Si-SiC Matrix C/C Composite Sliding Wear Mechanism and Their Applications

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Abstract

Applied use of Silicon infiltrated SiC matrix carbon fiber-reinforced carbon composites (hereinafter referred to as Si-SiC matrix C/C composites) Si-SiC matrix C/C composites to improve the properties of C/C composites for use as materials in sliding parts such as brakes is on the increase. As such, we have investigated the behavior of sliding wear on these materials by measuring and observing the amount of sliding wear volume and friction coefficient of the Si-SiC matrix C/C composites, based upon analysis in which these attributes were converted to dimensionless numbers for evaluation of life-span. Based on the results, we conclude that 1) when contact pressure (compressive stress) is applied to a Si-SiC matrix C/C composite, a difference in level between the contact surfaces occurs according to the difference between the elastic modulus of the C/C composite portion and the Si-SiC matrix portion of the material of which the composite is composed, and this difference in level grinds against the opposing material, causing abrasion, 2) the aforementioned difference in level becomes a primary factor, indicating higher friction coefficient values for Si-SiC matrix C/C composite material than for the friction coefficient of the C/C composite material, and 3) when comparing Si-SiC matrix C/C composite material and C/C composite material as a brake component, the Si-SiC matrix C/C component material is superior, having a higher friction coefficient and a lesser amount of wear volume associated with braking mechanisms (component life is longer).

Keywords: C/C composites, Si-SiC matrix, wear volume, dimensionless number

1. Introduction

While the adoption of C/C composite materials (Wrzesien et al., 1976) is on the increase in industrial components such as high-temperature structural materials (refractory materials and kiln furniture), lightweight structural materials (conveyance arms), and sliding components (brakes), utilizing the lightweight, high-strength, high-ductility, and heat-resistant properties of these materials, the scope of application for these materials is restricted by their low elastic modulus, as well as wear and deterioration caused by specific use environments.

The author has discovered the synthesis mechanism (Hanzawa, 2012) of a dense Si-SiC matrix C/C composite by maintaining the unique characteristics of C/C composites while compensating for their shortcomings, targeting practical application of industrial materials and parts, and by creating dense Si-SiC matrix C/C composites (Hanzawa & Nakagawa, 2002, 2003; Hanzawa, 2005) which are produced by Si-impregnation and synthesis of C/C composites having a carbon fiber yarn structure under certain conditions. Furthermore, the author has developed Si-SiC matrix C/C composites (Hanzawa & Hashimoto, 2010) using partial Si-impregnation as a material design technology to compensate for the shortcomings (low bending strength and tensile strength) while maintaining the advantages (high elastic modulus and compressive strength) of Si-SiC matrix C/C composites, and has confirmed that this method is effective for controlling mechanical properties (Hanzawa, 2012).

In addition, with the aim of establishing design technologies for applying Si-SiC matrix C/C composite materials to sliding components, studies have been conducted in which the friction coefficient and the form of wear volume change depending on contact pressure and frequency of sliding (Matsubara et al., 2000), the coefficient of friction changes depending on atmospheric pressure (Matsubara et al., 2000, 2003), the friction coefficient and

wear particle mode change depending on contact pressure and rotational sliding speed (Ko et al., 2003), and the friction coefficient and amount of wear volume change depending on contact pressure and temperature (Ko et al., 2002). For example, a sliding test (Figure 1 shows an overview of an experimental apparatus) wherein temperature and contact pressure of C/C composites and Si-SiC matrix C/C composites in according to the published work (Ko et al., 2002) and shown in Figure 2, produced results regarding the measurement of friction coefficient and wear volume amount in which the differences between materials and sliding properties are indicated, but the sliding behaviors of the analysis of that mechanism were not explained.

