Electrostatic tool wear in diamond turning of amorphous polymers

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Abstract

An increasing amount of products is made from polymeric materials. Examples are contact lenses, spectacle lenses, intra-ocular lenses and drums for copiers. Also in prototyping polymeric materials are more and more used, e.g. lenses for DVD/CD players. For higher flexibility and higher accuracies, these products are being precision turned with diamond tools. Since diamond is the hardest material in the world and polymers are relatively soft only little tool wear is expected, but the opposite is the case. Some industrial laboratories claim that electrostatic discharging between tool and workpiece causes diamond tool wear. This may be true, as both diamond and polymer are electrical insulators. During cutting friction appears and this would cause electrostatic charging. This paper presents some results of the influence of electrostatic charging in the precision turning process of polymers on diamond tool wear.

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 [1]. Scission of the polymer chains during the cutting process may also result in an additional charging during turning. 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. Both processes can cause significant tool wear.

Measurement of electrostatic voltage

To measure the electrostatic charge that is produced during cutting, a non-contact electrostatic voltage measuring method [2] is used, so the cutting process is not disturbed. As the capacity (C) of the workpiece decreases with decreasing thickness (d), the voltage (V) is not constant at a constant charge (q) generation at the free surface:

\[ V = \frac{q}{C} \]

with \( \varepsilon \) the relative permittivity and A the surface. In figure 1 the voltage decrease can be seen against time during orthogonal turning of tubular polycarbonate (PC). In section A the feed is set to 7.5 \( \mu \)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 be built up again before discharging could start again. In section B the feed is reduced to zero (no cutting, thus 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. 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 800 V/mm for polymethylmethacrylate (PMMA) and 1600 V/mm for polycarbonate (PC) [3]. The breakdown strength of dry air is 1000 V/mm [4]. This means that discharging can occur during diamond turning of PC and this was also observed.

Luminescence

It has been suggested by industry that diamond tool wear may occur by electrostatic discharging. It was shown in the previous section that the electric field during dry cutting of PC reaches the breakdown strength of air; 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 2. From this figure it is clear that luminescence occurs between chip and tool rake face. During cutting of PMMA no luminescence was visible. These observations were also verified by

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**Figure 1:** Electrostatic voltage against time during diamond turning of PC (RH=30%).

**Figure 2:** Side view of the turning process of PC, showing light emission (\( v_c = 1 \) m/s, \( f = 5 \) \( \mu \)m/rev).

**Figure 3:** Recorded \( \text{N}_2 \) spectrum during turning of PC with a diamond tool.
spectroscopic measurements with an Ocean Optics HR2000 spectrometer. Figure 3 shows the recorded spectrum as a function of cutting speed during diamond turning of PC. Clearly visible is the characteristic wavelength of 337 nm of N₂ second positive system. Contrary to PC the PMMA samples showed no recorded spectrum, meaning that no luminescence is generated during turning of PMMA. This seems to be in accordance with the measured surface charges, from which it could be concluded that PC should show luminescence while PMMA should not.

**Influence of chain scission**

It may be questioned whether charging of the polymers during turning results from polymeric chain scission. PC and PMMA have different chain densities. PC has a chain density of 2.94⋅10²⁶ chains/m³ and PMMA has a chain density of 0.77⋅10²⁶ chains/m³ [5]. It could be expected that, if chain scission contributes to charging, PC would show a higher charge than PMMA since more polymeric chains should be destroyed during cutting. To check this Gel Permeation Chromatography was used to measure the chain length distribution of the polymer before and after cutting. Table 1 presents the results of these measurements.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mₙ before cutting in g/mol (Poly Dispersity Index)</th>
<th>Mₙ after cutting in g/mol (Poly Dispersity Index)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>16323 (2.54)</td>
<td>16738 (2.58)</td>
</tr>
<tr>
<td>PMMA</td>
<td>~ 10⁻¹ (–)</td>
<td>38902 (7.31)</td>
</tr>
</tbody>
</table>

The Mₙ value of the PMMA before cutting was out of the range of the GPC apparatus and should therefore be of order 10⁷ g/mol. For PC it can be seen that the Mₙ number actually increases a bit, which is probably due to variations of chain density within the used material. However, for PMMA it can clearly be seen that chain scission occurs, since Mₙ decreases two orders of magnitude for the cut sample. It can therefore be stated that the amount of charging during cutting is not the result of chain scission, but purely a matter of friction, since PC charges more than PMMA.

**Tool wear experiments**

Several tool wear experiments were performed [6]: dry turning PC and PMMA and wet turning PC. Wet turning is chosen, because an increase in relative humidity causes the surface charge to decrease. In fact, above 70% RH, no surface charge can be measured anymore [3]. It was also observed that no luminescence occurred during cutting in a humid environment. If electrostatic discharging should be the dominant tool wear mechanism, tool wear should decrease significantly by applying humid conditions. By choosing these three conditions it should be possible to observe the influence of tribo-electricity on diamond tool wear. Only dry turning PC resulted in luminescence, therefore it was expected that dry turning PC would result in more tool wear than the other two conditions. It was found that in applying a humid condition during turning the diamond tool wear did not decrease significantly (factor 2). The observed wear pattern (figure 4) was the same for both dry and wet cutting conditions. The sharp cutting edge is worn to a facet both on rake and clearance face and it reaches less far on the rake face than the used depth of cut (25 micrometer). PMMA showed the same wear pattern, but the tool wear expresses itself as crater wear. This might be a cause of the actual cutting mechanics, but this will be further investigated. PMMA also showed “chipping” of the cutting edge [6]. This chipping might originate from the observed chain scission that results in reactive radicals that attack the cutting edge.

**Conclusions**

Experiments have shown that luminescence as a result of high electrostatic field strengths (and possible discharging) can appear in diamond turning of polymers. Applying humid cutting conditions causes the luminescence to disappear. Tool life experiments show that the observed tool wear does not decrease significantly by applying humid conditions while cutting PC (that shows luminescence in dry cutting). Therefore it can be concluded that a different tool wear mechanism must be dominant. This is confirmed by the observed tool wear of PMMA that does not show luminescence during cutting, but shows a same wear pattern on a different place on the tool. For PMMA it was found that polymeric chain scission during turning results in a serious wear of the cutting tool.

**References**