Vol. 36, No. 3 (2014) 229-235

Tribology in Industry

www.tribology.fink.rs

RESEARCH

X-Ray Emission during Rubbing of Metals

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Keywords:

X-ray
Emission
Triboluminescence
Triboelectricity
Stick-Slip motion

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A B S T R A C T

A good deal of work carried out in recent past has shown that the triboelectromagnetic radiation produced during peeling of a scotch tape, breaking rock sugar with a hammer, peeling of mica sheets etc. may extend even to X-ray energies. Work on peeling of scotch tape has been particularly successful in demonstrating visible X-ray emission in modest vacuum. The present work looks at the possibility of X-ray emission during rubbing of metals and other selected material pairs in air. Experimental results indicate that X-ray emission indeed occurs during rubbing of even common engineering metals and also other selected material pairs under certain restricted rubbing configurations. It was observed that X-rays could be detected when one of the rubbing surfaces was a thin metal sheet. It was also observed that with the increase in sliding speed X-ray emission increased whereas the increase in load did not have much influence on the emission. Vibration at the contact was found to be an important influential parameter. With the increasing vibration X-ray emission increased. This X-ray emission at the rubbing contact between common engineering materials, if exploited properly, can be of significant use in in-situ monitoring of tribological processes.

1. INTRODUCTION

In recent years there has been a great interest in triboluminescence which in general refers to luminescence generated when certain materials are pulled apart, ripped, scratched, crushed or rubbed causing emission of electrons, ions and photons. This triboelectromagnetic radiation has been shown to extend even to X-ray energies [1]. Although research works since 1930 have shown that peeling of a scotch tape, breaking rock sugar with a hammer, peeling of mica sheets can all be sources of X-rays of various intensities [2,3] following the earlier works Camara et al. [4] only recently demonstrated for the first time that peeling common adhesive tape in a moderate vacuum produces visible emission along with nanosecond 100 mW X-ray pulses with 15 KeV peaks and this they correlated with stick–slip peeling events. This observation motivated further developmental work in this direction and considering that peeling of scotch tape cannot be operated continuously a new method of repeated contacts between silicones with epoxy was used to generate X-ray [5] but this is certainly the early stage of the development of some basic form of a usable source of both soft and hard X-ray devices and more work is needed for practical use.

Triboluminescence is essentially a frictional process and this has been known for centuries in one form or other [6]. One of the postulates to relate friction between contacting solids in relative motion to emission of charged particles is the triboelectric effects at the rubbing contacts. Here adhesion between the interacting surfaces may be taken as the sum of Van der Waals and electrostatic forces and a relation between adhesion and triboelectricity could be arrived at [7]. This however does not explain the emission during scratching of solids where abrasion rather that adhesion is the primary friction and wear mode. Emission of charged particles and photons in air, vacuum and different other environments during scratching of ceramics, glass, anodic aluminum oxide films, polymers and mica by diamond stylus has earlier been demonstrated [8-11]. Emission of photons has also been reported during crushing and scratching of solids [12] but photons detected during sliding of solids were in UV or IR ranges. No X-ray emission during sliding of metals has hitherto been reported.

The proposed stick slip mechanism responsible for the emission of X-rays form the scotch-tape is that with peeling the tape becomes positively charged and the polyethylene roll becomes negatively charged so that large electric fields are built up and become sufficiently strong to trigger discharges. As the pressure reduces during peel off, the accelerated electrons due to discharge generate Bremsstrahlung X-rays when they strike the non adhesive side of the tape [4]. The explanation is now well accepted. However there are at least two issues those need further study. Firstly Camara et al. and others could observe X-ray luminescence only in vacuum though the process of tribocharging may occur even in air possibly with low intensity. Secondly it is possible that this X-ray generation mechanism may apply to other material pairs too.

The present work explores the possibility of X-ray emission during rubbing of metals and other selected pairs of engineering materials in air.