Accordingly, this paper attempts to clarify the mechanism of sliding wear of Si-SiC matrix C/C composites through the use of Si-SiC matrix C/C composites obtained by varying the amount of Si-SiC matrix present in the C/C composites, as a test material by converting friction coefficient and wear volume amount produced in the experiment into dimensionless numbers and by making adjustments to the sliding surface and wear particles before and after the experiment according to observations made. Furthermore, the effectiveness of using Si-SiC matrix C/C composites for brake components is also considered, albeit within the scope of comparison with C/C composites.
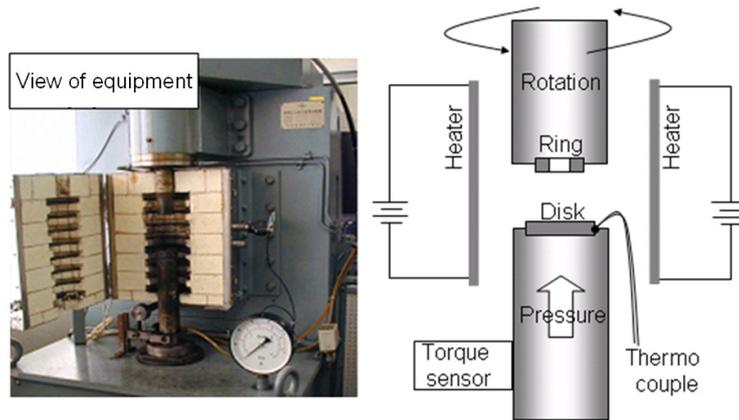
Figure 1. Sliding wear volume and friction coefficient evaluation testing machine (made by SHINKO ENGINEERING CO., LTD.)
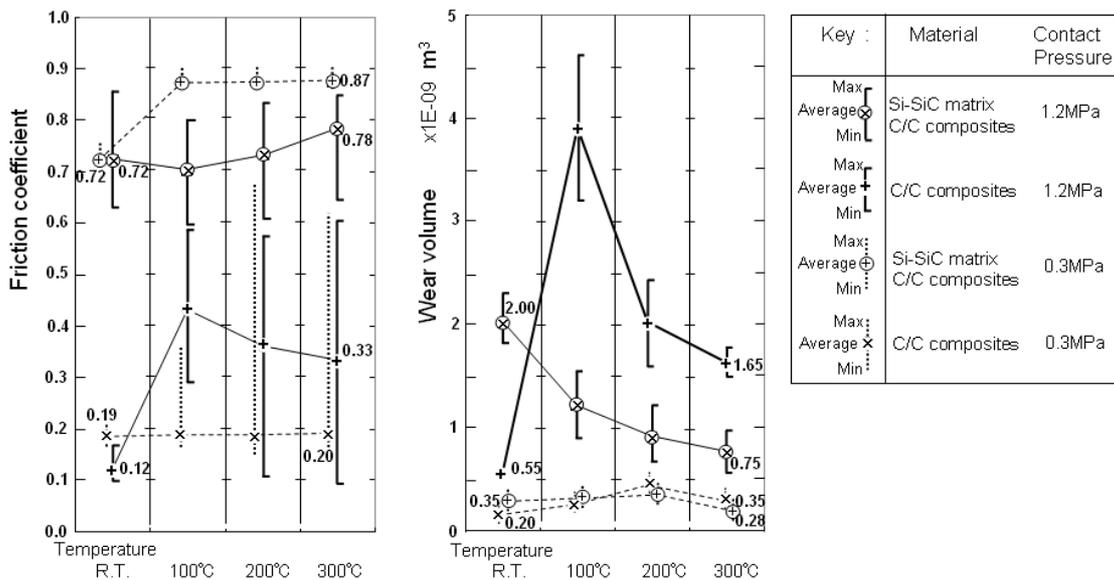
Figure 2. Temperature dependence of friction coefficient and wear volume amount of the C/C composites and Si-SiC matrix C/C composites

Contact pressure = 0.3 MPa/1.2 MPa, Ring rotating speed = 10 rpm (arithmetic average rotating speed on the sliding surface = 0.0157 m/sec) Atmospheric temperature at 25 to 300 ℃. Data taken from Ko et al. (2002).

2. Experimental Procedure

Method: A sliding wear volume and friction coefficient evaluation testing machine made by SHINKO ENGINEERING CO., LTD. (Figure 1) in which a disk (42 × 42 × 8 mm) and a ring (OD 36 × ID 24 × thickness 8 mm) made of Si-SiC matrix C/C composites (obtained by varying the amount of the Si-SiC matrix present in the C/C composites) is attached. The equipment has a mechanism for imposing a lower side shaft with a torque sensor loaded with a disk, opposite an upper side rotating shaft with a ring on the bottom. This equipment can be operated in room atmosphere for controlling the disk temperature and also make measurements using sliding temperature as a parameter. The amount of wear volume is calculated based on differences in the bulk density, weight, and thickness of the specimen before and after the test. The equipment is used to measure friction coefficient and wear volume amount under conditions of constant pressure, speed, and temperature (contact pressure of 1.2 MPa, ring rotating speed of 200 rpm (arithmetic average speed of 0.314 m/sec), measuring time of 10 min., and atmospheric temperature of 25 ºC).

Preparation of materials:

1) For C/C composites with no Si-SiC matrix present AC200-C/C composites made by ACROSS CO. Ltd., are machined into disk and ring form (G0 in Figure 3.1).
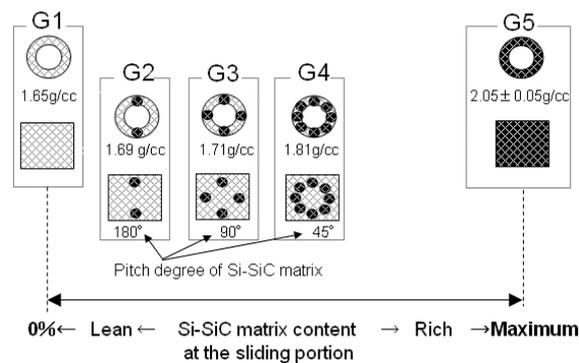
Figure 3.1. Distribution status and bulk density of the Si-SiC matrix of the disks and rings used

2) The material obtained by adjusting the amount of the Si-SiC matrix in the Si-SiC matrix C/C composites is prepared using a method (method for producing partial Si-SiC matrix C/C composites (Hanzawa & Hashimoto, 2010)) for scattering spots of Si-SiC matrix over part of the C/C composite. This is done using a method for machining holes of 0.5 mm in diameter into the AC200-C/C composites, displacing cylindrical Si powder compacts (6 mm in diameter, 10 mm thickness) from the machining holes, and melting/impregnating the Si from the machining holes. Here, bulk densities of the ring of 1.69 g/cc, 1.71 g/cc, 1.81 g/cc are prepared by changing 0.5 mm diameter holes by 180º (2 pcs.), 90º (4 pcs.), and 45º (8 pcs.) (G2, G3 and G4 in Figure 3.1). As an example of the conditions controlling the amount of the Si-SiC matrix in the Si-SiC matrix C/C composites, the X-ray photo of G3 was obtained by synthesizing a Si-SiC matrix at a pitch of 90º on the ring and the disk and is shown in Figure 3.2.
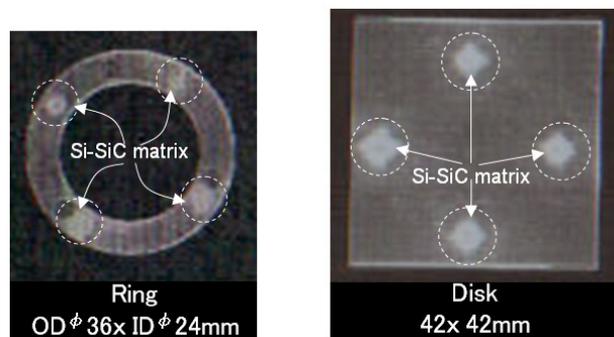
Figure 3.2. X-ray photo of partial Si-SiC matrix C/C composites

