Microplasma Generation in Gap of Sliding Contact through Discharging of Ambient Gas due to Triboelectrification

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Abstract—Recently, microplasma generated in the gap of a sliding contact was discovered by the success in taking its image. This plasma is called tribomicroplasma. This paper presents recent results on the characteristics and mechanism of tribomicroplasma generation. It first presents a model of triboelectromagnetic phenomena which embraces tribocharging, tribomicroplasma generation, triboemission and postemission for understanding the general features of the phenomena. Next the energy of electrons is presented as an important factor which causes microplasma generation through an electron avalanche process. The coincidence of the tribophoton energy spectrum with that of gas-discharge plasma is then presented to verify the mechanism by which triboplasma is generated through discharging of ambient gas due to the intense electric field caused by triboelectrification. This is followed by two-dimensional side and plane images of total, ultraviolet and infrared photons emitted at and in its vicinity of the sliding contact. The plane image shows that the plasma is generated along a circle having a tail. The size of the plasma increases with a decrease in gas pressure. It also increases with an increase in the curvature of one of the two sliding partners. These natures which are dependent on the gas pressure and the size of the curvature are explained by Paschen’s law of gas discharge.

Keywords—Electrons, discharge, luminescence, microplasma, photons, triboelectrification, tribology

I. INTRODUCTION

When a solid slides against another, various kinds of particle emissions are observed from the sliding contact and its vicinity. They are negatively and positively charged particles and photons [1, 2]. The charged particles are electrons [3], and negative and positive ions [4]. These particles are emitted during sliding and also after the sliding stops. The particle emissions are referred to as triboemission and postemission, respectively [5]. As we detected the same number of the negatively and positively charged particles from the sliding contact, the author proposed that microplasma is generated at the sliding contact and its vicinity [6], since plasma is “a highly ionized neutral gas in which the charge of electrons is balanced by the charge of the positive ions” [7]. Based on these observations, the author proposed a new term, triboelectromagnetic phenomena, which embraces tribocharging [8-12], microplasma generation, triboemission and postemission, since all these phenomena are deeply connected with each other in terms of their origins and their characteristics. Fig. 1a shows the most advanced model of the triboelectromagnetic phenomena proposed by Nakayama [5]. Recently, the author, et al. verified the existence of the predicted plasma in the rear gap of a sliding contact by the successfully taking its image while a diamond pin was sliding on a sapphire disk in dry sliding in ambient air. Fig. 1b shows the first tribomicroplasma image successfully measured in dark [13]. The colors represent the intensity distribution of the photons emitted in arbitrary units in the order of red = 100% > yellow > green > blue > black = 0 and the circle shows the contact area. The plasma is generated in the rear part of a sliding contact. The surface potential caused by the triboelectrification was measured using a non-contacting type surface potential measurement apparatus (Trek Japan, Electric voltmeter model 334) and found that the frictional track surface on the sapphire disk charged negatively against the diamond pin. The microplasma is generated through an electron avalanche process by the intense electric fields due to triboelectrification or tribocharging in the gap of sliding surfaces. Further, very recently, the author also succeeded in taking an image of the triboplasma generated in an oil-lubricated sliding contact and confirmed that triboplasma is generated even under oil lubrication [14]. The discovery of triboplasma

Fig. 1. Conceptual model of triboelectromagnetic phenomena (a) and triboplasma image (b) [5]

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will contribute not only to advancing electrostatic science but also to developing a new advanced technology in the field of tribology by solving various difficult tribological problems, especially curious tribochemical reactions that we are unable to explain by the traditional tribological theory based on frictional temperature rise combined with catalytic action.