2. EXPERIMENTAL

At the outset in order to understand the magnitude and kind of X-ray emission during peeling of a scotch tape the experiment in reference [4] was repeated but unlike the earlier one this experiment was conducted initially manually in air and the emission was detected and measured using an Amptek X-123 CdTe spectrometer, tuned to detect X-rays. The detector was placed roughly 50 mm away from the peeling zone and the observed X-ray spectrum obtained is shown in Fig. 1. The spectrum resembles those obtained earlier but understandably with low intensity due to the absence of vacuum. This gives peak energy of around 120 KeV and a total count of 55497 over around 10 seconds. Considering that the tests were carried out in air the results establishes the validity of our test procedure.

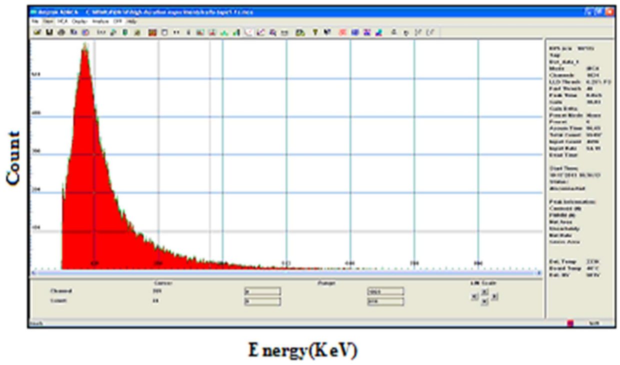


Fig. 1. Plots of X-ray emission count versus X-ray energy during peeling of a common scotch tape (as received from the spectrometer.

A number of preliminary tests with other selected material pairs were also carried out manually in air over a small duration of time ~ 10 seconds. The material pairs included (a) high speed rubbing of a smooth polycarbonate plastic (commonly used compact disc material) on a smooth stainless steel block (b) unwrapping of a piece of Velcro tape (c) high speed rubbing of a thin sheet of paper on a smooth stainless steel block and (d) high speed rubbing of a steel disc on a brass disc. Plots of total count against energy in KeV for these tests are compared in Fig. 2. In all these tests X-ray energy exceeded 120KeV and they had continuous spectrum and therefore they may be taken as hard X –rays. These are very rough preliminary tests and the test duration may differ slightly but not widely.

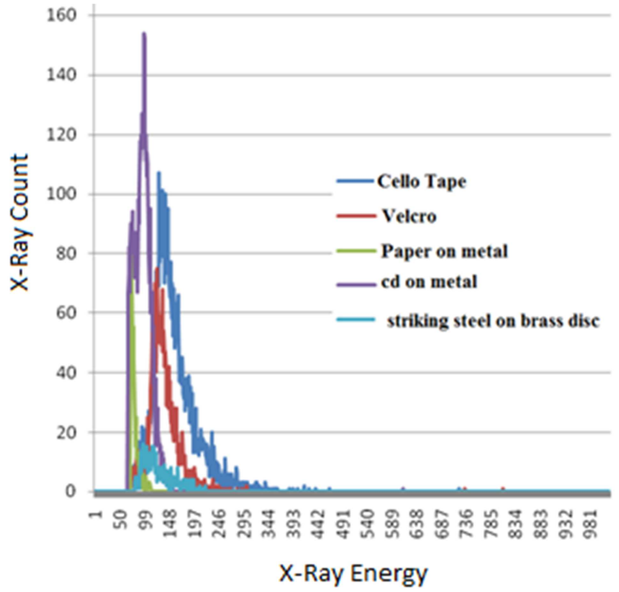


Fig. 2. Plots of emission count versus energy during high speed rubbing of some uncommon material pairs.

Comparison of peak counts with the reported results is therefore not justified. However, the comparison of the energy spectrum shows that there may be many possible tribo-contacts other than peeling of scotch tape that emit X–rays with energy levels comparable to that from scotch tape peeling.

Inspired by these preliminary tests we conducted a series of systematic sliding experiments with selected pair of materials with the objective of firstly detecting X–ray emission in air and secondly the parameters those affect the emission most. It was felt that the results of emission tests in air would be of more practical value. A Commercially available Tribometer (CSM Tribometer, Switzerland) was used for sliding tests. The apparatus uses a static pin of diameter varying between 8 mm to 10 mm and this is pressed against a rotating disc. There are provisions for varying material of the mating elements, load and sliding speed and also measuring in-situ friction and wear. Our phenomenological study of X-ray emission at the sliding contacts between a pair of metals and other materials reveals that emission is possible only when certain very specific working conditions are maintained. Some of these conditions are as follows:

2.1 Thin Metal Sheet: Its Size and Area

No emission could be detected in the usual pin-on-disc configuration with a solid metallic pin pressing against a solid thick metal disc. It was observed that one of the necessary conditions for emission was that one of the rubbing (Fig. 3) materials needs to be a thin sheet and this was obtained in the present configuration by attaching a thin metal sheet of around 150 μm thick at the rubbing edge of the pin.

