"The origins of triboemission – Correlating wear damage with electron emission

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Abstract

Triboemission – i.e. the emission of photons, electrons and other charged particles that arise from a sliding contact – may play a key role in tribochemical processes, such as lubricant degradation. However, the mechanisms that give rise to this type of emission are not well understood. For the first time, we present spatially resolved measurements of electron emission, obtained as a range materials are worn. These are obtained from scratch tests, carried out under vacuum conditions (10^-3 Torr), in which microchannel plates coupled to a phosphor screen are used to image electron emission.

The results show that electron emission occurs at specific locations on the worn surface and, depending on the conductivity of the material, these sites remain active and decay with a time constant of up to several seconds. SEM images of the worn surface at these sites reveal that either surface fractures or molecular fracture products, which then bombard the surface leading to secondary emission. The strong geometric correlation between damage topography and electron emission distributions shows the potential of using this technique to monitoring wear and crack formation in real time and under high (30x) magnification.

1. Introduction

The emission of particles, (photons electron, protons, positive and negative ions), that are stimulated by frictional contact between sliding bodies, is often referred to as ‘triboemission’ [1–3]. Numerous studies have demonstrated that this type of emission can occur under vacuum conditions, the majority of which measured spatially averaged signals from optical and electrical probes, located in the vicinity of a sliding contact [1–7]. These signals show instantaneous peaks, caused by bursts of emission, with durations typically less than a few milliseconds. When the probability density of these events is analysed, Shannon spectral entropies for a 40 ms time window are between 0.23 and 0.26 [8,9], which suggests partially deterministic mechanisms are responsible. However, until now, the exact origin of these events is unclear.

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rubbing can lead to particle emission. These include: i) thermal emission due to frictional heating [24,20,25]; ii) field emission due to an accumulation of surface charge caused by triboelectrification [26]; iii) fractoemission [6]. The last of these is a complex process that can include thermionic and field emission, but is also believed to result from strong electric fields due to charge separation between opposing faces of wear cracks [27]. Due to the difficulty in obtaining spatially resolved measurements on moving surfaces, very little direct evidence of these different emission mechanisms has been acquired under sliding conditions. If more were known about how triboemission occurs, its role in tribochemical process could be better understood and optimised.

The current paper reports research using a recently developed measurement system [12] to spatially resolve emission events as surfaces are scratched by a single asperity contact. Results are presented in terms of emission images for different materials in order to shed light on how intensity and spatial distribution depend on material characteristics. Furthermore, SEM images of the wear track show how the distribution of emitted particles is strongly correlated to damage geometry on the sample surface.

2. Test methods

The test apparatus, shown schematically in Fig. 1, simulates a single sliding asperity contact and uses microchannel plates (MCP) – i.e. arrays of electron multipliers – coupled to a phosphor screen to capture spatial distributions of the resulting triboemission. The asperity contact is produced by loading a 100 μm radius diamond tip (Syntone-MDP Ltd) onto the rotating disc specimen by a 1 mm diameter steel arm and dead weight loading arrangement, applying 0.5 N. This setup is located within a vacuum chamber maintained at 10⁻⁵ Torr by a turbomolecular pump and Pirani gauge (Edwards Vacuum). The disc is rotated by an external motor, via a dynamically sealed shaft, to produce a contact sliding velocity of 50 mm/s.

The two MCPs, in a chevron arrangement with an active diameter of 75 mm, are located 10 mm above the sliding contact. The MCPs are coupled to a phosphor screen, which converts the multiplied electrons into photon images that are captured by an external, light shielded, high speed camera (Miro ex2 with Fujian 35mm f1.7 lens) at a rate of 170 Hz. The voltages applied to the upper and lower MCP and phosphor screen are 0, +1.5 and +5 kV, respectively (note the lower MCP is grounded so as not to influence the trajectory of charged particle emission).

The MCPs have the following detection efficiencies: i) 0.01–50 keV electrons: 10–85%, ii) 1–50 keV positive ions: 5–85%, iii) UV radiation 300–1100 Å: 5–15%, iv) UV radiation 1100–1500 Å: 1–5%, v) soft X-rays 2–5 Å: 5–15%, [28,29]. The system therefore has the ability to detect the above particles; however, those detected in this study are expected to be electrons, since positive ions must have energies above 1 keV due to the biasing of the plates and photons have considerably lower detection efficiencies. Furthermore, other tests in our lab show a correspondence between MCP and electrometer charge measurements, which suggest that the response is not dominated by photon emission.

