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Exo-electron Emission from Sandblasted Steel

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The exo-electron glow curves up to about 250°C were measured for the sandblasted steel specimens, which had been kept in air for 2 min 30 sec, 2 hr 30 min or 13 hr after the sandblast. It was found that the plots of the integrated total counts against the keeping time in double-logarithmic scales gave a straight line with negative slope and that the emission peak moved to higher temperatures and at the same time the emission intensity decreased with the keeping time. It was also found that at the higher heating rate the peak intensity became larger and the peak temperature became higher than at the lower heating rate and that the remaining counts above a given temperature in the glow curve was linearly related with the temperature in semi-logarithmic scales, regardless of the heating rate. Comparing the behavior of exo-electron emission with that of the thermoluminescence of phosphors, it is supposed that electron traps are distributed on or in the deformed solid surface.

The phenomena of exo-electrons have been studied by many workers, which are emitted from solid surfaces stimulated by various treatments such as mechanical deformation and irradiation by X-rays. Some workers[1,2] have analyzed the exo-electron phenomena by means of the glow curve, which shows the characteristics of emission intensity observed at a constant rate of temperature rise, and estimated the electron trap depth. But they have not referred to the dependence of the glow curve on the time elapsed after the stimulation of the solid surface.

The reproducibility of the emission seems to be dependent on the method of surface treatment. In a previous paper[3] it was found that exo-electron glow curves were well reproducible if experimental conditions of surface treatment were properly regulated and the solid surface was uniformly deformed by suitable means such as sandblasting.

The purpose of the present work was to examine the dependence of the glow curves for sandblasted steel on the time for which the specimens, after sandblasted, were left in various atmospheres at room temperature, and to investigate the exo-electron decay mechanism.

Experimental

The details of the experimental apparatus have been

1) J. F. Young and D. J. Williams, *J. Appl. Phys.*, **34**, 3157 (1963).

2) H. Birgfellner and H. Hüller, *Acta Phys. Austriaca*, **14**, 56 (1961).

3) Y. Tamai and Y. Momose, *J. Appl. Phys.*, **39**, 5329 (1968).

described elsewhere.[4] A disk of commercial mild steel, 20 mm in diameter and 2 mm in thickness, was used. Prior to the experiments the mild steel specimens were annealed in air for 2 hr at about 400°C. Commercial standard sand (60 mesh through, the components: SiO_2 92%, Al_2O_3 4%) was used as blasting material.

A given amount (280 g) of sand was blown against the specimen by compressed air or nitrogen gas, at the gauge pressure of 1 atm, through a glass-made nozzle (2 mm, dia.) for 30 sec. The distance between the specimen and the blasting nozzle tip was 86 mm.

The counting device of the emission was a kind of open windowless Geiger-Müller counter. The working anode voltage was 1320 V and the accelerating voltage of 96 V was applied between the specimen holder and the grid (brass gauze) located at 10 mm above the holder. The counter gas was a mixture of ethanol (20 mmHg) and argon (83 mmHg). The measurements were conducted in the following way: The specimen was kept in air, argon or oxygen for a given time after sandblasting (this time is called "keeping time" hereafter) and then mounted on the specimen holder. It took about 3.5 min to evacuate the counter chamber, fill the counter gas in it for washing then repeat the same process again before the start of the counting. After one-minute counting at room temperature for steady operation of the ratemeter, the specimen was heated to about 250°C at the rate of 16°C/min or 27°C/min. Both the total counts and the count rate were recorded by a scaler and a ratemeter. The natural counting rate was approximately 0.8 counts/sec.

Results

Change of Glow Curves for Blasted Specimens Kept in Different Atmospheres. The black oxide film on the annealed specimen was removed under the present blasting conditions, and the freshly deformed metal surface was gray. Figure 1 shows the glow curves at a heating rate of 27°C/min for various keeping times in air (20°C, 50% relative humidity) after the sandblast by compressed nitrogen gas. In the glow curves, the intensity of the emission first rises, with rise of temperature, to a maximum at a definite temperature then slowly falls down to nearly the natural count rate. As seen in Fig. 1, as the keeping time becomes longer, the glow curves show a broader peak, the peak intensity and the total counts are smaller and the peak temperature is higher, but the emission intensity is almost the same in the higher temperature region in all cases.