An example of G3 in which Si-SiC matrix is distributed at 90º intervals on the sliding portion of the ring and disk.

3) Dense Si-SiC matrix C/C composites are prepared by a method (Hanzawa, 2012) for impregnating 55 wt% Si as against the wt% of the AC200-C/C composites to be processed into disks and rings of 2.05 ±0.05 g/cc in bulk density (G5 in Figure 3.1).

Here, the AC200-C/C composites and the Si-SiC matrix C/C composites prepared by utilizing the AC200-C/C composites have a structure in which sheets of the carbon fiber yarn extending in the X direction, and sheets of the carbon fiber yarn extending in the Y direction, are alternately laminated. Therefore, they have directionality. Accordingly, we machined the disk and the ring so that the X-Y surface became the sliding contact surface (see Figure 4).
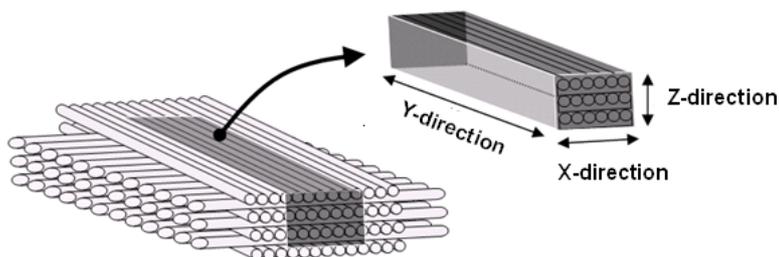
Figure 4. Machining direction of a test specimen from composites including carbon fiber yarn and sheets

3. Test Results

Friction coefficient and wear volume amount of specimens G1, G2, G3, G4 and G5 in Figure 3.1 were measured according to the method described above in 2. Experimental procedure. The results are shown in Figures 5 and 6.

From the results, it has been found that friction coefficient increases do not significantly exceed 0.3 for C/C composites when a Si-SiC matrix is present, regardless of the quantity of matrix. In addition, an increased friction coefficient against C/C composites occurs in the same circumstances as in Figure 1, in which number of rotations, temperature, and contact stress differ.

Furthermore, it has been found that wear volume amounts increase rapidly when even minute amounts of Si-SiC matrix are present and decreases as the amount of the Si-SiC matrix increases. The results were roughly equivalent to or less than those for C/C composites when the amount of the Si-SiC matrix is at its maximum under the conditions shown in G5.
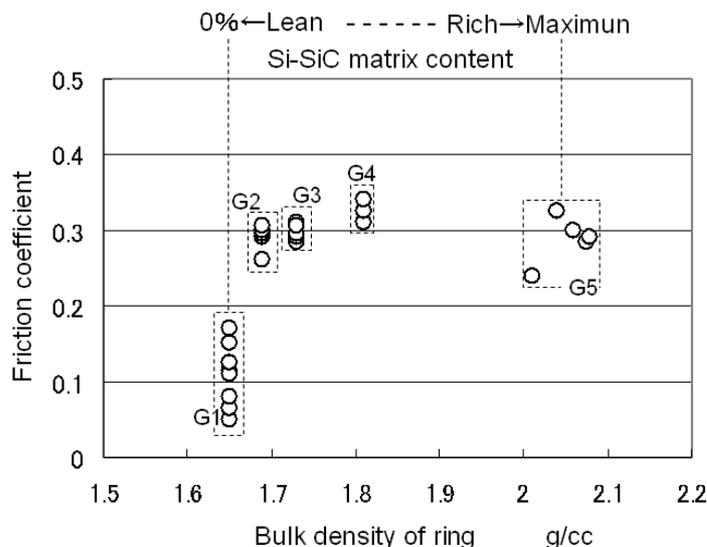
Figure 5. Friction coefficient of C/C composites with and without the Si-SiC matrix

Contact pressure = 1.2 MPa, Rotation speed = 200 rpm, at 25 ºC, Evaluation 10 min
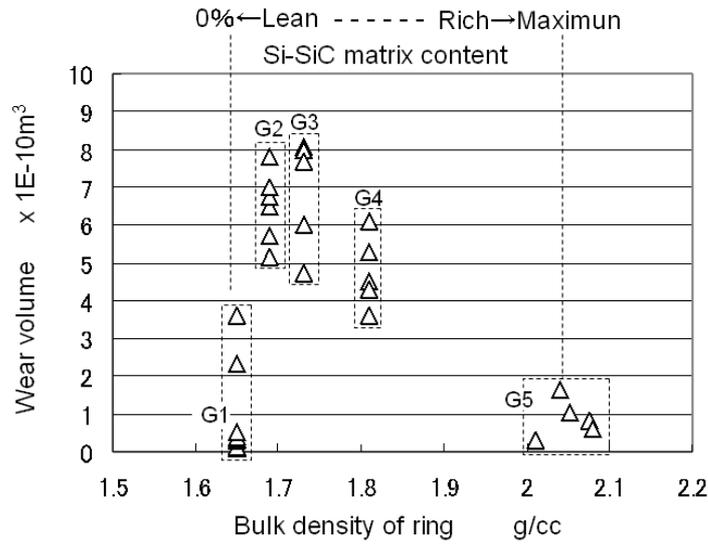
Figure 6. Density dependence of wear volume of the C/C composites with and without the Si-SiC matrix

