Mechanical Property Evaluation of Si-SiC Matrix C/C Composite with the Use of Complex Rules

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Abstract

Si-SiC matrix C/C composites are known to be synthesized through the following process. With the C/C composite having a yarn-like structure of carbon fibers as a base material, the Si-SiC matrix C/C composite is obtained by synthesizing a trunk Si-SiC matrix after impregnating Si into the clearances between yarns and then synthesizing a branch Si-SiC matrix which stretches from the trunk Si-SiC to the inside of the C/C composite. Compressive strength of the Si-SiC matrix C/C composite is increased up to about twice as large as that of the base material C/C composite. However, the tensile strength of this composite is decreased to about one fourth of that of the base material C/C composite, and the bending strength is decreased to about a half of that of the base material C/C composite. This paper reports that 1) degradation of tensile/bending strength caused on the Si-SiC matrix C/C composite is an unavoidable phenomenon and 2) a technique for forming only a part of the base material C/C composite into the Si-SiC matrix structure is an effective means of structural component design by increasing compressive strength of the base material C/C composite and restraining degradation of tensile/bending strength.

Keywords: C/C composite, Si-SiC matrix, Cu matrix, Degradation of strength, Complex rules

1. Introduction

Si impregnated C/C composites (Evans, *et al.*, 1976) were developed in the 1970s as a material having features such as heat resistance, abrasion resistance, oxidation resistance intrinsic to Si impregnated SiC ceramics (Popper, 1961) and having light weight and high strength intrinsic to carbon fiber reinforced carbon (hereinafter referred to as C/C) composite (Wrzesien, *et al.,* 1976). However, there are still few cases where this Si impregnated C/C composite has been utilized for industrial components.

This is because the Si impregnated C/C composite (Fitzer, 1987) produced by synthesizing Si-SiC matrix in pore parts on the carbon fibers while maintaining carbon fiber structure and characteristics (suggested by Fitzer) do not have the strength for them to be used as structures which need to be impervious to the stress from actual temperatures and forces in real applications. So far, authors have figured out its synthesizing mechanism by synthesizing a three-dimensional structural matrix of Si-SiC using the C/C composite (Chang, Nakagawa & Okura, 1991) having a structure of carbon fiber yarns and using its characteristic pore structure and then by creating the Si-SiC matrix C/C composite (Hanzawa & Nakagawa, 2002; Hanzawa & Nakagawa, 2003; Hanzawa, 2005) while converting only a part (12 Vol.%) of the carbon fiber to SiC and leaving the most part of the carbon constituent (Hanzawa, 2012).

This paper clarifies the drawbacks and advantages of the mechanical properties of the Si-SiC matrix C/C composite in comparison with the mechanical properties of the C/C composite (base material thereof) and the Cu matrix C/C composite. Furthermore, factors that vary the mechanical properties of the base material C/C composite by the Si-SiC matrix synthesis are analyzed using comparative observation with a structure of Cu

matrix and complex rules. In addition, this paper verifies that partial Si-SiC matrix C/C composite, devised to compensate for the drawback that properties deteriorate when the Si-SiC matrix and the C/C composites are combined, is an effective means for structural component design.

2. Experimental Procedure

Three kinds of materials are used for this experiment: 1) AC200 (AC200 made by ACROSS Co, http//:www.across-cc.co.jp/jp/about_c_c/technology.html) C/C composite **(**Chang, Nakagawa & Okura, 1991**)** having a structure in which a sheet of carbon fiber yarn extending in the direction of 0° and a sheet of carbon fiber yarn extending in the direction of 90° are laminated alternately, 2) Si-SiC matrix C/C composite **(**Hanzawa, 2012**)** in which Si is impregnated in the C/C composite (AC200) before being synthesized, 3) Cu matrix C/C composite **(**Hanzawa & Ishikawa, 2003**)** in which Cu is impregnated in the C/C composite (AC200) before being synthesized.

Si-SiC matrix C/C composite is prepared according to a method **(**Hanzawa, 2012**)** for heating raw materials, which are prepared by taking Si powder in the C/C composite (AC200/100×100×10 mm), at 1600°C in an atmosphere of argon with 100 Pa of pressure and impregnating Si into the C/C composite. Figure 1 shows X-ray diffraction data of the composite, and a part of carbon constituent comprising the C/C composite reacts with impregnated Si to be converted to SiC. On the other hand, Cu matrix C/C composite is prepared as follows: a crucible with C/C composite (AC200/100×100×10 mm) and a mass of Cu is put in a furnace first of all, these are heated at 1150°C in vacuum, the C/C composite in a state of heating/vacuum is immersed in a crucible in which molten copper is contained, and then Cu is impregnated in the C/C composite by maintaining the temperature and filling nitrogen to increase furnace pressure up to 100 kgf/cm^2. Continuously, a method **(**Hanzawa & Ishikawa, 2003**)** for pulling up the Cu impregnated C/C composite from the crucible in an atmosphere of nitrogen at high temperature/pressure and then rapidly quenching immediately was used. Figure 2 shows X-ray diffraction data of the composite thus obtained: there is no reaction between carbon constituent and Cu constituting the C/C composite; the C/C composite is comprised only of carbon and Cu.

