Experimental Determination of Cutting Temperature and Force When Turning Assab Steel with Coated Carbide Inserts

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Abstract. The study is about an experimental investigation of the different factors influencing the temperature occurring at the coating/substrate and chip interface when machining Assab steels 760 and DF2 with two different coated carbide tools. Results show that tool temperature was higher when turning Assab steel 760. Temperature along the major flank face was higher that that at the minor flank. However, the magnitude of temperature was lower than expected with maximum only around 260 °C near the tool tip. The performance of Al₂O₃ coated WC inserts appeared to be better compared to TiN coated WC inserts. The cutting temperature was lower with alumina coated tools. While turning Assab DF2 steel, cutting temperature was lower compared to Assab 760 steel for the same coated tool.

Introduction

Machining is one of the most widely used processes in manufacturing and has been the focus of research and development for many years. In any metal cutting or chip type machining process, it is known that heat generated during cutting is an important factor that influences the performance of cutting tool [1-3]. The increase in productivity lies with increase in metal removal rate and this can be achieved by increasing the input cutting variables like the cutting speed, the feed rate and the depth of cut. To do this in a cost effective manner depends on one of the main areas related to metal cutting is the cutting tool. The use of cutting tools specially the coated tools represents state-of-the-art machining technology and present day machining processes are becoming increasingly demanding upon cutting tool materials [4-6].

The heat generation near the cutting edge of the tool during machining increases with the increase of power to remove more material in a shorter time. The power consumed in the process is largely converted into heat [7] and there are three regions of heat generation in turning, namely the shear zone, tool-chip interface and the tool-workpiece interface (Fig. 1). The main heat source is located in the primary shear zone, the second heat source accounts for tool-chip friction and interfacial deformation, and the third zone is due to tool flank friction. Researchers have reported many findings in their papers in relation to these topics which refer to different manufacturing processes [8-10]. The heat generated in the process is dissipated by the cutting tool, the workpiece, the chip produced and the cutting fluid. Hence the cutting tool has to withstand higher temperatures during machining.

Researchers have undertaken various techniques to measure the temperatures generated during machining processes. The main techniques used to measure the temperature are by (i) tool-chip or tool-work thermocouple, (ii) embedded thermocouple, and (iii) thermal radiation. All these techniques fall into the direct method. The indirect method of temperature measurement involves micro-structure or micro-hardness analysis which provides a snapshot result as opposed to continuous data.
A thermocouple is a simple temperature sensor consisting of two dissimilar metals in thermal contact and the contact point produces a small open circuit voltage as a function of temperature. The thermocouple is called a tool-chip or tool-workpiece thermocouple if the two dissimilar metals are the cutting tool and the work material. This technique is relatively easy to apply which measures the mean temperature over the entire contact area [11-13]. The tool-chip thermocouple estimates the average temperature, not the maximum temperature at the tool-workpiece interface [14]. The main limitations of this technique are that both tool material and work material has to be electrically conductive, cutting fluid can not be used, calibration is tedious and laborious, secondary voltages may occur, and many tool-workmaterial combinations do not form ideal thermocouples [15].

Thermocouples embedded in the cutting tool or work material can be used to measure the cutting temperature at a single point or at different locations to establish the temperature distribution in the tool. Researchers [16] have used this technique to measure the temperature along the radial and longitudinal position of the work material. Another technique is the use of an insulated thermocouple implanted into the workpiece and during machining when the workpiece is sheared, the insulation of the thermocouple is broken and an instantaneous hot junction is formed between the wire and the workpiece in the cutting zone. This generates an electromotive force (emf) and as a result an interface temperature can be calculated from the emf generated. The main advantage of this technique is that electrically non-conductive tool materials can be used. However, maximum temperature at the tool-chip interface may not always be recorded [17].

The use of infrared camera in the field of temperature measurement in metal cutting has an advantage in the sense that it is a non-contact technique and hence there is no disturbance in the temperature field. Researchers [18-20] have used infrared techniques to relate cutting temperature to flank wear, ascertain temperature distribution on the rake face, and determine temperature effect on the chip formation. It involves measurement of thermal radiation emitted during the cutting process by using infrared sensitive photographic film [21] or a pyrometer/infrared thermometer [22]. The machining process must be dry as no cutting fluid can be used and measurement of interface temperature is really difficult as the tool-workpiece interface is generally obscured. Moreover, the temperature measurement could be misleading if an incorrect emissivity value is chosen.

The purpose of the present investigation was to determine temperatures at the tool flank and rake faces when turning two different steels with TiN coated carbide and Al$_2$O$_3$ coated carbide tools.

