Diamond Tool Wear when Cutting Amorphous Polymers

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Abstract
Precision turning of polymeric materials increases form and shape accuracies in respect to the conventional techniques, but the relatively large tool wear of the mono-crystalline diamond tools may be a problem. This paper will discuss possible tool wear mechanisms that occur during diamond turning of glassy (amorphous) polymers. Special attention is given to thermal-oxidative tool wear, tribo-electric tool wear and tribo-chemical tool wear. It will be shown that tribo-electric and tribo-chemical tool wear play an important role in the precision turning process of polymers.

Keywords:
Wear, Polymer, Electrical discharge

1 INTRODUCTION
Much research on tool wear has been performed in the past, e.g. [1] [2] [3], but only few references are found on tool wear mechanisms during diamond turning of glassy polymers [4] [5]. Evans [1] used the following classification for diamond tool wear: adhesion, abrasion, tribo-thermal and tribo-chemical. In this paper tribo-electric tool wear will be added to this list, because industry states that tool wear caused by discharging may be a problem in the lens manufacturing process. Usually more than one wear mechanism is active. But, generally only one is dominant for a certain tool/workpiece combination and a certain cutting regime.

Adhesive tool wear will be excluded as a dominant diamond tool wear mechanism, since adhesive wear always occurs on the softer material (in this case the polymer) of the two adhering materials.

Looking at abrasive tool wear it can be stated that this can only be excluded by chemical investigation of the polymer. It is known from the production of contact lenses [6] [7] that relatively hard silicon particles abrade the diamond tool during turning. The materials used in this study, polymethylmethacrylate (PMMA) and polycarbonate (PC), were chemically investigated by energy dispersive X-ray (EDX) analysis and they contained no elements that could cause abrasive tool wear.

The next paragraphs deal more extensively on the other three possible diamond tool wear mechanisms.

2 THERMAL-OXIDATIVE TOOL WEAR
Graphitisation of diamond in air is called oxidation, which occurs at approximately 800 K [8]. To investigate the possibility of thermal-oxidative tool wear to occur in diamond turning of polymers a diamond tool with encapsulated thermocouple was developed. A small diameter thermocouple (wire ø25µm) was inserted in a hole produced by excimer laser drilling. The thermocouple was fixed in the middle of the tool by a heat conducting epoxy. The thermal response of the tool was checked by a calibration procedure that involved touching the cutting edge along a slowly cooling aluminium cylinder. This way it was possible to get the difference between recorded temperature of the thermocouple and the actual temperature of the cutting edge. This was also modelled [9].

Temperature measurements are performed on tubular PMMA with a width of cut of 0.7 mm. For the temperature measurements several cutting speeds \( v_c \) were used and for every cutting speed four feed rates were used (0.1, 1, 10 and 25 µm/rev). The results of the temperature measurements can be seen in figure 1.

Material removal rates in the precision turning process typically have a value of less than 1 mm³/s. This means that during the precision turning process the temperature at the cutting edge is significantly less than the temperature at which oxidation of the diamond takes place, so no thermal-oxidative tool wear is expected.

3 TRIBO-ELECTRIC TOOL WEAR
3.1 Introduction
Since glassy polymers and diamond are electric insulators, static electricity can be expected during the turning process, because of friction between tool and workpiece [10]. Scission of the polymer chains during the cutting process might also result in an additional charging

Figure 1: Temperature at the cutting edge during diamond turning of PMMA.
during turning (§3.2). The charge at the surface will accumulate at the cut surface and result in an electric field. The electric field can create a discharge between the workpiece and the diamond tool, or it might induce a plasma with radicals (§3.3). Both processes can cause significant tool wear.

### 3.2 Measurement of electrostatic voltage

#### Measurement during cutting

To measure the electrostatic charge that has been produced during cutting, a non-contact electrostatic voltmeter is used, so the cutting process is not disturbed. As the capacity (C) of the workpiece decreases with decreasing thickness (d) of the workpiece, the voltage (V) is not constant at a constant charge (q) generation at the free surface:

\[ V = \frac{q}{C} = \frac{q}{d \varepsilon R A} \]  

(1)

with \( \varepsilon \) the relative permittivity and A the surface. In figure 2 the voltage decrease can be seen against time during orthogonal turning of tubular PC.

In section A the feed is set to 7.5 \( \mu \text{m/s} \), a decrease in voltage with decreasing thickness of the workpiece is observed. The high peak appeared after discharging stopped and charge had to built up again before discharging could start again. In section B the feed is reduced to zero, no cutting and no reduction in thickness, and a step in the measured voltage can be seen. The measured voltage still decreases in time, since the relaxation of the polymer still causes some small cutting action. In section C the feed is set back to its initial value and the voltage starts at the same value as where it stopped before reducing the feed to zero. The slope is the same as in section A. From this measurement it follows that cutting results in more charging than pure sliding.