The purpose of the present article is to present the characteristics and mechanism of microplasma (tribomicroplasma) generation in the rear gap of a sliding contact, which have recently been investigated by the author and his coworkers. I present first the energy of electrons (triboelectrons) emitted from a sliding contact, which is deeply concerned with microplasma generation and that of photons (tribophotons) emitted during sliding, to show that tribomicroplasma is generated by the discharge of ambient gas. Next, I present two-dimensional images of total, ultraviolet (UV) and infrared (IR) photons emitted from a sliding contact and its vicinity to show how the plasma is distributed around the sliding contact. Then, the effect of gas pressure and the geometry of the sliding partner on the size and the pattern of the triboplasma are presented. Finally, the characteristics of plasma generation are explained by Paschen’s law of gas discharge.

II. ENERGY OF ELECTRONS AND PHOTONS

The energy of triboelectrons was measured using a retarding potential method to know whether the emitted electrons have enough energy to cause tribomicroplasma generation through a gas discharge mechanism. Fig. 2 shows the emitted energy distribution while a diamond stylus scratches three kinds of materials-- an insulator (Al₂O₃, alumina ceramics), a semiconductor (Si), and a conductor (Al) under a residual air pressure of \( p = 1 \times 10^{-4} \) Pa at normal forces \( F_N = 0.7 \) to 1.4 N and sliding velocity \( V = 7.0 \) cm/s (rotational velocity \( U = 60 \) rpm) [15]. The energy of the emitted electrons was in the order of insulator > semiconductor > conductor [15]. The emission intensity in metal Al was negligible and the main energy in the semiconductor Si ranged from 0 to 100 eV. However, the energy in the insulator Al₂O₃ peaked at several hundred electron volts with tailing reaching even to a keV. Though this energy was measured in a vacuum, it suggests that electrons having enough high energy to generate microplasma are also emitted to cause microplasma generation through an electron avalanche process in the case of an insulator even under atmospheric pressure.

To verify gas-discharge mechanism due to triboelectrification proposed by Nakayama, the energy spectrum of photons emitted from the sliding contact and that emitted from the gas-discharge plasma were measured and then they were compared. Fig. 3 shows the spectrum of the tribophotons emitted from the sliding contact of a diamond pin with a tip radius of 300 \( \mu \)m sliding on a sapphire disk in dry air under atmospheric pressure at \( F_N = 980 \) mN and \( V = 36.5 \) cm/s (\( U = 155 \) rpm).
rpm). The spectrum has many strong narrow bands in the UV region, accompanied by a narrow band at 696 nm in the visible region and a weak broad band from 696 nm to the IR region. Fig. 3b shows the spectrum of photons emitted from the discharging of dry air [16]. The spectrum also has many strong narrow bands in the UV region. Comparison of the two kinds of spectra in sliding and in gas-discharge plasma revealed that the peak positions in the UV region of both spectra completely coincide. This coincidence verifies that the photons emitted from the sliding contact originated from gas-discharge plasma; that is to say, gas-discharge plasma is generated at the sliding contact.

The spectrum of tribophotons naturally depends on the gas species, as seen in Fig. 4. The photon spectra in the UV region of tribophotons all coincided with those of gas-discharge plasma [16]. Comparison of the spectrum of tribophotons measured in the air, N2 and O2 in the UV region, showed that the tribophotons in the UV region originated from the discharging of N2. A 696-nm peak is seen in the visible region for all tribophoton spectra. As this peak did not appear in the spectrum of air discharge, this 696-nm photon emission did not originate from the plasma gas itself, but from the surface impurities and defects excited by the electrons and/or UV photons produced in the triboplasma, i.e., cathodoluminescence and/or photoluminescence. As the 696-nm peak did not appear in the tribosystem of diamond sliding against single-crystal MgO and single-crystal SiO2, this 696-nm peak should be inherent in Al2O3. The origin of the 696 nm narrow band has recently been assigned to the photon emission from Cr3+ impurity ions in the sapphire disk excited by the electrons and photons emitted from the triboplasma [17].