**EXPERIMENTAL PROCEDURE**

**Machine Tools, Work Material and Toolings**

The turning processes were conducted on a Colchester (Master vs 3250) conventional lathe which had a feed in the range of 0.036 – 1.2 mm/rev and a spindle speed in the range of 14 – 2300 rpm powered by 7.5 kW motor. The work materials used in the investigation were Assab steel 760.
(AISI 1045) and Assab steel DF2. Table 1 shows some useful properties and composition of the materials.

Table 1  Workmaterial properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical composition (wt %)</th>
<th>Hardness</th>
<th>Hardening temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assab steel 760</td>
<td>0.50 C, 0.50 Mn, 0.25 Si</td>
<td>210 HB</td>
<td>840 – 870 °C</td>
</tr>
<tr>
<td>(AISI 1045)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assab steel DF2</td>
<td>0.90 C, 1.20 Mn, 0.50 Cr, 0.50 W, 0.10 V</td>
<td>190 HB</td>
<td>790 – 850 °C</td>
</tr>
</tbody>
</table>

Two types of coated carbide inserts GC4015 and GC4025 with ISO designation of CNMG 120408-PM were used. GC 4015 has a single layer of TiN coating while GC4025 has a single layer of Al₂O₃ coating. The rake angles of both tools were -5°. The cutting conditions for ASSAB steel 760 when machining with TiN coated insert are shown in Table 2. Table 3 shows cutting conditions of Assab DF2 steel for TiN coated and Al₂O₃ coated tools.

Table 2: Cutting conditions for ASSAB steel 760 with TiN coated WC insert

<table>
<thead>
<tr>
<th>Cutting speed (m/min)</th>
<th>Feed rate (mm/rev)</th>
<th>Depth of cut (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.16</td>
<td>1.0</td>
</tr>
<tr>
<td>150</td>
<td>0.12</td>
<td>1.0</td>
</tr>
<tr>
<td>225</td>
<td>0.16</td>
<td>1.0</td>
</tr>
<tr>
<td>350</td>
<td>0.22</td>
<td>1.0</td>
</tr>
<tr>
<td>500</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>100</td>
<td>0.16</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 3: Cutting conditions for ASSAB steel DF2

<table>
<thead>
<tr>
<th>WC insert</th>
<th>Cutting speed (m/min)</th>
<th>Feed rate (mm/rev)</th>
<th>Depth of cut (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiN coated</td>
<td>100</td>
<td>0.16</td>
<td>1.00</td>
</tr>
<tr>
<td>Al₂O₃ coated</td>
<td>100</td>
<td>0.16</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Temperature Measurement using Infrared Technique and Its Mounting Device on the Lathe

A high resolution radiometric (Model 9001) infrared thermal imaging camera was used to measure temperature of the cutting tool. The thermal imaging camera consisted of an infra red detector, the scanning unit, and the VGA video monitor. The camera was designed to operate at wavelengths in the infra red spectral range (3.6-5 µm) while the temperature range selected for this investigation was -20 °C – 1500 °C. The optical system of this IR camera focused the infrared energy emitted by the cutting tool onto a 320 × 244 array of PtSi detectors.

As the emissivities of TiN coated and Al₂O₃ coated tools were not available on hand, these values were determined. The emissivity values of IR thermometer were adjusted until the temperature recorded by the IR thermometer was equal to a known tool temperature and this was repeated for each tool. Emissivity of TiN coated tool was determined to be about 0.15 while that of
Al₂O₃ coated tool was found to be about 0.2. These values were set to measure the tool temperature during the investigation.

A mounting device for the IR thermometer was fabricated and attached to the carriage of the lathe as shown in Fig. 2. The device moved along with the movement of the lathe carriage with the IR camera focused on the tool tip. The camera could be rotated and moved towards the tool-work interface as required. The IR thermal image was displayed on a video monitor.

![Figure 2 Experimental set-up with IR camera](image)

Force Measurement

A Kistler quartz dynamometer integral with charge amplifier (Model 9257A) was used for measuring forces on the cutting tool. The cutting force ($F_v$), the feed force ($F_f$), and the radial force ($F_r$) acting on the tool were displayed on the Yokogawa DL1540 digital oscilloscope.