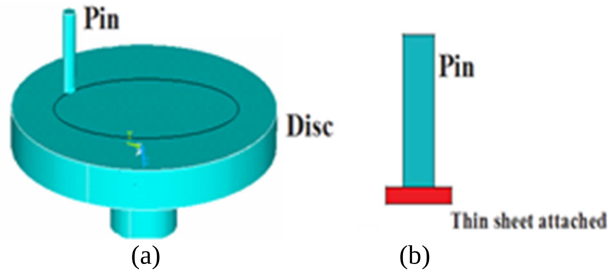


Fig. 3. (a) A typical arrangement for a pin rubbing on a disc, (b) A thin metal sheet attached to the pin end.

Figure 4 shows how the total emission counts vary with sheet diameter and sheet area in contact.

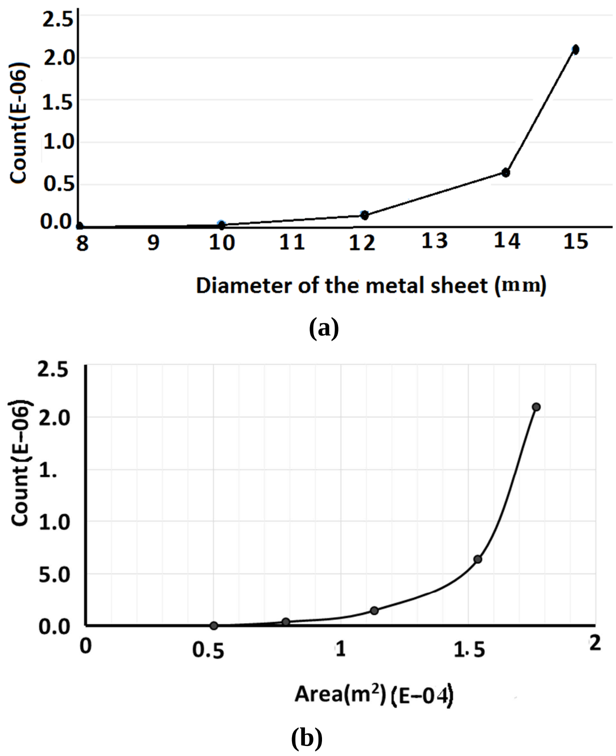


Fig. 4. Variation of total count against the attached copper sheet (a) diameter (b) area rubbing against steel disc at 4 N load 0.45 m/s linear speed with a duration of 60 s.

Here we can observe that only when the sheet protruded out of the solid metal pin dimension X-ray emission could be detected and furthermore with increase in protruded sheet area the emission count increases. This probably indicates that some form of stick-slip motion occurs at the contact between the projected metal sheet part and the rotating disc due to uneven conformity between the rubbing pair and this seems to be a necessary condition for such emission.

2.2 Sliding Speed and Load

Another interesting observation was that emission increased many fold with relatively small changes in sliding speed but it remained fairly constant with the increase in load, Fig. 5 demonstrates this. The results again probably emphasises that with higher speed making and breaking of contacts is likely to increase at the projected metal sheet part whereas increase in load does not affect the emission generation mechanism much.