III. TWO-DIMENSIONAL DISTRIBUTION OF PHOTON EMISSION

Figs. 5a and 6a show the principles of the apparatuses to measure two-dimensional side and plane images of tribophotons, where OM, ICCD, and PC are optical microscope, intensified charge coupled device, and personal computer, respectively [13]. By inserting filters which can pass UV, visible and IR photons, we can obtain two-dimensional images of these photons. Figs. 5b, 5c and 5d show two-dimensional side and plane images of total, UV and IR photons emitted from the sliding contact of a diamond pin with a tip radius of 300 μm on a sapphire disk in ambient air, respectively [13]. The photon images were measured from the start of the pin sliding to avoid a significant change of disk surface due to wear. The UV photon images show the plasma image itself, since triboplasma emits UV photons as described above. So, it is clearly seen that microplasma is generated in the rear gap of a sliding contact in the UV plasma image of Fig. 5b. It is also seen that the IR image is so weak compared to the UV image. The two-dimensional UV plane image shows that plasma is distributed in the shape of a circle having a horseshoe pattern on it. The UV photon emission is very weak at the sliding contact. This means that plasma generation is very weak at and near the sliding contact. There is a dark region between the sliding contact and the center of the horseshoe pattern. The reason for the existence of the dark region will be reported soon. On the other hand, IR photons are emitted along a ring having the same diameter as the UV circular image. However, it is curious that IR photon emission is weak where UV photon emission is strongest, i.e., at the center of the horseshoe. The reason why IR photon emission is weak at the strongest UV point has already been reported very recently [17]. Although the UV and IR photon images do not have a tail, the total photon image has it. This is because the visible photon image has a tail.
IV. EFFECT OF GAS PRESSURE ON PLASMA SIZE

As plasma is generated by a gas discharging mechanism, plasma generation should be a function of gas pressure $p$. Fig. 7 shows two-dimensional plane images of total photons emitted under various air pressures from $p = 1.0 \times 10^5$ Pa to 1.6 Pa in the tribosystem of a diamond pin with a tip radius of 500 $\mu$m on a sapphire disk in a dry air atmosphere [18]. The diameter of the plasma ring increased with a decrease in air pressure. However, the plasma disappeared, leaving a circular photon emission at the sliding contact at an air pressure $p = 1.6 \times 10^1$ Pa because of the lack of air density. The photon emission from the sliding contact should mainly be IR photon emission due to frictional heating. The tribophoton emission in air becomes maximum at $3 \times 10^3$ Pa, as seen in Fig. 8. This means that triboplasma becomes maximum at this gas pressure. In the case of organic n-butane gas, plasma intensity also becomes maximum at almost the same gas pressure as in air, where high-molecular weight products are formed to coat the frictional surface and reduce friction and wear [19].

V. EFFECT OF GEOMETRY ON PLASMA SIZE

As plasma is generated in the gap of a sliding contact, the gap shape should affect the size and distribution of the plasma. To check this, the effect of the geometry of a smaller (moving) sliding partner on triboplasma distribution was investigated as a function of the tip radius of the pin under atmospheric dry air pressure. Fig. 9 shows two-dimensional plane images of the total photons emitted from the sliding contact of a diamond pin with different tip radii ranging from 0.030 mm to 4.00 mm on a single-crystal sapphire disk at $F_N = 0.5$ N and $V = 34$ cm/s ($U = 160$ rpm) under atmospheric dry air pressure. Herzian elastic contact area was measured under light illumination. The mark in each image in Fig. 9 shows the contact area, the diameter of which increased with an increase in the radius, $R$ under the constant normal force [20]. It is seen that the size of the plasma increases with an increase in the tip radius $R$. In the region of a small tip radius, the plasma ring was circular, but with a bigger radius the ring shape changed to an ellipse elongated in the direction of sliding.

Fig. 10a shows a composite image where an effective plasma image overlapped on the maximum plasma area (black area), where the effective image is displayed by camera auto-contrast mode. Fig. 10b shows the photon intensity profile. It shows that most of the plasma is generated in the effective plasma zone and that plasma is strongest at the center of the horseshoe and
then at the sliding contact [20].

