Influence of Tool Material on Forces, Temperature and Surface Quality of Ti-15333 Alloy in CT and UAT

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Abstract

Ultrasonically assisted turning (UAT) is a progressive machining method in which vibration is applied to the cutting insert in the direction of the cutting tool velocity to reduce the cutting forces, significantly and increase the surface finish noticeably. However, the key question about the tool damage caused by the vibration and its effect on the cutting forces, surface roughness and process zone temperature is still unknown in UAT.

This paper presents experimental analysis of the effect of worn tool in UAT and conventional-turning (CT) of $\beta$-Ti-15V-3Al-3Cr-3Sn (Ti-15333) alloy on surface quality of a machined surface, temperature of the process zone and cutting forces using KC5510 (PVD TiAlN) and CP500 (PVD (Ti,Al)N-TiN) cutting inserts. In UAT, the tool edge damages in CP500 inserts increased with tested machining time resulted a growth of 8 N and 10 N in tangential force component in CT and UAT, respectively. Similarly, with the progression of tool edge damage, a growth of 1.7% and 9.3% in process zone temperature was observed in CT and UAT, respectively. The surface roughness results revealed a gradual degradation with machining time, however, the results UAT with a worn tool was significantly better when compared to CT, with a virgin tool.
Keywords: Tool wear; Surface roughness; Machining; Cutting forces; Temperature in process zone; Ti-alloys.

1. Introduction

In recent decades, machining of the alloys has always been a subject of interest in the power-generation, chemical, aerospace and biomedical industries and were mainly focused on nickel and titanium based alloys [1]. The mediocre machinability of Ti alloys using conventional-machining-processes is the main disadvantage due to its high strength and lower thermal conductivity. The high level of cutting forces and concentrated temperature at the tool-workpiece interaction zone resulting diminutive tool life and hence, poor quality finish of machined components.

With the advancement in technology, new advanced alloys such as Ti15Zr12Nb and Ti6Al2Sn4Zr6Mo were introduced on need basis of strength and resistance to corrosion. However, the main problem associated with those materials is its machinability with conventional machining processes. The high contact pressure and process zone temperature resulted minute tool life and poor surface quality [2-5]. There have been numerous efforts to enhance the machining of these hard-to-cut alloys using advanced coating techniques used in cutting inserts [2, 3, 6], new tool materials [7], conventional/cryogenic coolants [8-11], assisted/hybrid machining processes [12-14] and internal processes, e. g. Alloy modification without significant changes in material properties [15, 16].

Among many, ultrasonically assisted turning (UAT) is one of the developed process which has shown significant improvement in the machining of hard-to-cut alloys [15, 17-28]. UAT transforms a continuous cutting process into a transient one by superimposition of ultrasonic-vibration on the cutting insert, resulting in an intermittent contact between them and a machined workpiece. This technique has shown 50% improvement in surface quality and 65% decline in cutting forces in the machining of Ti and nickel-based alloys. Most recently, Muhammad et al. [14, 29-31] introduced a new variant of UAT called hot ultrasonically assisted turning (HUAT), which has shown an added decline in cutting forces and improvement in surface quality. However, no attempt was made to examine the influence of tool life in either UAT and in HUAT on finished product quality.
Therefore, in the current work, an experimental procedure was adopted to study the influence of tool edge condition on resulted cutting forces, average process zone temperature and surface quality of a machined components using two types of cutting inserts (CP500 and KC5510) as recommended by the tool suppliers for the conventional turning regimes of β-Ti-15V-3Al-3Cr-3Sn (Ti-15333).

2. Experimental Procedures

2.1. Cutting Inserts and Workpiece Material

A 50 mm bar of β -Ti alloy (β-Ti-15V-3Al-3Cr-3Sn designated as Ti-15333) having a length of 300 mm was used in CT and UAT tests. Additional detail about the studied alloy can be found elsewhere [15, 19]. The CP500 and KC5510 cutting inserts recommended by the manufacturer for Ti alloys were used in experiments. The CP500 cutting inserts are suitable for intermittent cutting, whereas KC5510 is an advanced micro-grain coating inserts consist of 6% cobalt of substrate material and is recommended for moderate cutting of hard-to-cut materials. The specifications of these inserts are presented in Table 1.