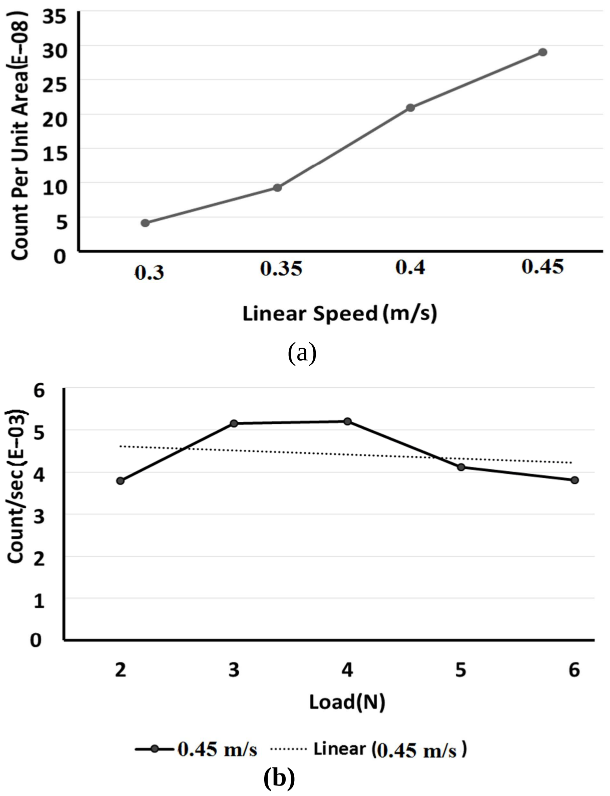


Fig. 5. Varistion of (a) count/unit area with linear speed and (b) count/sec. with load for 10 mm diameter copper sheet rubbing against a stainless steel disc under a normal load of 2 N .

2.3 Vibration at the Contact Zone

Vibration at the contact seems to have a major effect on the emission. It is well known that in rubbing a relatively soft metal with a hard one adhesive wear along with metal pick-up, layer deposition and eventual formation of wear debris occurs and a friction induced vibration is expected in such situations. In order to see the effect of this vibration on emission we carried out a sliding test with a 12 mm diameter tin foil of 150 μm attached to the pin end (see Fig. 3) rubbing against a steel disc at a sliding speed of 0.2 m/s and 4 N load. Irregular metal deposition on the disc and metal pickup on the tin surface were observed after some initial sliding of 6-7 minutes. Emission count was recorded for the first 60 s in each 100 second interval. Very little vibration and accompanying emission could be noted during this period. However beyond around six minutes the count shot up to a fairly high level. This is shown in Fig. 6.

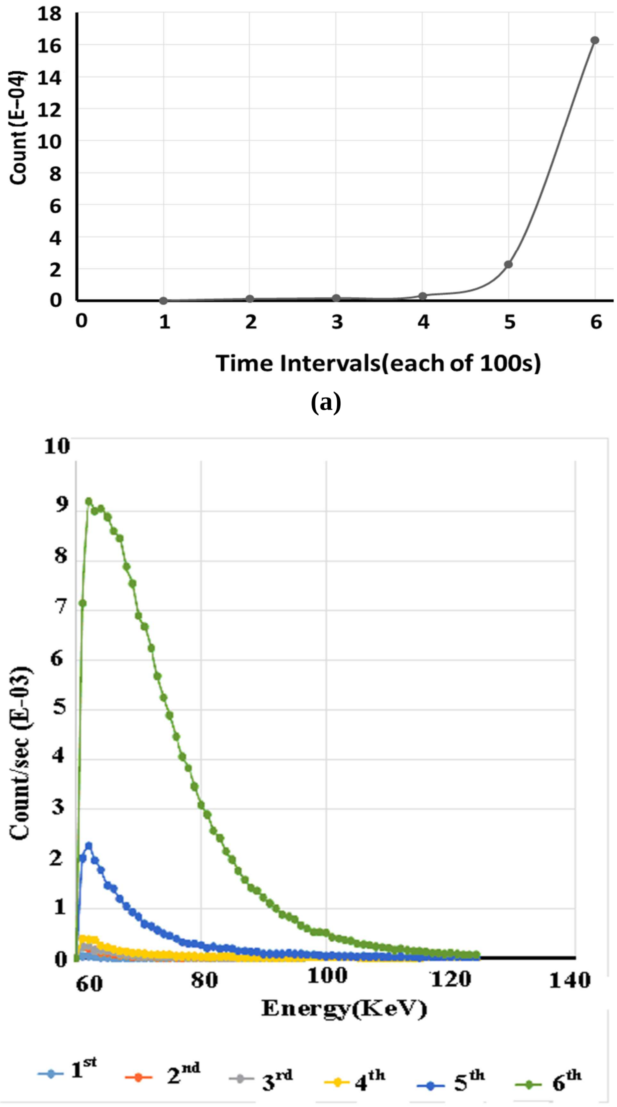
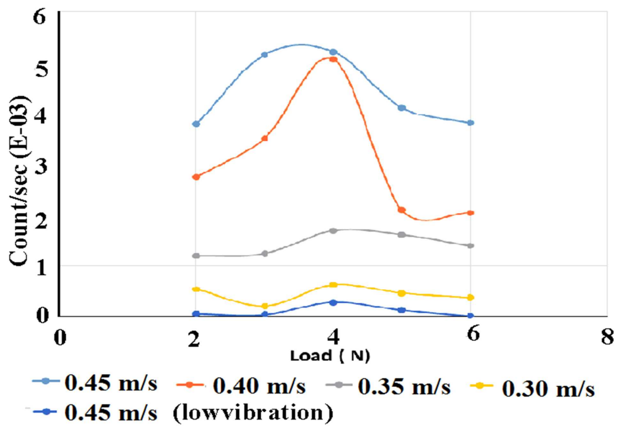
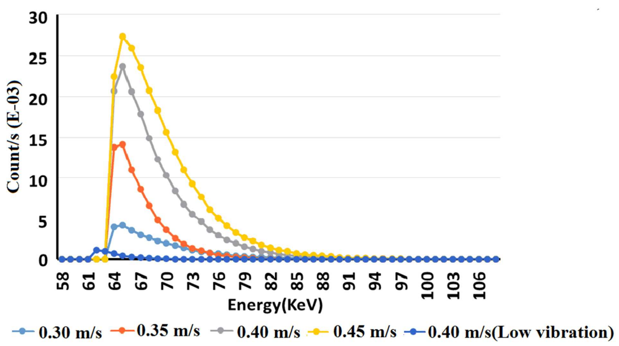


