5551 Laptop running on Windows 7. The cutting conditions were varied during the experimental process with cutting speed, $v_c = 150\text{–}250\ \text{m/min}$ and $f_n= 0.1\text{–}0.3\ \text{mm/rev}$. The depth of cut was kept constant at 0.5 mm. The Hommel-Etamic T8000 RC was used for the measurement of surface roughness. Each measurement of surface roughness was repeated four times and the average values were recorded. The software used to analyse the surface roughness is Turbo Wave V7.53. The work piece effective machining length was kept constant for the cutting experiments at 190 mm.

3 EXPERIMENTAL RESULTS AND DISCUSSION

Optical measurements of the tool wear were taken at different cutting speeds and feed rates conditions. Graphical tool wear images at various spiral cutting distances were also monitored during cutting operations and are as shown on Figure 2. The dominant wear mechanism observed was on the flank, followed by crater wear on the rake. Increasing cutting speed enhanced thermal and chemical activities on the tool chip interface. An increase in mechanical load ($f_n$) caused an increase in fracture mechanisms.

<table>
<thead>
<tr>
<th>Feed rate, $f_n$ [mm/rev]</th>
<th>Cutting speed, $v_c$ [m/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>250</td>
</tr>
<tr>
<td>0.3</td>
<td>SCL = 380 m</td>
</tr>
<tr>
<td></td>
<td>$v_c = 150\ \text{m/min}$</td>
</tr>
<tr>
<td></td>
<td>$f_n = 0.3\ \text{mm/rev}$</td>
</tr>
<tr>
<td>0.2</td>
<td>SCL = 600 m</td>
</tr>
<tr>
<td></td>
<td>$v_c = 150\ \text{m/min}$</td>
</tr>
<tr>
<td></td>
<td>$f_n = 0.2\ \text{mm/rev}$</td>
</tr>
<tr>
<td>0.1</td>
<td>SCL = 1700 m</td>
</tr>
<tr>
<td></td>
<td>$v_c = 150\ \text{m/min}$</td>
</tr>
<tr>
<td></td>
<td>$f_n = 0.1\ \text{mm/rev}$</td>
</tr>
</tbody>
</table>

Figure 2: Tool flank wear as a function of cutting speed and feed rate
The spiral cutting length (SCL) was measured at the maximum flank wear of $V_B = 300 \, \mu\text{m}$. It has been observed that the feed rate and cutting speed have an effect on flank wear. However, feed rate had more detrimental effect on spiral cutting length than cutting speed in these experiments. Figure 3 illustrates the spiral cutting length for different cutting conditions.

**Figure 3: Spiral cutting length vs tool wear**

Increasing the cutting speed increased the thermal loading which increased the tool wear rate. Figure 4 shows the effect of feed rate on the work piece surface roughness. Increasing the feed rate produced rougher work piece surfaces.

**Figure 4: Feed rate vs surface roughness values at varying cutting speeds on first pass**

Figures 5 and 6 shows the microstructure of the machined surface with new and worn tool produced during the turning of Ti6Al4V at a high cutting speed ranges ($v_c = 150 - 250 \, \text{m/min}$ and $f_n = 0.1 - 0.3 \, \text{mm/rev}$). The white arrow indicates the direction of cutting action. The subsurface microstructural deformation caused by machining, consisted of deformed grain boundaries in the direction of cutting and elongation of grains.

Figure 5 seems to have more deformation when compared to Figure 6 and from these results it suffices to conclude that worn tools do not have much effect on the machined surface as much as new tools. A new tool produces a rougher surface than a worn tool. The nature of microstructure distortions findings tend to complement the types of defects which were analysed and reported by Che-Haron [19].
There is plastic deformation of the top layer of the machined surface when machining Ti6Al4V alloy at these cutting conditions. This can be seen for most cutting conditions with both a new or worn tool.

The sub-surface deformation process is influenced by the occurrence of severe shear stresses generated under aggressive high speed machining conditions coupled with the observed high tool wear above. There was no noticeable change of the surface due to plastic deformation as the cutting parameters increased from this view.

Furthermore, there was also no evidence of sub-surface defects such as cracks, laps and visible tears after turning Ti6Al4V alloy under the flooded cooling conditions.

**Figure 5: The effect of cutting speed and feed rate on the work piece surface integrity with a new cutting tool edge**
Figure 6: The effect of cutting speed and feed rate on the work piece surface integrity with a worn cutting tool edge

Figures 7 and 8 are the graph plots displaying the micro-hardness depths at cutting speed of 150 m/min and the feed rate ranges 0.1 - 0.3 mm/rev where Figure 7 is a plot for a new tool and Figure 8 being the plot for a worn tool. The graph shows that the increases in feed rate also cause an increase in the surface micro-hardness on the work piece. In all cutting conditions work hardening of the deformed layer beneath the machined surface up to 500 μm caused higher hardness than the average hardness. Worn tools tend to affect the machined surfaces differently and gave higher surface hardness than new tools.
Figure 7: Micro-hardness versus distance from the surface at $v_c = 150\text{m/min}$ with new tool

It is observed from comparing the micro-hardness profiles in Figure 7 and 8 that the pattern of micro-hardness variation is below the average hardness for a distance of $40\ \mu m$ and $140\ \mu m$ respectively from the surface for the feed rates of $0.1\ \text{mm/rev}$ and $0.2\ \text{mm/rev}$ (Figure 7). In comparison with Figure 8, the micro-hardness profiles tend to be similar at the three feed rates of $0.1$, $0.2$ and $0.3\ \text{mm/rev}$. The micro-hardness values fluctuate and pick between the depths, below the surface, of $10\ \mu m$ and $80\ \mu m$ before tending to come down to the average hardness value within the depth range of $80$ to $500\ \mu m$.