Since the electric field is determined by the charge on the surface and not by the (measured) voltage, first the charges have been calculated using equation 1. From these charges an electric field can be calculated of 1000 V/mm for PMMA and 1600 V/mm for PC [9]. The breakdown strength of dry air is 1000 V/mm [11]. This means that discharging can occur during diamond turning of PC and this was also observed (see §3.3).

#### Influence of chain scission on surface charge

The measured voltage during turning of PC is higher than that during turning of PMMA. A possible explanation for this could be that during turning of PC more chains are cut than during turning of PMMA. When chain scission occurs, radicals are formed that may contribute to additional charging. More chain scission would result in more charging. Since PC has a higher chain density than PMMA (2.94 \( 10^6 \) chains/m\(^3\) for PC and 0.77 \( 10^6 \) chains/m\(^3\) for PMMA [12]), it can be expected that PC will charge more than PMMA.

To validate whether chain scission occurs, gel permeation chromatography (GPC) measurements were performed on the bulk material and the cut chip. GPC is a size-exclusion technique that can determine the molecular weight of a polymer. Although the measurement error is smaller than 2%, variations in the bulk material may be larger (up to 10%). Table 1 shows the results of the used PC and PMMA. It can be seen that the cut PC has a higher \( M_w \) than the uncut PC, but this can be ascribed to variations of the bulk. Uncut PMMA has an \( M_n \)-value higher than \( 10^6 \) g/mol, since it was not measurable by the used GPC instrument. However, the cut PMMA was, indicating that chain scission occurred during turning.

<table>
<thead>
<tr>
<th></th>
<th>( M_n ) in g/mol</th>
<th>( M_w ) in g/mol</th>
<th>PDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC uncut</td>
<td>16323</td>
<td>41506</td>
<td>2.543</td>
</tr>
<tr>
<td>PC cut</td>
<td>16738</td>
<td>43203</td>
<td>2.581</td>
</tr>
<tr>
<td>PMMA uncut</td>
<td>&gt;10( 6 )</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PMMA cut</td>
<td>38902</td>
<td>284493</td>
<td>7.313</td>
</tr>
</tbody>
</table>

Table 1. Results of GPC measurements of uncut and cut materials (mean \( v_c \); 2.4 m/s, feed 0.25 \( \mu \text{m/rev} \), depth of cut 5 \( \mu \text{m} \)).

Although it was expected that PC would show more chain scission, the opposite is the case. Although the charging of PMMA can still be attributed to chain scission, this cannot be the case for PC. Therefore, frictional effects should be investigated for the charging of PC. From increasing cross-linked PMMA grades it is known that surface charge increases with it, too [9]. This indicates that chain scission can play a role in surface charging.

#### Influence of relative humidity on surface charge

Humid air conducts electric current better than dry air. The influence of humid air on the charging of the workpiece surface has been investigated by adding water vapour to the dry air. The surface charge has been derived for different levels of relative humidity (RH) of the environment during turning. Figure 3 shows the relationship between the surface charge on the workpiece and the relative humidity of the cutting environment. It can be seen that applying high RH values prevents tribo-electric charging.

![Figure 3: Influence of relative humidity on surface charge during turning of PMMA [10].](image)

### 3.3 Visualisation of electrostatic discharging

#### Visualisation

It has been suggested by industry that diamond tool wear may occur by electrostatic discharging. The electric field during dry cutting PC reaches the breakdown strength of air and therefore it should be possible to visualize this breakdown during the precision turning of PC. Cutting with a faceted tool on tubular PC (width of cut 2 mm) in a dark environment resulted in the luminescence shown in figure 4. From this photo the luminescence appears near the cutting edge and at the rake face of the tool. During

\(^1\) \( M_n \) is the number averaged molecular weight, \( M_w \) is the weight averaged molecular weight and PDI is \( M_w/M_n \). Mono-disperse polymers have PDI=1.
However, these elements cannot be found in the react with the carbon from the diamond to form CO or.

The OH radicals however are highly reactive and can measured light intensity if the setup has changed. The coupling of lens to fibre can cause a big difference in therefor not react with the carbon atoms in the diamond.

It was shown that frictional aspects are responsible for the charging of PC, this is in accordance with [10] where it was shown that higher sliding velocities result in higher photon intensities.