Contact pressure = 1.2 MPa, Rotation speed = 200 rpm, at 25 ℃, Evaluation 10 min
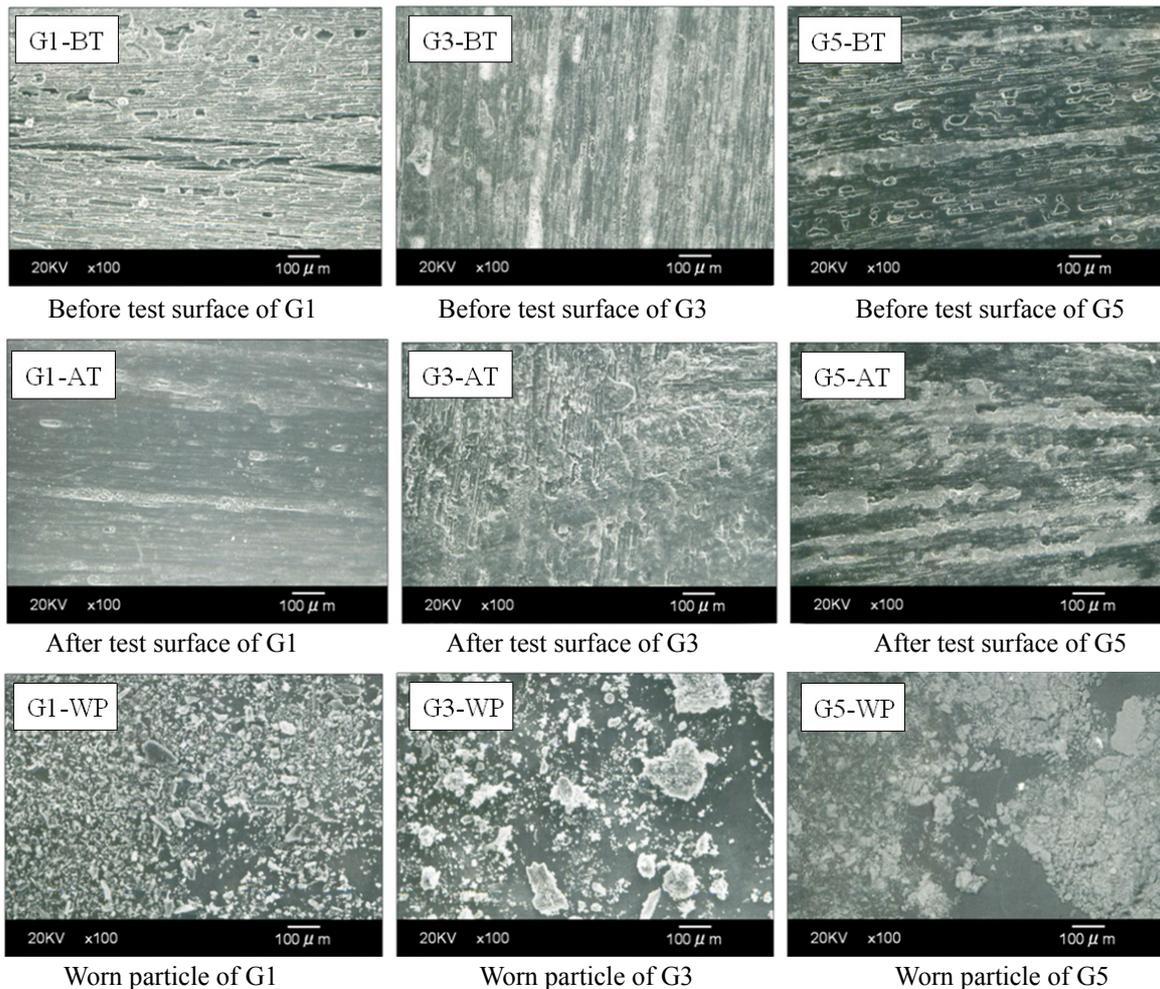
Figure 7. Surface and worn particles of the C/C composites with different Si-SiC matrix concentration before and after the sliding test

The G1-BT, G3-BT and G5-BT are SEM photos of the surface of specimens G1, G3, and G5 before the sliding test (x100 magnification).

The G1-AT, G3-AT and G5-AT are SEM photos of the surface of specimens G1, G3, and G5 specimen surface after the sliding test (x100 magnification).

The G1-WP, G3-WP and G5-WP are SEM photos of the worn particles on the surfaces of specimens G1, G3 and G5 after the sliding test (x100 magnification).

Figure 7 shows SEM photos of the sliding portion of the G1, G3 and G5 specimens before and after the sliding experiment and the SEM photos of the worn particles generated by the experiment.