An encoder on the disc shaft is coupled to a DAQ (NI 6009), which acquires the disc's angular position and synchronises this with the camera acquisition. This enables the emission events to be correlated to the position of the stylus on the specimen surface. After each test, scans of the specimen surfaces were performed using a variable pressure SEM (pressure of 60 Pa, 15 kV beam voltage and a ×100 magnification). This method uses a custom made jig to ensure that the sample is oriented in the same position in the SEM before and after each test.

Three types of disc specimen materials are tested; pure Al2O3, Al with a 5 μm thickness Al2O3 oxide layer, produced by anodising a polished Al specimen, (Metroplating Ltd. UK), and SiO2 glass. The disc samples have diameter 46 mm and thickness 6 mm and are cleaned with toluene then isopropanol in ultrasonic bath for 15 min each, prior to each test.

Al2O3 is a HCP crystalline granular insulating material (volume resistivity > 10¹⁵ Ω cm). While Al and Al2O3 specimens is an insulating/conductive composite with a hardness mismatch between coating and substrate making it prone to cracking failure. The SiO2 specimen is insulating (volume resistivity 10⁴–5 Ω cm) and was chosen for its smooth surface (0.007 μm Ra roughness), which enables identification of surface damage. The nominal Hertz contact pressure for the interface between each disc specimen and the diamond tip is > 10 GPa and sufficiently high compared to each material’s hardness to cause severe wear.

3. Results and discussion

The average intensity of each phosphor screen image is plotted as a function of time in Fig. 2 for the scratch tests on Al2O3 and Al + Al2O3 layer. As observed by Nakayama et al. [8] and others [1–6], the emission is characterised by numerous high intensity peaks representing bursts of emission. It is also evident that the pure Al2O3 specimen shows a sustained low level of emission, probably due to charging, which builds for the first 15 seconds of sliding and remains approximately constant for the remainder of the test (note sliding starts at t = 5 s). Fig. 2(b) shows only the highest intensity peak of Fig. 2(a). Here, the intensity rises rapidly (over < 10 ms) and then decreases gradually (over ~300 ms). This is in contrast to triboemission measurements by previous researchers who observed bursts that fall rapidly after their initial rise, even for tests carried out in alumina specimens [1–3,5,8]. We suggest that this discrepancy is because previous measurements were made by single point sensors permanently located close to the stationary stylus specimen. This means that continued emission from the moving surface after the contact has passed (i.e. “after-emission” [27]), was not be detected. Conversely, in this experiment, emission from the whole of the wear track is recorded. Fig. 2(d) shows the average emission versus time for the scratch test on the oxidised Al specimen. This shows large emission peaks however no baseline emission or after emission is observed. The emission from this specimen, which we attribute to the fracture of the oxide layer, can be observed in greater detail in Fig. 2(d).

Fig. 3 displays the same average phosphor-screen intensity data in Fig. 2, but this time plotted against the cycle number and

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Fig. 1. Schematic diagram of test apparatus.
angular disc position of the stylus relative to the disc (with each coloured square representing the average phosphor-screen intensity). The horizontal lines on the figure show that emission is occurring repeatedly at specific locations of the disc surface (approximately 90 and 180° for the pure Al₂O₃ and 50 and 135° for the Al + Al₂O₃) as it rotates. Furthermore, the map of pure alumina test shows vertical lines of gradually decreasing intensity emanating from these horizontal lines. These correspond to the after-emission, first shown in Fig. 2(b). The Al + Al₂O₃ specimen on the other hand shows no vertical after-emission.

In addition to providing spatially averaged data, the phosphor-screen images can be viewed individually as the examples in Fig. 4 show. Here, four video frames are presented, each corresponding to a different time within a specific disc revolution. The upper-left image shows an initial burst of emission occurring at the scratch tip. The shape of the emission is linear, suggesting it may originate from a crack or grain boundary on the specimen. Subsequent frames show the emission occurring at 0.6, 1.06 and 1.6 s after this initial event. From this, it can be seen that the emission pattern has rotated 92°, 213° and 291°, respectively, corresponding to the rotation of the disc. This clear example of continuous after-emission occurring throughout an entire disc revolution is further shown by the video file (see Supplementary material) and it is again in contrast to the discrete, single frame, emission events of the oxidised aluminium specimen tests.