RESULTS AND DISCUSSIONS

Temperature Measurement

For temperature measurement at predetermined locations along the flank faces of the tool, a transparent scale was made manually and attached on the monitor aligning with the flank faces displayed on the monitor. The IR camera was focused on these predetermined points on the scale attached to the video monitor. In this way measurements were made starting from the tool tip along the major flank and minor flank at an interval of 1mm. Fig. 3 shows a thermal image and temperature captured during machining at a particular location on the tool flank.
Fig. 4 shows the temperature distribution on the TiN coated cutting tool along major and minor flanks when turning Assab steel 760. As expected, temperature along major flank was higher than the minor flank. However, the magnitude of temperature was observed to be lower than those already reported in different literatures [1& 23-24]. The cross hair of the IR camera when focused at the tool tip, chip formation may have blocked the tip and the temperature recorded may have that of chip. However at the minor flank, where the chances of blocking the measurement points from cross-hair by chips are minimal, temperatures recorded were also low. Hence it could be said that temperatures measured along major flank were also not blocked by the chip formation.

Fig. 5 shows temperature along the major flank at various speeds ranging from 100 m/min to 500 m/min at a fixed feed rate of 0.16 mm/rev and at a constant depth of cut of 1.0 mm. Again the magnitudes of temperatures were observed to be low with maximum temperature around 250 °C. However the maximum temperature was observed to be not at the tool tip but some distance away from the tool tip. This agrees with most of works published in different literatures. From Fig. 6, it is observed that in turning two different materials with the same tool (TiN coated), cutting tool temperature was lower when turning Assab DF2 steel compared to Assab 760 steel. This suggests that the thermal conductivity of DF2 steel could be higher and there was quick heat dissipation through the chips.
According to Fig. 7, temperature stabilized about 20 s after the start of turning process. The temperature was recorded only after it was stabilized. Although the magnitudes of temperatures were low, tool temperature was observed to be the highest not at the tool tip but some distance away from the tip with gradually decreasing temperature away along the flank face. In turning the same material (DF2 steel) with TiN coated and Al\(_2\)O\(_3\) coated tools, temperature of Al\(_2\)O\(_3\) coated tool was lower according to Fig. 8. This could be due to a higher conductivity value of Al\(_2\)O\(_3\) coated tools. It is reported that Al\(_2\)O\(_3\) coated tools have conductivity equal to 36 W/mK compared to 20 W/mK of TiN coated tools. Fig. 9 shows the temperature distribution along the major flank and rake face of...
TiN coated tools when turning Assab steel DF2. From Fig. 10, a peak cutting temperature was observed at an intermediate speed (225 m/min) and that when the speed increased from this point, there was a drop in temperature. The effect of feed rate and depth of cut on cutting tool temperature are shown in Fig. 11 and Fig. 12. The trend in the variation of temperature with increasing feed was similar to that of speed. A peak temperature has been observed at an intermediate feed. However, with the increase of depth of cut, cutting temperature was found to decrease.

**Figure 9** Tool temperatures along rake and flank faces

**Figure 10** Tool temperatures at increasing cutting speed

**Figure 11** Tool temperatures at increasing feed rate

**Figure 12** Tool temperatures at increasing depth of cut
3.2 Force Measurement

Fig. 13 indicates that an increase in cutting speed resulted more or less a steady force for all three components with main component having highest magnitude. With the increase in cutting speed, the decrease in temperature and a steady force may be attributed to the higher metal removal rate resulting in higher heat dissipation by the chip and consequently lesser heat being conducted through the work material.

4. CONCLUSIONS

1. The IR technique resulted in lower temperature than expected. Along the major flank, maximum temperature was observed to be at a distance from the tool tip which was within one mm from the tip. The temperature along the major flank (130 – 250 °C) was higher than those at the minor flank (110 – 200 °C).
2. Within the range of 100 -500 m/min cutting speed, variations in temperature along the major flank and minor flank was in between 25-75 °C when machining Assab 760 steel with TiN coated tungsten carbide insert.
3. The relatively low cutting temperatures measured need further investigation. The measurement region has to be closely monitored to ensure that no chip blocks the measurement path. WC inserts may be used for turning high strength steels for better heat dissipation characteristics.
4. Increased cutting speed resulted in mixed response in temperature. A peak temperature is observed at 225 m/min cutting speed. From this speed, temperature dropped as the speed increased.
5. Increased feed rate also resulted in mixed response in temperature. A peak temperature is observed at 0.16 mm/min feed rate. Then afterwards, temperature dropped as the feed increased. The temperature response with regard to depth of cut is different from what is observed with cutting speed and feed rate.
6. Al₂O₃ coated WC resulted in lower temperature than TiN coated carbide when machining either Assab 760 or DF2 steel. Al₂O₃ coated WC has higher thermal conductivity and this may explain why the temperature in Al₂O₃ coated WC was low.
7. The cutting force remained almost steady with the increase of cutting speed. Additional investigations are necessary to understand the reasons of low cutting temperature measured by IR thermometer.

References