Here, the G1-BT, G3-BT and G5-BT are the SEM photos (x100 magnification) of the G1, G3 and G5 specimen surfaces before the sliding. G1-AT, G3-AT and G5-AT are SEM photos (x100 magnification) after the sliding test, and the G1-WP, G3-WP and G5-WP are SEM photos (x100 magnification) of the worn particles on the surfaces of the G1, G3 and G5 specimens after the sliding test.

When observing the condition of the surface of each specimen before and after the test (BT shows before, AT shows after) the G1-AT and G5-AT photos show relatively smooth conditions and stripe patterns due to the carbon fiber in the C/C composites, G3-AT shows considerable unevenness, but there was no striped pattern seen due to C/C composite. Additionally, when comparing worn powder size, pulverization of the abrasive powder occurs increasingly from G3-WP to G1-WP to G5-WP.

4. Discussion

A brake component representative of a sliding component is a structural component in which a stationary object (stator, disk in this experiment) is pushed upon a mobile object (rotor, ring in this experiment). The kinetic energy of the mobile object is transformed into frictional heat and wear volume, causing the mobile object to come to rest. Although wear volume on the brake component is unavoidable, longer-lasting materials result in less wear volume when isometric kinetic energy is absorbed. At the same time, the higher friction coefficient of a material, the greater the braking force of a brake component.

With this in mind, the evaluation was made by making dimensionless numbers for wear volume amount of Si-SiC matrix C/C composites and C/C composites to attempt to find out the wear mechanism of Si-SiC matrix C/C composites. In addition, comparison and evaluation related to life of brakes made with C/C composites and those made Si-SiC matrix C/C composites were made using values (dimensionless numbers) for wear volume amount for each material, divided by its friction coefficient.

4.1 Dimensionless Number Obtained by Wear Volume Amount (Wear Mechanism of Si-SiC Matrix C/C Composites)

The amount of wear volume generated by sliding Wx [m^3] is obtained as the result of the movement of the ring (mobile object) and the disk (stationary object) with friction coefficient (μx) along a sliding distance Lx [m] while applying contact surface pressure Px [MPa] to a component of contact area Sx [m^2]. Therefore, it is possible to convert wear volume amounts into a dimensionless number A (specific wear value) using Equation (1).

Wear dimensionless number A (Specific wear value [-])

$$= \textit{Wear volume amount Wx [m}^3]/(\textit{Contact area Sx [m}^2] \times \textit{Sliding distance Lx [m])} \tag{1}$$

Here, the wear volume amounts for test specimens G1, G2, G3, G4 and G5 (Figure 6) are the results of sliding experiment with contact surface pressure Px = 1.2 [MPa], contact area Sx = 5.65E-4 [m^2], sliding distance Lx = 0.314 × 600 [m] (ring's arithmetic average sliding speed: VAx = 0.314 [m/sec], sliding time Tx (Tx = 600 [sec]). With this considered as a prerequisite, the number obtained by converting wear volume amount (Figure 6) to dimensionless number A is shown in Figure 8. In Figure 8, we were able to confirm a first phenomenon in which dimensionless number A rapidly increases when there exists slight Si-SiC matrix, and a second phenomenon that dimensionless number A gradually decreases along with the increase in amount of Si-SiC matrix.

For the first and second phenomena, we formed a hypothesis that a difference of elastic modulus between a part with the Si-SiC matrix and a part without the Si-SiC matrix forms a difference in the amount of compressive deformation and that this difference in the amount of compressive deformation forms a level difference on the sliding surface which serves to grind opposing sliding materials.

Figure 9 shows a hypothesis model of sliding circumstances of the ring and the disk of the C/C composite (corresponding to the specimen G3) on which the Si-SiC matrix is disposed at four places at intervals of 90º and

wear volume serving for grinding opponent materials on the sliding surface. We believe that this model causes wear volume via the following steps.

Step 1) Compressive stress of $Px = 1.2$ MPa is applied to the ring of 0.008 m in thickness.

Step 2) Since elastic modulus of the Si-SiC matrix C/C composites and the C/C composites is $E_{Si-SiC-C/C} = 57800$ MPa, $E_{C/C} = 54000$ MPa (the published tensile elastic modulus cited (Wang et al., 2008), tensile and compressive elastic modulus is the same value), respectively, level difference Dx [m] occurs within the sliding surface when the Si-SiC matrix part of the ring transforms from a status of Time = T to a status of Time = T + ΔT, and its magnitude is 1.17E-8 [m] from Equation (2).

$$Dx \ [m] = ((Px/E_{C/C}) - (Px/E_{Si-SiC-C/C})) \times Th \qquad (2)$$

Step 3) When there are four Si-SiC matrix C/C composites of 6 mm in diameter (7.85E-5 [m^2]) along the arithmetic average circumferential length CL = 0.0942 [m] of the ring, the C/C composites account for 80% of the ring contact area $Sx = 5.65$ E-5 [m^2], and therefore the Si-SiC matrix C/C composite grinds the C/C composite part, which accounts for 80% of the ring's arithmetic average circumferential length CL. In other words, when there is one Si-SiC matrix C/C composite of 6 mm in diameter (7.85E-5 [m^2]), the length of the C/C composites part obtained by reducing 5% of circumferential length CL is ground when the ring makes a circuit. Accordingly, an amount (a dimensionless number) of the ring, on which the Si-SiC matrix C/C composites are at 2, 4, and 8 positions per meter of circumferential length, ground by level difference caused by a difference of elastic modulus is 1.1E-7, 9.9E-8, 7.2E-8, respectively, by Equation (3). These calculation values plotted in Figure 10 nearly coincide with dimensionless number A obtained in the experiment.