2.2. Machining

A universal 300 Harrison Lathe machine was used for CT and UAT of Ti15333 alloy. The tool post of the lathe machine was reformed to support a piezoelectric transducer to impose vibrations (20 kHz of frequency and 10 μm of amplitude) on the cutting insert as shown in Figure 1. The ultrasonic system developed at Loughborough University, UK, is an open loop system and is optimized for the above ultrasonic parameters. The maximum force reduction and improvement in surface finish is reported for Ti and Ni-based alloys [17, 18, 22, 32]. A four jaw chuck was used to clamp the workpiece on the lathe machine. A mechanical dial gauge was used to adjust the eccentricity of the workpiece material. The following cutting conditions were employed in this investigation:

- Cutting speeds (m/min): 10 and 30.
- Feed rate (mm/rev): 0.1.
- Depth-of-cut (mm): 0.3.
- Dry cutting.
- Time interval \( t \) (s): 100, 300, 500 and 700.
All experiments were conducted four times to achieve realistic statistics for the experimentally achieved data.

A Kistler dynamo-meter was used to capture cutting forces in real-time. The output signal from the dynamo-meter was passed through an amplifier followed by a picoscope to get a digital format of all cutting forces. Later on, a Matlab program was used to calculate the average cutting forces for all tests.

For thermal measurements, a FLIR ThermaCAM™ SC3000 system was used for real-time acquisition. The new Stirling-cooled quantum well-infrared-photon (QWIP), enable the FLIR ThermaCAM™ system to image the process at lower noise exposure and better image uniformity using continuous mode of recording. Further details of the system can be found in experiment elsewhere [14].

The surface roughness analysis of machined specimens was carried out using Mitutoyu-Surftest-211 equipment. A standard calibrated block available with the instrument was used to calibrate the system before taking surface roughness reading in experiments. The standard, arithmetic means surface-roughness parameter ($Ra$) was calculated. The $Ra$ measurements were taken at different locations of the specimens at specified time intervals as mentioned above, and each test was repeated at least four times to achieve a good statistical data for $Ra$.

Similarly, a 3D optical measurement system, Infinite-Focus by Alicona was used for tool wear analysis. A special tool fixture was designed to ensure accurate positioning of the cutting insert at various stages of its life in experimentation (Figure 2a). The orientation of the plane of the fixture (Figure 2b) was achieved through a series of trials, carried out on the Alicona Infinite-Focus system to get a good-quality scan of the inserts. A 5x objective of the system was used because of its larger field of view compared to a 10x objective, and it was found that it was fully capable to cope with the wear-prone region even when the wear progress occurred along the flank face of the insert. A stepwise procedure was used to carry out for tool wear analysis in both CT and UAT. Initially, the inserts were used to performed CT and UAT on the Ti-15333 for selected time intervals. An ultrasonic bath was given to the inserts after machining to remove unwanted solid, semi-solid or liquid contaminants, which can include metallic and non-metallic debris, chips, dirt particles and other elements from
the surface of the insert. A cleaning procedure with pressurized air was used to ensure removal of any dirt particles to get more accurate scan of the cutting insert.

The Alicona machine software has an in-built feature known as *difference measurement*, which is dedicated to volume measurement. This feature was used to calculate the amount of volume reduction for the cutting inserts after machining by comparing a scan of the virgin sample (a reference scan) with that for the used insert. All experiments for UAT and CT were conducted on the in-house state-of-the-art experimental setup available at Loughborough University, UK. Additional details about the experimental setup can be found elsewhere [15, 19]. The experiments were repeated three times for each cutting condition. For CP500, the spread in data was huge because of one inserts each at both cutting speeds does not fail due to BUE formation. However, the rest of the data are reasonably in good shape and the results were repeatable in both CT and UAT.