3.4 Tool life experiments

Expected tool wear behaviour as a result of electric field

Assuming that discharging occurs, the energy during acceleration of a charged particle in an electric field can be calculated by:

\[ U = E \cdot q \cdot \lambda \]  (2)

With \( E \) the electric field strength and \( \lambda \) the mean free path of the charged particle (\( \lambda = 10^{-5} \) m for an electron in atmospheric air). Turning PC would result in a maximum energy of an electron of 16 eV and 8 eV for PMMA. During discharging several processes can occur: excitation of the air and impact of the electrons on the diamond. For excitation of nitrogen in air an energy is required of approximately 9 eV. From these values and the spectral measurements of PC and PMMA it can be concluded that discharging during turning of PC will occur and discharging during turning of PMMA is absent. During turning of PC enough energy would be available to break a diamond bond with bond dissociation energy of 7.4 eV. For PMMA the required energy is just sufficient for dissociation to occur. The ionisation energy of \( \text{H}_2\text{O} \) is 12.6 eV and for \( \text{O}_2 \) 12.1 eV [14], which implies that ionisation of \( \text{H}_2\text{O} \) and \( \text{O}_2 \) can occur during turning of PC. Whether these ions would have enough energy to dissociate the diamond lattice is questionable, since \( \lambda \) becomes significantly smaller for these ions (~10^{-7} m).

But it is known that OH radicals can be formed during discharging in air [11]. Based on these calculations it can be expected that PC will show (more) tribo-electric tool wear than PMMA during dry turning, since it produces a higher electric field that is capable of OH radical formation. OH radicals have been detected in the spectrum (§3.3).

From figure 3 it follows that the surface charge decays to zero at RH>70%, implying that the energy for breaking a carbon atom out of the diamond lattice will not be sufficient anymore. It is expected that tribo-electric tool wear will decrease or be absent during application of high RH values.

Experiments and results

To investigate the influence of tribo-electric tool wear during diamond turning of polymers, tool life experiments are conducted. All materials are precision turned with a natural (type IIa) mono-crystalline diamond tool (110)(100). Length of cut is 85 km with a depth of cut of 25 µm and a feed rate of 20 µm/rev. The mean cutting speed was 6.6 m/s. Every material was cut with three tools to ensure tool wear reproducibility.

Figure 6a shows the diamond tool wear after turning PC in dry conditions. Turning of PC resulted in wearing the cutting edge to a facet; see figure 6c for the schematic representation of the observed tool wear. PC adhering to the facet wear at largest chip thickness decreased from 9 µm to 5 µm in wet mode), but the observed wear pattern was the same for both conditions.
During wet cutting of PC, tribo-electric tool wear is active. The amount of tool wear during dry cutting of PC is more than that during dry turning of PMMA. Since the environment is less, the observed wear pattern is the same. The same wear pattern is also observed in the turning of PC in a humid environment. Although dry cutting of PC resulted in discharging, it was expected that the diamond tool wear would be different (and more) than that during dry turning of PMMA and turning PC in a humid environment. Although the observed wear during turning of PC in a humid environment is less, the observed wear pattern is the same. The same wear pattern is also observed in the crater of the diamond tool after turning PMMA. It resulted in crater wear and a heavily damaged cutting edge ("chipping"). The crater wear shows the same kind of wear pattern as observed at the facet wear during cutting of PC.

3.5 Discussion
Since dry cutting of PC resulted in discharging, it was expected that the diamond tool wear would be different (and more) than that during dry turning of PMMA and turning PC in a humid environment. Although the observed wear during turning of PC in a humid environment is less, the observed wear pattern is the same. The same wear pattern is also observed in the crater of the diamond tool after turning PMMA. Since the amount of tool wear during dry cutting of PC is more than during wet cutting of PC, tribo-electric tool wear is active during precision turning of polymers. Although all experiments resulted in the same wear pattern and tribo-electric wear can be excluded during wet cutting (no charging, hence no discharging and no plasma), one or more other tool wear mechanism must also be active.

4 TRIBO-CHEMICAL TOOL WEAR
Although temperatures are too low for thermal oxidation to occur (section 2) during diamond turning of polymers, it is believed that a chemical process causes the observed wear patterns in figure 6. Paul and Evans said that [2] ‘the chemical significant step in tool wear is when carbon atoms are pulled from the tightly bonded diamond lattice'. Their work concluded that polymers could be turned without chemical tool wear, because they do not have unpaired d-electrons.

In contrast to the work of Paul and Evans [2] in this paper it is concluded that tribo-chemical tool wear can have an important role in the precision turning of polymers. The reason for this is the observed chain scission (§3.2) that results in highly reactive radicals. Traditionally, radicals are regarded as main active particles that initiate chemical transformations [11]. Since chain scission was observed during cutting of PMMA the “chipped” cutting edge can be ascribed to a chemical reaction of the created (polymer) radicals and the diamond tool. The wear pattern that is observed during turning of both PC and PMMA may be ascribed to a chemical cause, since the other wear mechanisms were excluded. Further research on the tribo-chemical tool wear will be performed.

5 CONCLUSIONS
Several diamond tool wear phenomena have been discussed in this paper. Although tribo-electric phenomena have been observed during diamond turning of polymers, experiments indicate that it is not the dominant tool wear mechanism for the used polymers of this research. Tribo-chemical tool wear is one of the known wear mechanism that is remaining, but further research is needed on this subject.

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7 REFERENCES