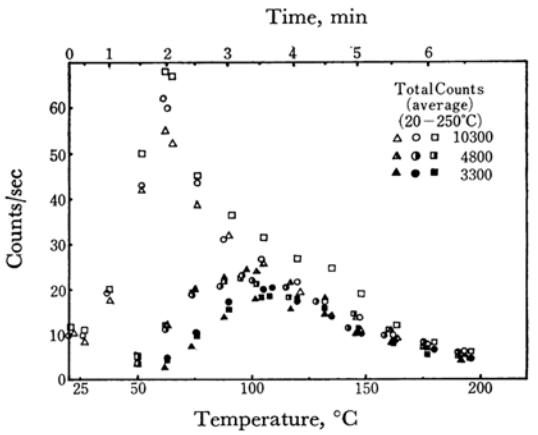

Fig. 1. Exo-electron glow curves for various keeping time in air after sandblasting.
△ ○ □: 2 min 30 sec
▲ ◑ ◨: 2 hr 30 min
▲ ● ■: 13 hr

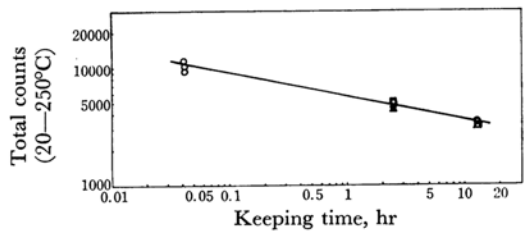

Fig. 2. Total counts of exo-electron glow curve (20—250°C) *vs.* keeping time.
○: Keeping in air (20°C, 50% relative humidity)
□: Keeping in oxygen (20°C, 1 atm)
△: Keeping in argon (20°C, 1 atm)

The plots of the total counts, N, against the keeping time, t, in double-logarithmic scales are shown in Fig. 2, which give a straight line with a negative slope. The empirical equation of the decay in air (20°C, 50% relative humidity) therefore was represented by

$$N(t) = C \cdot t^{-a}, \tag{1}$$

where a and C are constants, with $a = 2.0 \times 10^{-1}$ and $C = 2.9 \times 10^4$ (t: sec). Differentiation of Eq. (1) gives a decay of exo-electron emission in air;

$$\frac{dN}{dt} = -a \cdot C \cdot t^{-(a+1)}. \tag{2}$$

The decay equation in this form has been reported by many workers.[5,6] Lohff and Raether obtained the values of $a \cdot C$ and $(a+1)$ for various metals abraded by steel brush and for example the values of $a \cdot C$ and $(a+1)$ for aluminum were 8×10^3 and 1.1, respectively.

On the other hand, in this experiment these values were 5.8×10^3 and 1.2; namely the emission intensity of the sandblasted steel under the present blasting conditions had the same order as that of the abraded aluminum in their study. According

4) Y. Tamai and Y. Momose, *Kogyo Kagaku Zasshi* (*J. Chem. Soc. Japan, Ind. Chem. Sect.*), **71**, 1423 (1968).

5) J. Kramer, *Z. Physik*, **128**, 538 (1950).

6) J. Lohff and H. Raether, *ibid.*, **142**, 310 (1955).

to Eq. (2), the emission intensity at 2 hr 30 min sandblast becomes to 0.1 counts/sec. This value is the same order as the emission intensity at room temperature in the glow curve of 2 hr 30 min-keeping time in Fig. 1.

Next, the effect of keeping the blasted specimen in other atmospheres than air was examined.[3] The gases employed were oxygen and argon. It was found that the general characteristics of the peak temperature, the peak intensity and the total counts were almost the same as that obtained for the specimen kept in air after the blast. In addition, according to Eq. (1), the decay line is also applicable to the cases of argon and oxygen, as shown in Fig. 2.

Dependence of Glow Curve on Heating Rate. The effect of heating rate on the emission intensity in the glow curve was examined. The glow curves of three different specimens were obtained, which were all kept in air (25°C, 62% relative humidity) for 2.5 min after the sandblast by compressed air and were heated at a constant rate, *viz.*, 16°C/min or 27°C/min. Table 1 shows the average

Table 1. Dependence of glow curve on heating rate

Heating rate (°C/min)	Average values Peak temp. (°C)	Peak intensity (counts/sec)	Total counts (25—250°C)
16	54	32	8.1×10^3
27	62	50	8.7×10^3

values of the characteristics of three glow curves in each case. At the higher heating rate the peak intensity became larger and the peak temperature shifted to a higher potential than at the lower heating rate. The dependence of the peak temperature on the heating rate has been reported by former researchers,[2] but the increase of peak intensity at higher heating rates has not been referred to, probably because of poor reproducibility in the former studies. The total counts were nearly equal in six measurements and independent of heating rates. Concerning this problem, Haxel, Houtermans and Seeger[7] have reported the similar results that the total number of exo-electrons from abraded metals was independent of the degree of temperature rise.