3. Results and Discussions

3.1. Tool Wear

The tool wear analysis was carried out using Infinite-Focus by Alicona. A reduction in volume at the cutting edge was achieved in both CT and UAT at the tested cutting parameters as shown in Figure 3 and Figure 4. A volume reduction of $1.6\times10^6 \, \mu m^3$ in CP500 inserts was calculated in CT at 100 s. The inserts experienced high level of cutting forces and process zone temperature after making initial contact with the workpiece materials resulted rapid reduction in the volume of the insert cutting edge. The progress in volume reduction amplified with an increase in machining time and a further reduction of $0.15\times10^6 \, \mu m^3$ in volume of the cutting edge was observed at 300 s. Similarly, a total reduction of $1.9\times10^6 \, \mu m^3$ in tool edge volume was measured after 700 s of machining of Ti-15333. A better performance was showed by the CP500 inserts in CT at 30 m/min. An average reduction of $1.5\times10^6 \, \mu m^3$ and $1.8\times10^6 \, \mu m^3$ in tool edge volume was observed at 100 s and 300 s, respectively, when compared to the virgin insert. The progression in tool damage continued with machining time and average reduction of $1.9\times10^6 \, \mu m^3$ and $2.1\times10^6 \, \mu m^3$ was calculated at 500 s and 700 s, respectively. The level of volume reduction at tested time interval in CP500 inserts at 10 m/min and 30 m/min was almost the same with some minor variation (see Figure 5).
Similarly, the performance of KC5510 cutting inserts was also evaluated at the studied cutting parameters. An average volume reduction of $1.8 \times 10^6 \, \mu m^3$ and $1.6 \times 10^6 \, \mu m^3$ at 100 s was calculated at 10 m/min and 30 m/min cutting speeds, respectively. A growth in volume reduction was observed with machining time and average decrease of $2.5 \times 10^6 \, \mu m^3$, $2.6 \times 10^6 \, \mu m^3$ and $2.7 \times 10^6 \, \mu m^3$ was measured at 300 s, 500 s and 700 s, respectively at 10 m/min. On the other hand, at 30 m/min, a reduction in volume of $2.2 \times 10^6 \, \mu m^3$, $2.4 \times 10^6 \, \mu m^3$ and $2.5 \times 10^6 \, \mu m^3$ was calculated at 300 s, 500 s and 700 s, respectively.

The CP500 and KC5510 inserts are designed for CT and showed better performance at both cutting speeds. However, the volume removed at both cutting speeds in CP500 cutting inserts was lower when compared to KC5510 cutting inserts (see Figure 3). The level of tool edge volume lost by CP500 inserts at the tested cutting speeds was approximately the same with some minor fluctuations. On the contrary, in KC5510 cutting inserts, the material removal rate was reduced with an increase in cutting speeds from 10 m/min to 30 m/min. The substrate material of these inserts contained small contents of Cobalt particles, providing them tougher and finer grain structure suitable for high load application.