There are two ways in which the phosphor-screen images in Fig. 4 can be processed. Firstly, they may be averaged to give the result in Fig. 5(a), where it can be seen that emission intensity is greatest at the stationary scratching tip and decays along the wear track. Alternatively, each video frame can be rotated by an angle corresponding to the amount that the disc has rotated during the test. If each video frame is processed in this way, then the result

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Fig. 2. Average phosphor screen intensity vs. time for Al₂O₃ specimen (a) complete test, (b) single revolution; Aluminium specimen + 25 μm Al₂O₃ layer (c) complete test, (d) single revolution.

Fig. 3. Average phosphor screen intensity as a function of time and disc position.
can be thought of a video in which the disc is stationary while the contact moves in a circular path around the wear track. This is possible, since the angular position of the disc is recorded and synchronised with the camera acquisition. Furthermore, if these rotated video frames are averaged they can show the variation in emission of the disc surface with each revolution. The results from applying this approach to a single rotation are displayed in Fig. 5 (b). This enables the linear emission pattern, first shown in Fig. 4, to be observed more clearly and confirms that the location of emission is constant. Furthermore, if emission is caused by damage of the specimen surface, then these images show a new method of monitoring the evolution of wear in real time. If the images are averaged without the rotation being applied, the spatial information is lost (Fig. 5(a)).

The results of this rotated average image processing method in Fig. 5(b) raise the possibility of correlating the recorded emission patterns with local topography of the specimen surface. With this aim, SEM images of the disc specimen were taken before and after testing. Fig. 6 shows one such example, in which the post-test SEM was taken at the same location on the disc surface where a high intensity burst of emission occurred. It can be seen from Fig. 6 that a grain of Al₂O₃ has been removed from the disc surface at this location. This mode of tribological failure, termed “pullout”, is well known for polycrystalline alumina [30] and its occurrence is responsible for the abrupt change in wear rate experienced by this material [31].

The disordered granular structure of the polycrystalline alumina, results in a complex wear process and numerous emission patterns which continually evolve throughout the test (see Supplementary video). An additional complication is that its roughness prevents surface fractures from being identified clearly by SEM. Therefore, in order to make the comparison between triboemission measurements and surface topography clear, tests were performed on a smooth (~8 nm Ra roughness) glass specimen. And, to further simply the wear process, an artificial scratch was made by hand on the disc surface using a steel point, prior to testing. This produced a radial fracture at a known disc location as shown, prior to testing, by the SEM images in Fig. 7(a) and, post testing, in Fig. 6(b). The wear track has intersected the long axis of the defect at approximately 90° so that the diamond tip has contacted only a small section of the crack's length. Fig. 7(c) is a rotated average emission intensity map from the same test. Here, it can be seen that the emission is concentrated in a single location on the disc surface. Furthermore, the zoomed in triboemission image in Fig. 7(d) shows a striking similarity to the SEM image of the wear track at the same location, both in terms of shape and orientation (being aligned radially on the disc).

Comparing the length scales in Figs. 7(b) and 7(d), shows that the features of the crack on the phosphor screen have been magnified by ~30×. This magnification results from the divergence of emission depicted in Fig. 1, and is believed to be caused by the repulsion between the emitted like charged particles as they travel the 1 cm distance from specimen to MCP. This suggests that the technique could be developed to monitor wear mechanisms in real time at high magnification, or more generally that MCPs could be used to detect defects and crack propagation in stressed components. Furthermore, magnification could be increased by extending the distance between the MCP and specimen surface.