Fig. 6. Variation of emission count with (a) the sliding intervals each of 100 seconds (b) energy at different sliding intervals.

Another experiment lends support to the effect of vibration on emission. A 10 mm diameter copper plate attached to the pin end was rubbed against a steel disc at varying loads and speeds. The plots show as discussed earlier that the emission increases with increasing sliding speed and remains nearly constant with the increase in load. This is shown in Fig. 7. However an exception was noted at a sliding speed of 0.4 m/sec and 4 N load. The count shot up significantly at this stage. Incidentally, large friction induced vibration was also noted at this point possibly because of misalignment of the contacting surfaces.



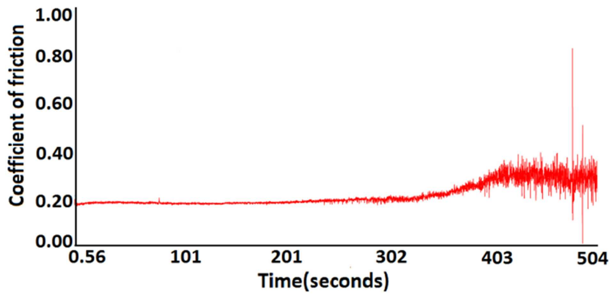
(a)



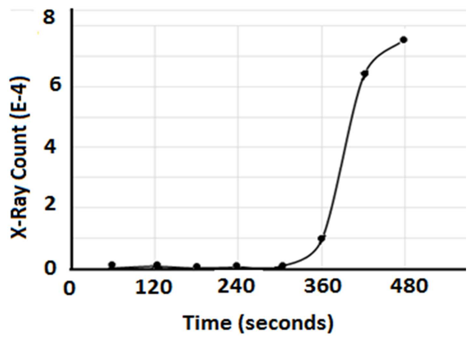
(b)

Fig. 7. Variation of emission count/s against (a) load and sliding speed, (b) energy at varying sliding speeds.

In order to get a direct correlation between contact friction and vibration an experiment similar to the preceding one was carried out where a pin with a 13 mm diameter copper plate attached at the rubbing end was slid against a stainless steel disc at a sliding speed of 0.60m/sec under a normal load of 4 N. Frictional force was noted as the time progressed. The variation of X-ray count with time and the corresponding variation of coefficient of friction with time are shown in Fig. 8.