Transition to vibro-impact machining in the UAT regime, affected the character of tool life in term of volume reduction. The decay in average volume of tested cutting inserts in UAT is shown in Figure 4. The levels of volume reduction for both cutting inserts in UAT was comparatively higher to those in CT. At 100 s, the level of volume lost by the CP500 insert was $2.7 \times 10^6 \, \mu m^3$. The volume reduction increased with an increase in time and average reduction of $3.0 \times 10^6 \, \mu m^3$, $6.4 \times 10^6 \, \mu m^3$ and $44.5 \times 10^6 \, \mu m^3$ was observed at 300 s, 500 s and 700 s, respectively. A rapid failure of the CP500 inserts was observed at 700 s resulted a rapid increase of volume reduction by a factor of 6. The decay in volume of one of the tested CP500 insert is shown in Figure 6. At 30 m/min, CP500 inserts have shown better performance upto 100 s and a reduction of $4.9 \times 10^6 \, \mu m^3$ in cutting edge volume was calculated. However, a rapid increase in volume reduction was observed for the subsequent time internals. A reduction of $13.8 \times 10^6 \, \mu m^3$, $44.8 \times 10^6 \, \mu m^3$ and $56.2 \times 10^6 \, \mu m^3$ was calculated at 300 s, 500 s, and 700 s, respectively. The catastrophic failure in CP500 insert in the form of plastic deformation was linked to the substrate composition of the CP500 insert, which caused significantly lower impact resistance [33].
A reduction of $3.2 \times 10^6 \mu m^3$ in KC5510 volume was observed at 100 s in UAT and 10 m/min cutting speed. With an increase in machining time, a further increase of nearly $1.0 \times 10^6 \mu m^3$, $0.8 \times 10^6 \mu m^3$ and $1.9 \times 10^6 \mu m^3$ was reported at 300 s, 500 s and 700 s, respectively. Similarly, these inserts demonstrated even better performance at 30 m/min in UAT. Initially, a reduction of $2.3 \times 10^6 \mu m^3$ in tool edge volume was calculated at 100 s. However, the decay in tool edge volume increased with an increase in time and a total decrease of $2.8 \times 10^6 \mu m^3$, $4.1 \times 10^6 \mu m^3$ and $4.2 \times 10^6 \mu m^3$ was calculated at 300 s, 500 s and 700 s, respectively. This extremely positive tool-wear behaviour of KC5510 insert in UAT, as compared to that of CP500, can be explained by its substrate composition [33]. The material removal development in the KC5510 cutting insert is presented in Figure 7.

Comparing the material removal progress in two studied inserts in CT and UAT, a shorter tool life for CP500 inserts was observed in UAT when compared to KC5510. Though, the coating was eventually removed in both inserts, but the substrate of insert KC5510 demonstrated significantly greater resistance to localized plastic deformation as well as resistance to failure once the physical damage began, resulted better performance in UAT [33, 34].

### 3.2. Cutting Forces

The results obtained from experimentation at 10 m/min demonstrated that a substantial drop of approximately 75% was achieved in $F_t$ in UAT as shown in Figure 8 and Figure 9. Similarly, a considerable decline of approximately 70% in $F_r$ was also recorded using both inserts. The superposition of vibrations on the cutting insert induces separation of cutting tool from the chip in one complete vibration cycle, resulted reduction in average force levels [18]. The tool come in contact with the chip at the penetration-stage resulted approximately peak level of the cutting forces observed in CT, where as the level of forces started to decline and reached to zero level during the retraction stage. As a result, a substantial drop in average $F_t$ and $F_r$ was observed in UAT.

The level of $F_t$ for both cutting inserts was almost the same due to its similar geometries at both the cutting speeds. In CT, $F_t$ of 98 N and 102 N was observed at 10 m/min using CP500 and KC5510 inserts, respectively. Similarly, $F_r$ of 46 N and 44 N was observed in CP500 and KC5510, respectively. Minor fluctuation in $F_t$ and $F_r$ was observed in both inserts with an
increase in machining time. The influence of cutting speed on $F_t$ and $F_r$ was negligible for both inserts in CT, whereas in UAT, a gradual growth in the level of $F_t$ and $F_r$ was observed with an increase in cutting speed from 10 m/min to 30 m/min as shown in Figure 10 and Figure 11. The level of $F_t$ increased from 25 N to 39 N and from 29 N to 37 N using CP500 and KC5510 inserts, respectively. Similarly, a growth of 4 N and 6 N was calculated in $F_r$ for CP500 and KC5510 inserts, respectively. This observation was expected because in UAT, the separation of the cutting tool reduced with an increase in cutting speed, resulting an increase in the level of $F_t$ and $F_r$ when compared to those obtained at 10 m/min [17-19]. A minor variation (upto a maximum of 12 N) in the level of $F_t$ and $F_r$ was observed with progression of tool edge damage for both inserts in UAT and CT, however, the effect of tool edge damage was not severe in the level of $F_t$ and $F_r$ in UAT. Hence, the level of $F_t$ and $F_r$ observed in UAT for both cutting inserts was considerably lower when compared to those observed in CT beside it poor tool life. This demonstrates the importance and significance of UAT in machining of high strength alloys with worn tools.