Dimensionless number A

$$= (Dx/CL) \times (100\% - 5\% \times (number \ of \ Si\text{-}SiC \ matrix \ C/C \ composites)) \qquad (3)$$

The aforementioned hypothesis was also applied to sliding of dense Si-SiC matrix C/C composites, obtained by synthesizing the Si-SiC matrix for entire C/C composites before calculating dimensionless number A for the wear volume amount of G5 (Figure 8). Here, since complex rules come into effect for the elastic modulus of Si-SiC matrix C/C composites (Hanzawa, 2012), compressive elastic modulus of the Si-SiC matrix is calculated as 68.3 GPa using Equation 4 (Hanzawa, 2012).

$$P_c = P_m V_m + (1 - V_m) P_f \qquad (4)$$

P_c = *Characteristic value of composites*, P_f = *Characteristic value of substrate*,

P_m = *Characteristic value of matrix*, V_m = *Volume fraction of matrix*

Where Pc = 57.8 GPa, P_m = Numeral to be determined, V_m = 26%, P_f = 54.1 GPa

Here, the area ratio of contact surface of the Si-SiC matrix C/C composite is Si-SiC matrix : C/C = $26^{(2/3)}$: $74^{(2/3)}$ = 33% : 67%[#, for equation 6] in the volume ratio of components in consideration of Si-SiC matrix : C/C = 26 : 74. In addition, a cell for forming the Si-SiC matrix is 300 μm in size (Hanzawa, 2012), and therefore it can be hypothesized that the thickness of comb type cells that grind opposite material on the sliding surface is 300 μm. Furthermore, since there are an infinite number of cell structures of the Si-SiC matrix of 300 μm in width/height in an inner layer part of the sliding surface, it was assumed that the inner layer part of the sliding surface is integral to its structure and that the influence of compressive deformation is uniform.

By substituting these preconditions into Equation (5) and (6), the level difference of G5 (Figure 8) is calculated to be Dy = 9.57E-10 [m] and dimensionless number A for wear volume amount is 6.8E-9. When this value is plotted in Figure 10, dimensionless number A obtained from calculation and experiment nearly coincides.

$$Level \ difference \ Dy \ [m] = ((Px/E_{C/C}) - (Px/E_{Si-SiC})) \times Th = 9.57E\text{-}10 \qquad (5)$$

Where, Px = 1.2 [MPa], $E_{C/C}$ = 57800 [MPa], E_{Si-SiC} = 68300 [MPa], Th = 0.0003 [m]

Dimensionless number A = (Dy/CL) × 67% [#] = (9.57E-10/RL = 0.0942 [m]) × 0.67 = 6.8E-9 $\qquad (6)$

Here, when level difference Dx (1.17E-8 [m]) on the contact surface of the test specimens G2, G3 and G4 obtained from Equation (2) is compared with level difference Dy (9.57E-10 [m]) of the contact surface of the test specimen G5 obtained from Equation (5), there is a nearly tenfold difference. In comparing G3-AT with G5-AT (the surface of the test specimen after the sliding test) in Figure 7, it was considered significant that surface roughness in G3-AT and the lack of such a characteristic in G5-AT are attributable to this difference in magnitude of level. In addition, when comparing G3-WP with G5-WP (abrasive powder) in Figure 7, the

significant presence of worn particles in excess of 100 μm in G3-WP and absence of worn particles in excess of 100 μm (presence of only fine compacted powder) in G5-WP are phenomena attributable to this difference in level. Furthermore, on looking at friction coefficient in Figure 5, the friction coefficient of G2, G3, G4 and G5 increases as against G1 (C/C composites) because level difference Dx or Dy becomes a convex that serves to grind the opposing material on the sliding surface.
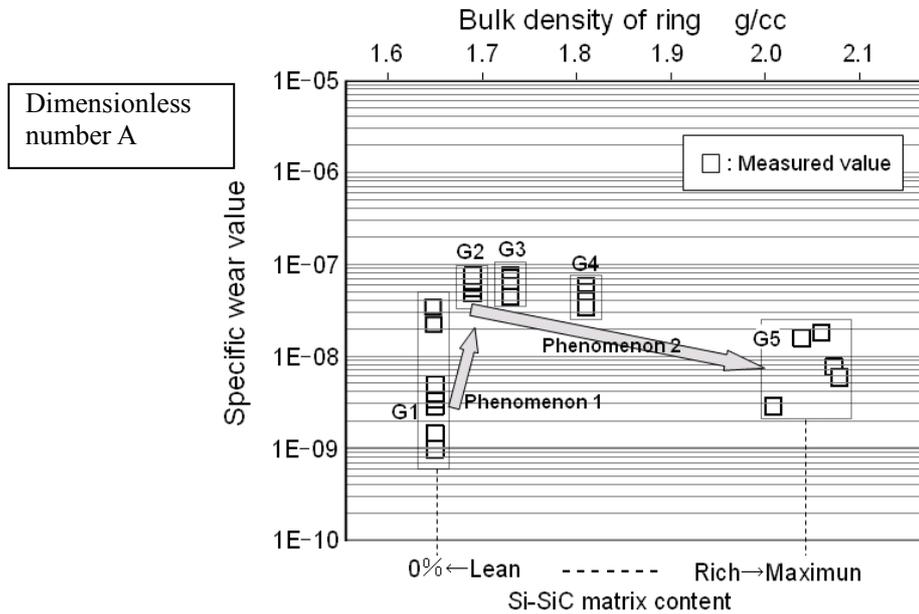
Figure 8. Dimensionless number A for wear volume amounts of C/C composites and Si-SiC matrix C/C composites