Fig. 11 shows the relation between the radius, \( R \), and the total photon intensity measured under the same experimental condition as in Fig 9, where total photon means all the photons emitted from the maximum plasma zone and the tail. The curve fits the equation \( I_{hv} = 12.1 \times 10^2 R^{0.47} \). This means that triboplasma intensity increases greatly with an increase in \( R \). This is quite surprising since plasma intensity increases with the radius in spite of constant mechanical input energy, \( E = F_N \times V \). This is probably due to the bigger plasma ring, which becomes the place for an electron avalanche at greater \( R \). This phenomenon should be important in practical tribology, since intense plasma is generated with an increase in the size of the machine element under the same mechanical input energy - namely, triboplasma generation plays an important role not only in a microscopic scale such as surface finishing and MEMS, but also in macroscopic tribosystems such as gears, bearings, engines and so on.

VI. DISCUSSION WITH PASCHEN’S LAW

Fig. 12 shows the effect of air pressure, \( p \), on the dimensions of the triboplasma, \( a \) and \( b \), the distance between the center of the sliding contact and the center of the plasma horseshoe \( l \), and the gap \( d \) at \( l \) [18]. The plasma size, \( a \), \( b \) and \( l \), increases with a decrease in \( p \) as suggested in Fig. 7. As \( l \) increases with the decrease in \( p \), the gap distance, \( d \), also increases with the decrease in \( p \).

Fig. 13 shows the effect of the tip radius, \( R \), on the distance, \( l \) and the gap, \( d \) at \( l \). The geometry of a hemisphere on a flat contact gives \( l = (R^2 - (R-d)^2)^{0.5} \) which fits the experimental curve. However, the value of gap \( d \) is constant at 1.3 \( \mu \)m, in spite of the increase in \( R \).

In a \( V_F - pd \) curve in parallel electrodes, the spark voltage, \( V_F \), becomes minimum at a certain \( pd \) value inherent in the gas species, where \( p \) is the gas pressure and \( d \) is the distance between electrodes (Paschen’s law) [21]. The \( pd \) value at the point of the \( V_F \) minimum for air
is \((pd)_{\text{min}} = 76 \text{ Pa cm},\) which corresponds to \(d_{\text{min}} = 7.5 \mu\text{m}\) under atmospheric air pressure \(p = 1 \times 10^5 \text{ Pa}\). As \(p\) decreases under constant \((pd)_{\text{min}} = 76 \text{ Pa cm},\) \(d\) increases. Therefore, \(d\) increases with a decrease in \(p\) in Fig. 12.

On the other hand, in Fig. 13, as \(p\) is constant under \((pd)_{\text{min}} = \) constant, then \(d\) is also constant even if \(R\) changes. So gap \(d\) is constant even if \(R\) changes in Fig. 13. The gap distance, \(d\), in parallel electrodes at Paschen minimum is \((d_{\text{min}}) = 7.5 \mu\text{m}\), as stated above, while the gap at which plasma becomes most intense in the present study is \(d_T = 1.3 \mu\text{m}\). When we consider that the complexity of the dynamic tribological system and the \(d\) value depend on the electrode geometry, surface roughness and material species, we can say that these two values are in good agreement.

Fig. 14 shows a model of triboplasma generation in the rear gap of a sliding contact through an electron avalanche process due to triboelectrification, and the triboplasma image measured during the sliding of a diamond pin with a tip radius of 500 \(\mu\text{m}\) on a sapphire disk in dry sliding in air [20].

VII. SUMMARY

Recently, triboplasma was discovered by the author, et al. through the systematic work on triboelectromagnetic phenomena in a study for solving the curious tribophysical and tribochemical problems in the field of tribology [13]. In this article, the characteristics and gas-discharge mechanism of tribomicroplasma generation in dry sliding has been presented based on the recent results obtained by the author and his coworkers. We still need further work to clarify the reasons, how the triboplasma ring is formed and how visible and IR photons are emitted. However, the discovery of triboplasma opened a new field of triboplasma science and technology. It is expected that triboplasma will contribute to the development of new advanced technologies in various fields of tribology from microscopic to macroscopic tribosystems.

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REFERENCES