3.3. Process Zone Temperature

The average process zone temperature in both UAT and CT was also examined experimentally for both inserts, as presented in Figure 12. The calculated temperature levels did not show the actual temperature generated at the tool workpiece interaction region due to the obstacle generated by the chip during the process zone temperature recording. Similarly, the problems associated with aligning the camera at a preferable angle due to the restrictions produced by the machine. Still the data obtained in the current study presented a good quantitative analysis of UAT and CT in turning of Ti-15333 using CP500 and KC5510 cutting inserts.

The prime cause of heat generated during machining processes is the plastic deformation in the primary and secondary zone of deformation with a minimal contribution of frictional effect (below 10%) [36]. The experimental results indicate that the average process zone temperature in CP500 and KC5510 cutting inserts in UAT was higher compared to those observed in CT. The possible reason is the amount of energy applied to the tool in the form of vibrations which increased the relative cutting velocity of the inserts in UAT [22].

The measured process zone temperatures in CT at 10 m/min using CP500 and KC5510 inserts were 288°C and 300°C, respectively. Additionally, with the superposition of vibration
on the cutting insert, yielded an additional growth of approximately 100°C in UAT (see Figure 13 and Figure 14). The level of process zone temperatures measured in CP500 and KC5510 inserts were 396°C and 405°C, respectively. Furthermore, a noticeable growth in the average process zone temperature was noticed for both inserts with a rise in cutting speed, as expected. The average growth of 113°C and 125°C was observed in CT using CP500 and KC5510 inserts, respectively, when cutting speed was increased from 10 m/min to 30 m/min. Similarly, the average increased in the process zone temperature of 109°C and 116°C was measured in UAT using CP500 and KC5510 inserts, respectively.

The cutting edge condition has a marginal influence on the average process zone temperature in the machining of Ti-alloys and in the current study as a growth in average process zone temperature was noticed with the tool damage progression. In CT, the rise in average process zone temperature was minor for both tools due to lesser damage to the insert edge. In CP500 inserts and 10 m/min, a growth of 5°C was measured at 700 s when compared to the level of temperature observed at 100 s. Similarly, a growth of 20°C was achieved at 700 s in KC5510 inserts. At 30 m/min, the level of process zone temperature increased from 401°C to 410°C in CP500 inserts where as in KCC5510 inserts an increase of 6°C was obtained.

On the contrary, a visible increase in the average process zone temperature was detected in UAT with the tool damage progression. In CP500 cutting insert, a total growth of 68°C was observed at 700 s and 10 m/min cutting speed when compared to those obtained at 100 s, where as in KC5510, a growth of 42°C was noticed at 700 s. Similarly, at 30 m/min cutting speed, the total rise in temperature at 700 s in CP500 and KC5510 cutting inserts was 44°C and 27°C, respectively, to those obtained at 100 s. One of the main disadvantages of the UAT with the studied alloy is the high process zone temperature, however, on the other hand, the rise in average process zone temperature further reduced the yield strength of materials and make it easy for the cutting insert to remove the excess amount of material with no significant effect on the machined specimen [14, 19].

The achieved experimental results concluded that as the machining time increases from 100 s to 700 s, the growth in process zone temperature was high in UAT to those obtained in CT for both the inserts leading to its poor life. However, the 6% cobalt content in the substrate of KC5510 cutting insert increased its toughness, leading to higher tool life in UAT when compared to CP500 cutting inserts.
3.4. Surface Roughness

Surface quality is measured as one of the vibrant factors in metal work as it is related directly to a fatigue-life of most structures [37]. Therefore, the surface topology analysis was carried out for machined surface using CP500 and KC5510 in both CT and UAT at studied time intervals. The level of Ra observed in CT for CP500 insert was 1.73 μm, whereas the level of Ra at 30 m/min was 1.09 μm. A significant improvement of 36% in Ra was achieved with an increase in cutting speed from 10 m/min to 30 m/min. Similarly, the level of Ra observed at 10 m/min and 30 m/min in KC5510 inserts were 1.82 μm and 1.02 μm, respectively.