Contact pressure = 1.2 MPa, Rotation speed = 200 rpm, at 25 °C, Evaluation 10 min
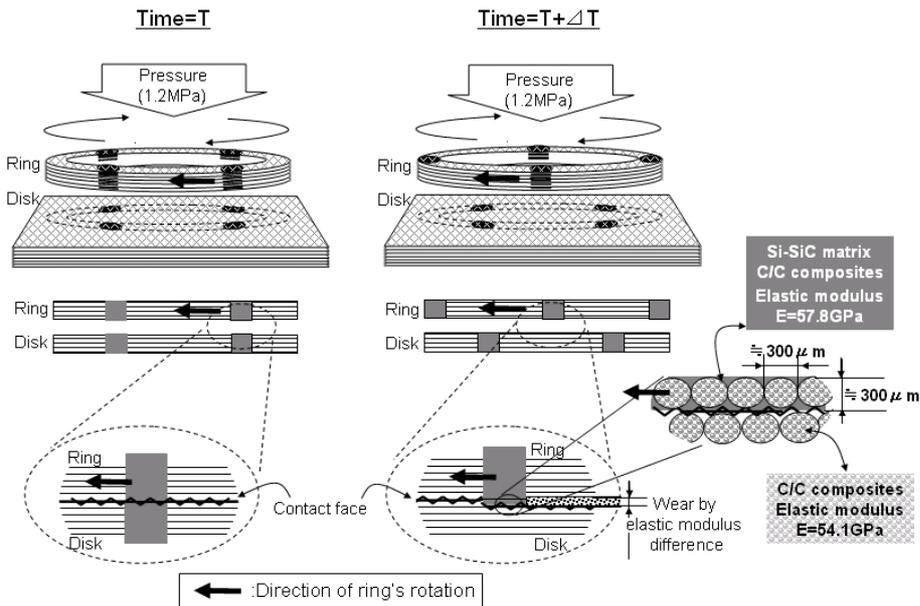
Figure 9. Wear mechanism model of Si-SiC matrix C/C composites
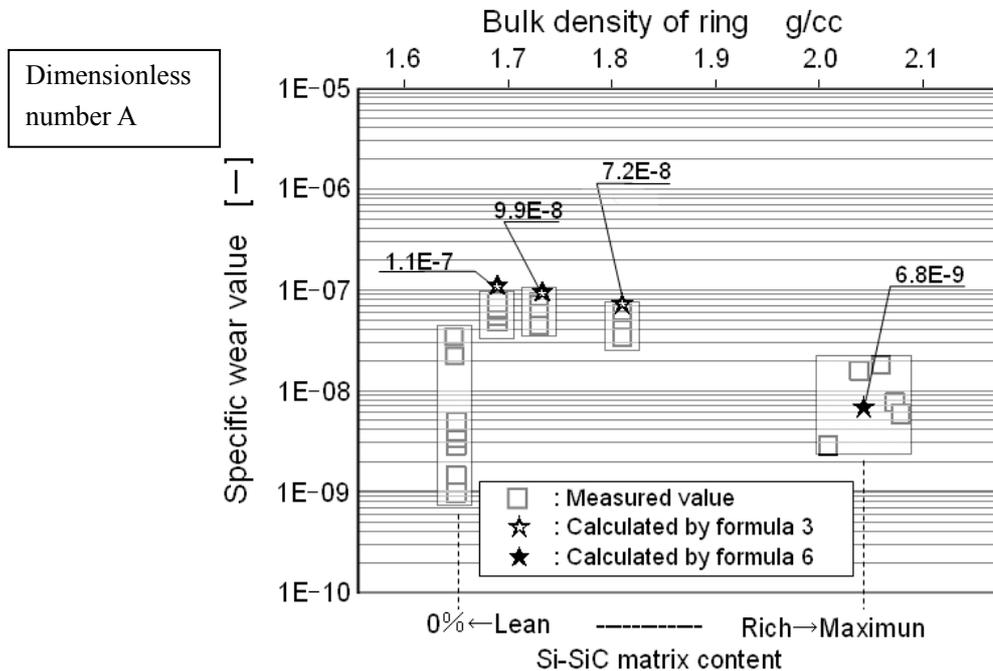
Figure 10. Dimensionless number A of wear volume amount of C/C composites and Si-SiC matrix C/C composites (comparison of calculation and actual measurements)

4.2 Dimensionless Number B Using Friction Coefficient and Wear Volume Amount (Performance and Life of Brake Component)

Performance (braking force) and life of a brake component using C/C composites and the Si-SiC matrix C/C composites were considered in terms of friction coefficients (Figure 5) and wear volume amounts (Figure 6) obtained from this experiment, and the published average value (Figure 2) of friction coefficient and wear volume amount (Ko et al., 2002) carried out by the same device as in this report experiment, for relative comparison.

It can be said that materials with larger friction coefficient is dominant over other materials in terms of performance (braking force) as a brake component when environmental conditions (temperature, speed, contact pressure) are the same. From this standpoint, it can also be said that the Si-SiC matrix C/C composites have larger friction coefficient than C/C composites and the Si-SiC matrix C/C composites have better braking properties than the C/C composites as a brake component, in an overall range of environmental conditions (temperature, speed, contact pressure) for friction coefficient in Figures 5 and 2.

