Evaluations of the Critical Commutating Current Densities of Carbon Brushes by Thermal Shock Testing

S. Sato*, A. Kurumada*, Y. Sho** and S. Motegi**
* Faculty of Engineering, The University of Ibaraki, Hitachi, Ibaraki, 316, Japan.
** Hitachi Chemical Co., Ltd., Hitachi, Ibaraki, 316, Japan.

A carbon brush for collector is required a smooth contact as much as possible for large current density, low heat generation, low wear rate and so on, in wide service conditions. Considering in views of the working condition in practical use and the manufacture of carbon brush, the relevant fields take up various topics for discussion and are necessary these coordinated evaluations to elevate the performance of brush. In this paper, we have an eye to the electric and the mechanical contacts are very locally reduced ones between brush and collector faces. Then we present two expressions of the critical commutating current densities to occur thermal stress fractures by fracture mechanics approach. Then, we reveal that these critical values involve two material parameters of the thermal shock resistance [1] Δ ($=\sigma_t k/E$, σ_t: tensile strength, k: thermal conductivity, E: Young's modulus, α: thermal expansivity) and the thermal shock fracture toughness [2] ∇ ($= K_{IC}k/E\alpha$, K_{IC}: fracture toughness value of mode I), respectively. The values of Δ and ∇ for nine kinds of carbon materials for brush are determined by means of arc discharge heating method for the disk specimens. These values are compared with the wear rate, black band width and other physical properties of these brushes.

A contact between brush and collector is not always at all over the surface, but is no more than at a very part in the apparent area. The part of effective mechanical contact calls as a h-spot in the memory of Hertz who developed the theory of elastic contact. Electrically conductive part is known as further small area than that of h-spot. The part of the electric contact has been designated as an a-spot by Holm [3].

The mean Joule's heat quantity $\bar{Q}_{a1}$ for an a-spot subjected to a mean collector current density $\bar{i}_{a1}$ under a contact voltage drop V_s is expressed as follows:

$$\bar{Q}_{a1} = \bar{i}_{a1} \times V_s = \bar{i}\xi_1\xi_2 V_s \qquad (1)$$

Where $\bar{i}$ is a mean collector current density for whole area ($b \times w$) of brush. ξ_1 and ξ_2 are concentration factors of h-spot area and a-spot area.

The mean sliding friction heat quantity $\bar{Q}_{h1}$ due to the mean pressure P and the sliding velocity V are expressed as follows:

$$\bar{Q}_{h1} = Q_h/\bar{a}_1\eta_1 = f\,P\,V\xi_1/j \qquad (2)$$

Where η_1 is a number of h-spot, f is a friction coefficient and j is the heat equivalent of work. Therefore the heat quantity Q_a for unit area is obtained as the sum of $\bar{Q}_{a1}$ and $\bar{Q}_{h1}$

$$Qa = \bar{Q}a1 + \bar{Q}h1 = \bar{i}\,\xi_1\,\xi_2\,V_s + f\,P\,V\,\xi_1/j \qquad (3)$$

Thermal stresses of brush which was locally heated on the face are simulated to a problem of transient thermal stresses of a thick disk heated eccentrically on the end surface.

The nondimensional thermal stress $\bar{\sigma}$ in the disk is expressed in general as follows [4]:

$$\bar{\sigma} = \sigma(1-\nu)k/E\alpha Q_0 R \qquad (4)$$

where σ is stress, ν is the Poisson's ratio, Q_0 is the heating quantity for unit area and unit time. $\bar{\sigma}$ takes different values due to the shape of disk, the size and the position of heating source and the heat transmission around the disk. Figure 1 shows distributions of the temperature, the radial and the circumferential thermal stresses $\bar{\sigma}_{rr}$, $\bar{\sigma}_{\theta\theta}$ in the case of the size and the position of heat source $a/R = 0.2$, $e/R = 0.5$ and the non-dimensional heat transfer coefficient $H = 1$ of the disk of the ratio of diameter to thickness $2R/2L = 1$. Thermal stresses converge to the maximums in the non-dimensional time over 0.5 . The stresses at the center of heat source occur the largest compressive $\bar{\sigma}_{rrmax}$ and $\bar{\sigma}_{\theta\theta max}$. Circumferential tensile stress at the outer edge adjacent to the heat source is remarked. According to the fracture criterion of graphite, the fractures under predominent compressive and tensile biaxial stresses occur when the stress intensity factor of shearing and the tensile

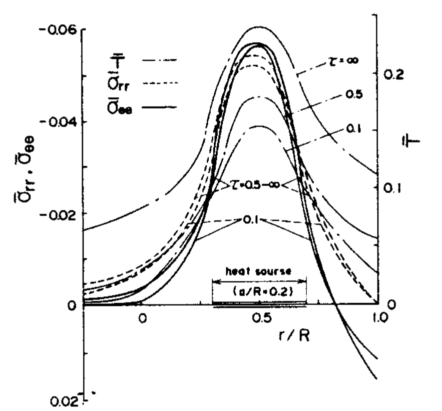

Fig. 1 Transient distributions of temperature and thermal stresses in a thick disk.

uniaxial stress attain at the fracture toughness value K_{IIC} and the tensile strength σ_t, respectively.