Additionally, a momentous decline in Ra was noticed in UAT for both inserts to those obtained in CT (see Table 2). The level of Ra decline from 1.73 μm to 1.01 μm in CP500 inserts and 10 m/min cutting speed. Similarly, 24% improvement in surface roughness was achieved in UAT at 30 m/min cutting speed. Furthermore, the superposition of vibration in cutting direction on KC5510 inserts resulted an improvement of 48% and 28% in surface quality at 10 m/min and 30 m/min, respectively. However, the difference in Ra levels was minimal in CP500 and KC5510 cutting inserts due to its similar geometries in both CT and UAT, but KC5510 inserts resulted comparatively better surface finish than CP500 inserts. Degradation in surface quality was observed in CT and UAT for both tools with the increased in machining time, as expected [35]. The level of Ra at 10 m/min cutting speed in CT increased from 1.73 μm to 1.75 μm at 300 s and then reduced slightly to a level of 1.74 μm at 500 s. Finally, the level of Ra reached to 1.80 μm at 700 s. Similarly, the levels of Ra observed for KC5510 inserts at 300 s, 500 s and 700 s were 1.61 μm, 1.79 μm and 1.95 μm, respectively. 16% degradation in surface quality at 30 m/min cutting speed was achieved in CP500 inserts at 700 s when compared to the results obtained at 100 s. Similarly, 26% increase in Ra level was measured in KC5510 inserts at 700 s. The quality of surface finished achieved in CP500 inserts was better in CT when compared to the surface finish obtained using KC5510 inserts. The prime reason for better surface quality of CP500 inserts in CT is due to its good performance and better tool life when compared to KC5510 inserts.

Similarly, degradation in surface quality of 39% and 34% in CP500 and KC5510 inserts, respectively, was measured in UAT at 700 s and 10 m/min cutting speed when compared
the surface finish achieved at 100 s. Also, an increase of 31% and 27% in Ra level was observed in CP500 and KC5510 insert, respectively at 30 m/min.

Comparing the results listed in Table 2, a significant improvement in surface quality was achieved in UAT when compared to CT at different stages of experimentations for both inserts. The improvement in surface roughness was noticeable beside the facts the tool life is poor in UAT for both cutting inserts as these were designed for CT processes.

In a nutshell, it was concluded that the tool life for KC5510 cutting insert was comparatively higher in UAT when compared to CP500 inserts and hence, resulted better surface finish in UAT at various cutting conditions. Additionally, the level of surface finish obtained in UAT for CP500 cutting inserts was prominently better when compared to the results obtained in CT.

4. Conclusions

The main conclusions of this work are:

- Substantial reduction of 70% in cutting forces was observed in UAT when compared to those in CT at lower cutting speeds.
- A great beneficial effect of vibrations on the machined surface was observed by achieving better surface quality in UAT. The measured level of Ra was still lower than 1.6 μm in UAT at 700 s.
- The KC5510 cutting inserts yielded comparatively improved surface finish in UAT when compared to CP500 due to its enhanced tool life.
- The level of cutting forces observed in UAT with worn tool was significantly lower to the level of forces observed in CT.
- The Process zone temperature in UAT for both the tool was approximately 34% higher when compared to CT at lower cutting speeds.
- Both inserts demonstrated poor insert life in UAT of Ti-15333 when compared to their performance in CT at the tested cutting conditions. However, based on the comparative analysis of the both inserts and surface quality achieved in the tests, KC5510 is recommended for UAT of Ti-15333.
Reference


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Table 1: Cutting inserts specification

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Figure 9: The average level of Ft and Fr observed in UAT and CT of Ti-15333 using KC5510 cutting inserts and V = 10 m/min

Figure 10: The level of Ft and Fr observed in UAT and CT of Ti-15333 using CP500 cutting inserts and V = 30 m/min

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Figure 14: Process zone temperature in UAT and CT at various time intervals using KC5510 inserts

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Table 1: Cutting inserts specification