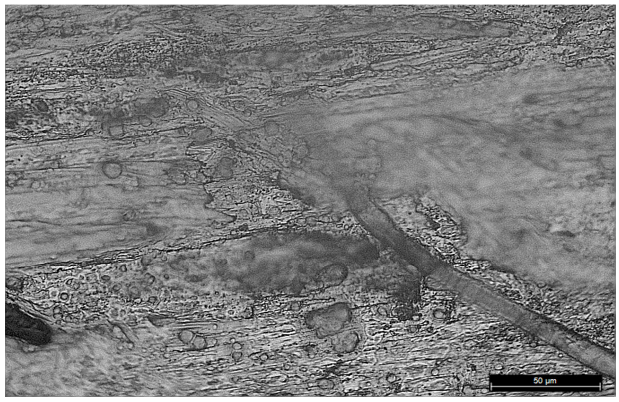


(a)



(b)

Fig. 8. (a) Fluctuation in coefficient of friction as the sliding proceeds and (b) the corresponding sharp rise in X-ray emission at the onset of friction fluctuation.



(a)

(b)

Fig. 9. Optical microscopy of the worn steel disc showing (a) metal deposition and (b) pits and scratch marks during rubbing of metal sheet against steel disc.

It can be seen that fluctuation in friction starts at around 300 seconds and it gets severe at around 400 seconds. This corresponds very well with the emission plot where the emission count starts rising at around 300 seconds and shoots up to high value at around 400 seconds. We also noted the surface undulation caused by copper deposits on the worn out steel plate in an optical micrograph given in Fig. 9.

3. DISCUSSIONS

The explanation of how sticky tapes emit X-rays has now been well accepted and many research groups have extended the work that started back in 1953 in Russia. Stick-slip is a very common phenomenon at the contacting asperity of rubbing solids under load and this is more so for stiff solids where plastic yielding at the asperity peaks is less likely.

For two rubbing surfaces, stick-slip motion occurs when the kinetic friction is less than the static friction, resulting in some elasticity in the system. When a tangential force is applied to initiate sliding contact higher static friction prevents motion until the force is sufficient to overcome the elasticity. As a result the sliding starts with the change from static to dynamic friction and the elastic force accelerates the surface with the rapid unloading of the asperities. The moving surface slows down with the next encounter of the asperities and friction grows rapidly until the surface finally comes to a halt and the cycle starts all over again [13]. This is a simplistic view but in real situations many aspects, such as, surface forces, surface topography, contact mechanics, temperature changes [14,15] etc. need to be taken into account. For very smooth and clean surfaces molecular surface forces would be operative promoting adhesion between the rubbing surfaces and therefore the triboluminescence following triboelectric effects, similar to that in peeling of scotch tape is expected during rubbing clean surfaces with nanometric scale surface heights.

However the results reported here needs to be considered in a different perspective. The extended thin sheet, higher speed and contact vibration, all probably point to macro-scale stick slip motion at the uneven surface contour of the thin sheet. The energy of X-ray is proportional to the charge that is generated at the contact and in this instant this has its origin in the friction energy dissipation. A full theoretical explanation is complex but if the energy dissipated at rubbing contact can be related to the tribocharging then it would be possible to identify material pairs that may not need vacuum to generate luminescent X-ray in air.

4. CONCLUSIONS

Here we reported X-ray generation at the contact between rubbing metals only when one of the surfaces was a thin metal sheet. It was observed that with the increase in sliding speed X-ray emission increased whereas the increase in load did not seem to make any difference in the emission. It was also observed that vibration at the contact is an important parameter. With the increasing vibration X-ray emission increased. Another important observation was that X-ray emission could be detected at the rubbing contact between thin sheets of copper, tin, aluminium with steel disc. In the preliminary tests we also detected emission for a number of other rubbing material pairs. It is expected that the X-ray emission would be of larger intensity in vacuum and more work is progress in this direction. The present study is useful in the way that the X-ray emission at the rubbing contact between common engineering materials can be of importance in mapping the surface contour and monitoring the friction and wear process in-situ during rubbing.

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