The results presented in this paper suggest that the phenomena of frictionally stimulated particle emission, referred to as triboemission, is in large part caused by surface fracture. In other words, triboemission is a subset of fractoemission in which fracture is caused by sliding wear – a view that is coherent with those of Dickinson et al. [6] and Miura et al [32]. This conclusion is supported by the following observations. Firstly, for both pure alumina and glass wear, maximum emission occurred in discrete locations where fracture has occurred (although it can be seen from SEM Fig. 7b that electrons are emitted from a region outside the wear track, the SEM image in 7b shows that fracture and material removal has also occurred at these locations). Secondly, after-emission exemplified by the curve in Fig. 2(b) are very similar to those measured after tensile fracture of alumina composites [27] (though this may also result from relaxation of excited states). Thirdly, for the Al+Al₂O₃ specimen test, fracture is the dominant failure mode due the stiffness mismatch between substrate and coating. Fourthly, no after-emission was observed with this specimen, which is congruent with the charge separation model (discussed below), since the conductive substrate conducts away charge from the cracked oxide layer. More generally, this agrees with Nakayama’s and others finding that triboemission increases with decreasing specimen conductivity [1].

An alternative explanation is that tribocharging, rather than fractoemission, is the cause of the observed emission – i.e. opposite charge accumulates on each of the two counter bodies during rubbing, and this results in an electric field, that is sufficiently strong at the sharp edges of defects to cause field emission. This would be in agreement with work by Nevshupa and co-workers [33,34] and is supported by previous observations that triboemission is more
intense when dissimilar materials are rubbed together. However, it is unlikely that tribocharging is the sole cause of the observed emission for the following reasons: i) additional tests were run in which the scratch applied to the glass disc at a location outside (1 mm away from) the wear track, and, in these cases, no localised emission was observed while rubbing, ii) Fig. 6 shows that the Al₂O₃ wear track is smoother than the unworn surface and it is only after grain pullout that emission occurs – this suggests that fracture is required to cause

Fig. 5. Phosphor screen intensity for scratch test on Al₂O₃ (a) average over whole test, (b) rotated average for single rotation.

Fig. 6. SEM image of Al₂O₃ specimen surface (a) before test, (b) after test showing location of emission/grain pull-out.

Fig. 7. SEM image of SiO₂ specimen surface (a) before test, (b) after test; Rotated average phosphor screen image during test from (c) whole specimen, d) defect location.
emission rather than simply a rough surface. It is therefore concluded that the observed triboemission is due to fractoemission, however, emission behaviour is also likely to be influenced by tribocharging and this is the subject of ongoing study.

It follows from this that knowledge of fractoemission mechanisms can be applied to triboemission behaviour. This is advantageous firstly because fractoemission has been studied in greater detail than triboemission and its mechanisms are better understood. Fractoemission is believed to result from a charge separation mechanism [27]: i) fracture causes crack faces with an uneven distribution of charge between them, either due to piezoelectricity or crystal defects [35], and a high field gradient due to the small distance between faces ii) fracture products and desorption of volatiles lead to an increased pressure within the crack, iii) gas discharge takes place within the crack due to pressure and electric field gradient, iv) electron bombardment of the crack walls leads to the emission of ions.

One of the motivations for this study is to shed light on the role of triboemission in tribochemical processes, such as boundary film formation and lubricant degradation. Assuming that triboemission is essentially fractoemission that occurs during rubbing, the following conclusions can be drawn. Significant triboemission effects will only occur in metallic components, if an oxide film or non-conductive coating is present. Secondly, when a liquid lubricant is present, its interaction with triboemission will be governed by the relative rate at which it can ingress into cracks relative to the crack’s velocity (estimates [35] suggest these rates are comparable).

As argued by Sweeting for fractoemission, if the rate of liquid ingress is less than the crack velocity, emission will be unaffected by the presence of liquid. Therefore, the emitted electrons that we detect will interact with the lubricant and may potentially initiate tribochemical reactions. Conversely, if the liquid lubricant reaches the fractured surfaces before discharge occurs, it will be subjected to the crack induced electric field and breakdown will depend on the liquid’s dielectric strength.

4. Conclusions

Triboemission may play a role in tribochemical processes, however there is uncertainty regarding the mechanisms responsible. This is mainly because, until recently, measurement techniques provided no spatial information. To address this, the current research uses a vacuum tribometer, in which an MCP and phosphor screen were positioned close to a single sliding asperity. Triboemission is measured using the electric field and breakdown mechanism [27]: electron bombardment of the crack walls leads to the emission of ions.

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Data statement

All data and results are made available upon request by email to the corresponding author or tribology@imperial.ac.uk.

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