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<th>Specification</th>
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<td>DNMG 150608 MF1 CP500</td>
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<td>Insert Material</td>
<td>Micro-grained tungsten carbide</td>
<td>fine-grained tungsten carbide 6% cobalt substrate</td>
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Table 2: The average surface roughness measurement of a machined surface at various time intervals

### CP500 Cutting Insert, \( V = 10 \text{ m/min} \)

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### KC5510 Cutting Insert, \( V = 10 \text{ m/min} \)

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<th>Ra, (µm)</th>
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<th>Ra, (µm)</th>
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<tbody>
<tr>
<td>100 s</td>
<td>CT</td>
<td>1.82±0.61</td>
<td>1.61±0.31</td>
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<td></td>
<td>UAT</td>
<td>0.96±0.32</td>
<td>1.15±0.29</td>
<td>1.35±0.31</td>
<td>1.47±0.26</td>
</tr>
</tbody>
</table>

### CP500 Cutting Insert, \( V = 30 \text{ m/min} \)

<table>
<thead>
<tr>
<th>Time</th>
<th>Surface Roughness</th>
<th>Ra, (µm)</th>
<th>Ra, (µm)</th>
<th>Ra, (µm)</th>
<th>Ra, (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 s</td>
<td>CT</td>
<td>1.09±0.41</td>
<td>1.00±0.32</td>
<td>1.16±0.39</td>
<td>1.31±0.22</td>
</tr>
<tr>
<td></td>
<td>UAT</td>
<td>0.82±0.24</td>
<td>0.91±0.39</td>
<td>0.99±0.23</td>
<td>1.19±0.36</td>
</tr>
</tbody>
</table>

### KC5510 Cutting Insert, \( V = 30 \text{ m/min} \)

<table>
<thead>
<tr>
<th>Time</th>
<th>Surface Roughness</th>
<th>Ra, (µm)</th>
<th>Ra, (µm)</th>
<th>Ra, (µm)</th>
<th>Ra, (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 s</td>
<td>CT</td>
<td>1.02±0.33</td>
<td>1.13±0.25</td>
<td>1.25±0.29</td>
<td>1.39±0.19</td>
</tr>
<tr>
<td></td>
<td>UAT</td>
<td>0.73±0.25</td>
<td>0.93±0.39</td>
<td>0.85±0.35</td>
<td>1.01±0.51</td>
</tr>
</tbody>
</table>
Figure 1: Setup used for CT and UAT experimentation

Figure 2: Special insert fixture (a); cutting insert placed on oriented plane of fixture (b)
Figure 3: Volume reduction in cutting inserts at various time intervals in CT

Figure 4: Material removal progress in CT in KC5510 insert [35]
Figure 5: Volume reduction in cutting inserts at various time intervals in UAT

\[ t_m = 100\, s, d_m = 17\, m \]

\[ t_m = 700\, s, d_m = 117\, m \]

Figure 6: Material removal progress to catastrophic failure in CP500 cutting inserts in UAT at cutting speed of 10 m/min at various stages [35]
Figure 7: Material removal progress of insert KC5510 in UAT at cutting speed of 10 m/min at various stages [35]
Figure 8: The average level of $F_t$ and $F_r$ observed in UAT and CT of Ti-15333 using CP500 cutting inserts and $V = 10$ m/min.

Figure 9: The average level of $F_t$ and $F_r$ observed in UAT and CT of Ti-15333 using KC5510 cutting inserts and $V = 10$ m/min.
Figure 10: The level of $F_t$ and $F_r$ observed in UAT and CT of Ti-15333 using CP500 cutting inserts and $V = 30$ m/min

Figure 11: The level of $F_t$ and $F_r$ observed in UAT and CT of Ti-15333 using KC5510 cutting inserts and $V = 30$ m/min
Figure 12: Process zone temperature in UAT and CT for both tools at 100 s and V = 10 m/min
Figure 13: Process zone temperature in UAT and CT at various time intervals using CP500 inserts

Figure 14: Process zone temperature in UAT and CT at various time intervals using KC5510 inserts