The remaining counts, n, above a given temperature in the glow curve, were plotted against the temperature. The representative plots of the data of the glow curves in Table 1 are shown in semi-logarithmic scales in Fig. 3, which give almost the same straight lines independent of the heating rate in the present conditions except the initial lower temperature region. The empirical equation is represented by

$$n = S\cdot e^{-\beta T}, \tag{3}$$

where S and β are constants and T absolute temperature. The values of S and β are 4.4×10^6 and $2.0\times10^{-2}\,\mathrm{deg}^{-1}$, respectively. The value of β in the glow curve of 2 min 30 sec-keeping time in Fig. 1 is also equal to the above value.

Discussion and Conclusion

As for the source of the emission, it was found that electrons mostly originated in the deformed sand (*i. e.* SiO_2 and Al_2O_3) embedded in the metal surface by sandblasting.[3] The emission was observed from mild steel surface abraded by steel brush or by iron powder-blasting, although the intensity was rather weak. But in this experiment the emission was so strong as it was probably brought about by deformed sand.

The relation of the remaining counts *vs.* the temperature is given by Eq. (3) regardless of the heating rate. This fact suggests that the emission during temperature rise may be essentially dependent on temperature rather than time. Also, the linearity in an examined temperature range, shown in Fig. 3, suggests that the emission may

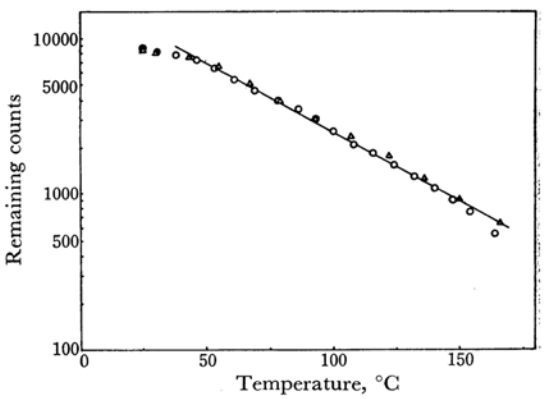

Fig. 3. Remaining counts in glow curve *vs.* temperature.
○: at the rate of 16°C/min
△: at the rate of 27°C/min

be due to the emission centers distributed in different levels of energy; this means that under the assumption that electrons are emitted by thermal energy corresponding to the depth of the electron traps in the deformed blast sand, the emission centers have the different thermal activation energies. If the emission peak in the glow curve corresponds to a single trap depth, the peak would decay as a whole and its maximum would remain at a definite temperature. However, as seen in Fig. 1, the

7) O. Haxel, F. G. Houtermans and K. Seeger, *Z. Physik*, **130**, 109 (1951).

maximum shifts to higher temperatures as the keeping time in air becomes longer; this means that a distribution of trap depth is presented and that the electrons to be emitted at lower temperatures decay more rapidly than those at higher temperatures.

Lepper[8] suggested that the behavior of exo-electron emission was very analogous to that of thermoluminescence and it has been reported by Randall and Wilkins[9] and Garlick and Gibson[10] that in the thermoluminescence glow curve of phosphors, such as KCl-Tl and ZnS-Cu, its peak shifted to higher temperatures as the phosphorescence decay proceeded.

According to Randall and Wilkins,[11] under the assumption that the distribution of the traps is exponential in form, if N_E is the number of traps between trap depth E and $E+dE$, then

$$N_E = A \cdot e^{-\alpha E} dE \tag{4}$$

and the emission intensity, I, at a given temperature is represented by

$$I \simeq f(skT) \cdot B \cdot t^{-(\alpha kT+1)}, \tag{5}$$

where A, s, B and α are constants and k Boltzman constant. Also, it was shown by Randall and Wilkins[11] that if there is an equal number of electrons in all traps: the trap distribution is uniform, the emission intensity is proportional to $1/t$.

On the other hand, in the present experiments the relation of the emission intensity *vs.* time at 20°C is given by Eq. (2). The negative slope with respect to time is 1.20 and therefore it is probable that the trap distribution is exponential in form. Comparing this value with that of Eq. (5), that is $(\alpha kT+1)$, the value of α becomes 7.9 eV^{-1}.

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8) J. Lepper, *Z. Naturforsch.*, **10a**, 47 (1955).
9) J. T. Randall and M. H. F. Wilkins, *Proc. Roy. Soc.* **A184**, 366 (1945).
10) G. F. J. Garlick and A. F. Gibson, *Proc. Phys. Soc.*, **60**, 574 (1948).
11) J. T. Randall and M. H. F. Wilkins, *Proc. Roy. Soc.*, **A184**, 390 (1945).