The determination of K_{IIC} by thermal stress is not easy, but the value can be deduced fairly from K_{IC} using the experimental relation. The maximum shearing stress at the center of an a-spot due to Joule's heating is expressed introducing the mean heating quantity Q_a into Q_o in Eq. (4) and the nonlinear relation between the mean commutating current density $\bar{i}$ and the contact voltage drop V_s;

$$V_s = v_1 \, \bar{i}^{\frac{1}{n}} \tag{5}$$

where v_1 is the voltage drop for unit current density, and n is a constant larger than unity depending to the polarity of brush. Concludingly the critical commutating current density $\bar{i}_{max}$, which resists to the thermal stress fracture at the center of a-spot, is expressed as follows:

$$\bar{i}_{max} = \left\{ \left(\frac{K_{IC}k}{E\alpha} \right) \frac{(1-\nu)\xi_4}{\bar{\tau}_s \xi_1 \xi_2 \xi_3 v_1 (b/2)\sqrt{\pi c}} - \frac{fPV}{j\xi_2 v_1} \right\}^{\frac{n}{n+1}} \tag{6}$$

The other hand, the critical commutating current density $\bar{i}'_{max}$, which resists to the thermal stress fracture at adjacent edge of the disk, is expressed as follows:

$$\bar{i}'_{max} = \left\{ \left(\frac{\sigma_t k}{E\alpha} \right) \frac{(1-\nu)}{\bar{\sigma}_{\theta\theta} \xi_1 \xi_2 v_1 (b/2)} - \frac{fPV}{j\xi_2 v_1} \right\}^{\frac{n}{n+1}} \tag{7}$$

where c is a radius of penny shape crack at the center of a-spot, ξ_3 is a stress intensity factor at the a-spot. ξ_4 is the ratio of fracture toughness K_{IIC}/K_{IC} ($\fallingdotseq$ 1.2). Nondimensional stresses $\bar{\tau}_s$ and $\bar{\sigma}_{\theta\theta}$ fluctuate of cause by the conditions of heat source. Constants ξ_1, ξ_2, ξ_3 and c are not easy to decide definitely. But it is noteworthy that $\bar{i}_{max}$ and $\bar{i}'_{max}$ involve the thermal shock fracture toughness ∇ (= $K_{IC}k/E\alpha$) and the thermal shock resistance Δ (= $\sigma_t k/E\alpha$) as material properties, respectively. Each property involving in the numerator and the denominator of ∇ and Δ is consistent with the required conditions for brush such as the high commutability, the low wear rate, the good setting stability and so forth. Therefore, carbon brush materials of the larger values of ∇ and Δ are not only the larger the commutating current densities, but also induce the required conditions to make better performance of brush.

Table 1 shows the physical properties of nine carbon brush specimens and the performances in a bench tests as the brush for mill and locomotive motors.

Figures 2 and 3 are the experimental values of ∇ and Δ which were determined by arc discharge heating methods for the disk specimens of carbon materials. In these figures, we find the carbon J is the best, then carbons E and F are better among the carbon materials. The values of

Table 1 Properties of carbon brushes.

specimens		A	B	C	D	E	F	G	H	J
apparent density (g/cm^3)		1.50	1.63	1.55	1.54	1.72	1.77	1.70	1.67	1.66
spesific resistance ($\mu\Omega$-cm)		7200	8000	6200	6900	3500	3500	4100	4400	1400
bending strength (MPa)		11.77	14.71	16.67	13.73	29.42	39.22	27.46	30.40	29.42
shore hardness		38	40	50	49	56	65	59	65	45
modulus of elastisity (GPa)		4.12	6.08	5.69	(5.00)	9.12	10.69	7.65	8.24	9.02
filler	kind of filler	lamp*	lamp	lamp + fur.	lamp + fur.	lamp	lamp	fur.**	fur.	coke
	mean grain size (μm)	500	290	160	160	500	500	94	76	(120)
use***		mill	mill	mill	mill	Loco	Loco	Loco	Loco	mill
rate of brush wear ($mm/10^3h$)		1.2	1.4	1.0	1.2	1.8	1.8	2.0	1.7	1.3
black band width (%)		8.3	7.0	8.5	8.2	1.2	0.6	6.0	8.0	1.2

* lamp-black ** furnace black

*** mill (=mill motor), Loco (=locomotive motor)

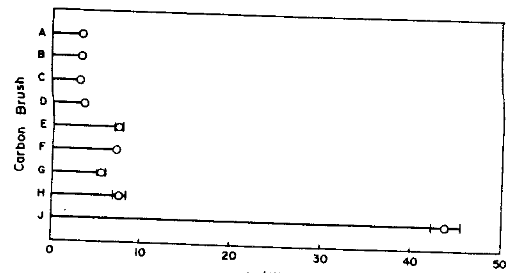

Fig. 2 Thermal shock resistances of different grades of carbon brush.

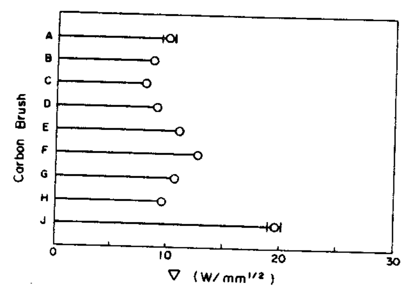

Fig. 3 Thermal shock fracture toughnesses of different grades of carbon brush.

∇ and Δ are almost consistent with the bench test data, but they are not every correspondences quantitatively comparing with the brush performances. But we consider concludingly the material parameter ∇ and Δ can be determined so simply and quantitatively, that more numbers of practical data of brushes are required to compare at more abundant utility conditions, because brush performances are considerably fluctuated due to delicate differences of the conditions.

References

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