Figure 8: Micro-hardness versus distance from the surface at $v_c = 150\text{ m/min}$ with worn tool

Figure 9 and 10 show the effect at a cutting speed $200\ \text{m/min}$ at different feed rates of $0.1$ - $0.3\ \text{mm/rev}$, while machining with a new and worn tool. Results show that at the cutting speed of $200\ \text{m/min}$, as feed rate increases the hardness decreases at a distance of $5\ \mu m$ from the machined surface. However, the worn tool increases the hardness even more. The hardness values at $100\ \mu m$ decrease significantly $5\ \mu m$ below the machined surface.
Figure 9: Micro-hardness versus distance from the surface at $v_c = 200 \text{ m/min}$ with new tool

Figure 10: Micro-hardness versus distance from the surface at $v_c = 200 \text{ m/min}$ with worn tool

Figures 11 and 12 show the plot of micro-hardness at a cutting speed of 250 m/min and feed rate of 0.1 - 0.3 mm/rev at a different tool conditions. The highest hardness was recorded when using a worn tool.
The total energy consumed to cut one pass (length of cut, \( l_n = 170 \text{mm} \)) as a function of cutting speed and feed was found to decrease dramatically as a function of increased feed rate and cutting speed. In all cases the same amount of material was removed albeit with dramatically different energy consumptions. When cutting at the highest cutting speed (250 mm/min) with the largest feed rate (0.3 mm/rev) and comparing to the lowest cutting speed (150 m/min) and lowest feed rate (0.1 mm/rev) there is a dramatic difference in energy consumption.

This equates largely to the machining time. It is clearly beneficial to operate the machine on an as needed basis only and for the shortest possible time. This once again points towards the energy consumption of the ancillary systems of the machine tool and the mechanical losses during operation.

This is further emphasised in Figure 13 where energy is depicted as a function of material removal rate. It clearly shows that the energy usage is strongly influenced by material removal rate. High material removal rates are generally commensurate with high performance and high speed machining and may have significant benefits as far as total energy use during machining.
CONCLUSION

The research experiments focused on the machining of titanium alloys using carbide cutting tools. The tool wear and surface roughness both deteriorated with an increase in material removal rate. It was also found that worn cutting tools produced a higher work piece surface hardness than a new tool. As far as overall energy management is concerned the data clearly demonstrated that higher material removal rates are preferred for significantly lower energy consumption. This is largely the effect of reduced machining time at the higher material removal rates which is essential for the same energy usage rate associated with the machine tool ancillary support systems. The higher material removal rates do however lead to increased tool wear. The experimental results showed that there is significant scope for improved energy management during machining and more specifically during machining of Ti-alloys. This can be achieved through the selection of optimum cutting conditions within high speed machining range such that energy use can be minimised.

REFERENCES


Dahmus, J.B. and Gutowski, T.G. 2004. An Environmental analysis of machining
Proc. of IMECE, ASME International Mechanical Engineering Congress and RD & D
Expo, in Proceedings of IMECE.

Calamaz, M., Coupard, D. and Girot, F. 2008. A new material model for 2D
numerical simulation of serrated chip formation when machining titanium alloy Ti-

Annamarie, T. 2004. RMI Titanium Alloy Guide, RMI Titanium Company,
Staffordshire.

and Applications, Koln, Wiley-VCH.

of the Machinability of Titanium Alloys, Research and Development Journal of the

Jaferry, S.I. and Mativenga, P.T. 2009. Assessment of the machinability of Ti-6Al-4V
alloy using the wear map approach, International Journal of Advance Manufacturing
Technology, 40(7-8), pp 687- 696.

Brazilian Society of Mechanical Sciences & Engineering, 26(1), pp 1-11.

Komanduri, R. and Hou, Z.B. 2002. On the thermoplastic shear instability in the
machining of a titanium alloy (Ti-6Al-4V), Metallurgical and Materials Transactions,
33(A), pp 2995-3010.

Pecat, R.E.O. 2012. Influence of milling process parameters on the surface integrity
of CFRP, IWT Foundation Institute for Materials Science, Vol. 1, pp 466 - 470.

Odelros, S. 2012. Tool wear in titanium machining, Uppsala (Sweden), AB Sandvik
Coromant.

Assessment when Machining Titanium Alloys, International Journal of Precision
engineering and manufacturing, 14(6) pp 936.


Trigger K. J. and Chao, B. T. 1956. Mechanism of crater wear of cemented carbide
tools, Transactions of ASME, 78(5).

Characteristics when Dry Turning ASTM Grade 2 Austempered Ductile Iron with PCBN
Cutting Tools under finishing Conditions, Journal of Materials Processing Technology,
Vol. 209, pp 2412-2420.

Turning Tools, Zurich, Switzerland,

Che-Haron, A. C. H. 2004. The effect of machining on surface integrity of titanium
alloy Ti-6% Al-4% V, Materials Processing Technology, Vol. 1, pp 5.