In addition, with respect to life of the brake component, it can be said that materials with less wear volume amount produced are superior to others when making an object in motion having a certain kinetic energy come to rest under a certain environmental conditions (temperature, speed, contact pressure). Through the use of wear volume amount (Figures 6 and 2) at each environmental condition of the C/C composites and the Si-SiC matrix C/C composites, dimensionless number A at each environmental condition is calculated (dimensionless number A of wear volume amount in Figure 6 is described in Figure 8), and dimensionless number A for wear volume amount in each environmental condition is divided by friction coefficient at each corresponding environmental condition to calculate dimensionless number B. It is considered that this dimensionless number B is a dimensionless number for the amount of wear volume that brings an object with a certain kinetic energy to rest. Figure 11 shows the results of the calculation of dimensionless number B. From these results, the following points can be considered:

1) The brake life of dense Si-SiC matrix C/C composites is longer than that of C/C composites.

2) Si-SiC matrix C/C composites which are only partly formed of Si-SiC matrix have higher friction coefficients and braking force, but their life is shorter, making them more desirable for emergency use than regular use.

3) It is known that C/C composite brakes used for aircrafts are subjected to wear during taxiing. In comparison

with the dimensionless number B, both the C/C composites and dense Si-SiC matrix C/C composites have greatly deteriorated braking life when sliding speed is low (when contact pressure is 1.2 MPa). As most of the large amount braking energy at the time of landing is transformed into frictional heat and the temperature of the material rises, the Si-SiC matrix C/C composites are characterized as having dimensionless number B that decreases gradually as the temperature rises and brake life lengthens. So, Si-SiC matrix C/C composites are considered advantageous materials for aircrafts.
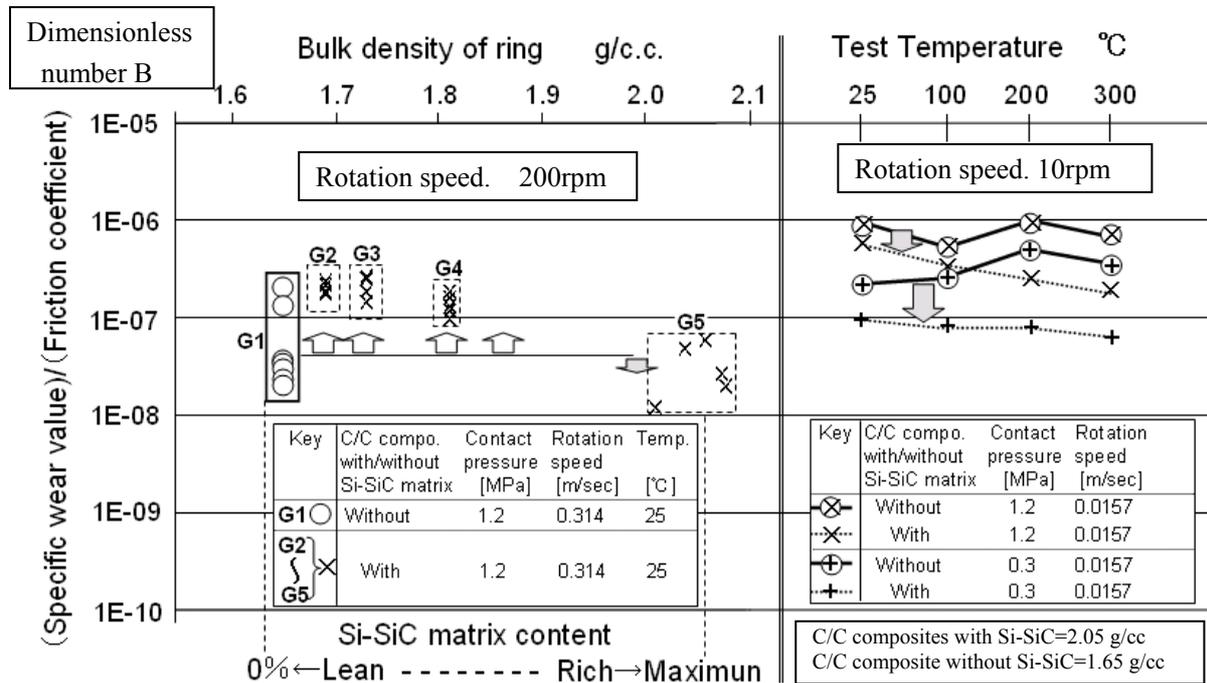
Figure 11. Dimensionless number B of C/C composites and Si-SiC matrix C/C composites

5. Conclusion

1) With regard to the sliding wear volume of the Si-SiC matrix C/C composites, we considered a hypothetical model in which a difference in the elastic modulus of the C/C composite part and that of the Si-SiC matrix part constituting the materials creates a level difference on the contact surface when contact surface pressure (Compressive stress) is applied to the Si-SiC matrix C/C composites, and this level difference grinds against the opposing material. This hypothetical model coincides with the results of dimensionless number analysis of wear volume amounts obtained in these experiments and should therefore be understood as an appropriate model.

2) From the standpoint of dimensionless number analysis of friction coefficients and wear volume amounts, the application of dense Si-SiC matrix C/C composites in brake components as an alternative material to C/C composites is superior in terms of braking force and component life. In addition, partial Si-SiC matrix C/C composites in which Si-SiC matrix is present in areas have high friction coefficients and braking forces, but their life is short, and therefore we have determined that partial Si-SiC matrix C/C composites are effective when used in brakes for emergency use, but not for regular use.

Acknowledgements

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