Thus obtained group of materials and base material C/C composite are processed into a specimen to evaluate the properties. Directions of processing property evaluation specimen are as shown in Figure 3: in view of the orientation of carbon fiber yarn in the C/C composite, the direction of the carbon fiber yarn aligned in the direction of 0° is determined to be the direction X, the direction of the carbon fiber yarn aligned in the direction of 90° is determined to be the direction Y, and the direction of sheet lamination of the carbon fiber yarn is determined to be the direction Z.

3. Experimental Results (Mechanical Properties)

Bulk density/porosity and bending strength, bending elastic modulus, compressive strength at room temperature of the Si-SiC matrix C/C composite, the Cu matrix C/C composite, and the C/C composite (AC200) used for the base material of these composite were measured.

Measurement of bulk density/porosity was made according to Archimedes method (at normal temperature) using specimens processed to a length of X=4mm, Y=40mm, Z=3mm for all three kinds of composite. Measurement of bending strength and bending elastic modulus is made using specimens processed to a length of X=4mm, Y=40mm, Z=3mm for all three kinds of composite and using 4-point bending method by applying load from the direction Z (lower span of 30 mm, upper span of 10 mm, crosshead speed of 0.5 mm/min). Value of bending strength is calculated in conformity to JIS-R1663 **(**2004**)**. Value of bending elastic modulus is calculated in conformity to JIS-R1644 **(**2002**)**. Furthermore, measurement of compressive strength is made using specimens processed to a length of X=10mm, Y=10mm, Z=10mm for all three kinds of composite, by applying load from the direction Z crosshead speed 0.5mm/min, (Using the universal testing equipment, AG-25TA, SHIMADZU Co.), in conformity with JIS-R1673 **(**2007**)** so as to measure strength that a specimen buckles. Table 1 shows Mechanical properties of C/C composite, Si-SiC matrix C/C composite and Cu matrix C/C composite. In the table, tensile strength data and tensile elastic modulus data are taken from report of Wang *et al.* **(**2008**)**.

From characteristic values in Table 1, with regards to the Cu matrix C/C composite densified without associated with new reaction synthesis between the impregnated Cu and the base material C/C composite, each value of compressive/bending/tensile strength and elastic modulus is increased more than those of the base material C/C composite, and therefore it can be said that Cu impregnation into the C/C composite contributes to improvement of these mechanical properties.

We found that synthesizing the Si-SiC matrix in the C/C composite may not contribute to improvement of the mechanical properties of the C/C composite. This is due to the Si-SiC matrix C/C composite being densified

incident to SiC synthesizing reaction between the impregnated Si and the base material C/C composite. There is a positive factor of increased compressive strength (+105% to base material C/C composite) and increased bending elastic modulus (+27% to base material C/C composite). However, there is a negative factor of decreased bending strength (-54% to base material C/C composite) and decreased tensile strength (-77% to base material C/C composite).

4. Discussion

4.1 Discussion (Observation of a State of Three-Dimensional Structural Trunk/Branch Matrix)

Since there exists a phenomenon that the bending/tensile strength of the Si-SiC matrix C/C composite are decreased as against the base material C/C composite, the factors are observed and examined from a standpoint of three-dimensional structural trunk/branch matrix.

Figures 4 and 5 show the result of observation of a state that three-dimensional structure of the Si-SiC matrix or Cu matrix is distributed. Here, Figure 4 [A1] is an optical micrograph taken after polishing the Y-Z surface (Figure 3) of the Si-SiC matrix C/C composite with #800 grinding stone, and Figure 4 [A2] is an optical micrograph taken after retaining the state of [A1] in the air at 880°C for one hour to remove carbon constituent. In addition, Figure 5 [B1] is an optical micrograph after polishing the Y-Z surface of the Cu matrix C/C composite with #800 grinding stone, and Figure 5 [B2] is an optical micrograph taken after retaining the state of [B1] in the air at 880°C for one hour to remove carbon constituent. It should be noted that a possibility for removing carbon constituent by heating at 880°C in the air is confirmed from thermogravimetry (Figure 6) of carbon powder of raw material of the base material C/C composite and carbon fiber.

The Si-SiC matrix C/C composite is a dense composite material **(**Hanzawa, 2012**)** obtained by performing Si impregnation at base points of pores at intervals of about 300μm in the base material C/C composite to synthesize three-dimensional trunk/branch Si-SiC matrix in the base material C/C composite. This material structure can also be understood from the state (Figure 4 [A1], [A2]) that a three-dimensional structure trunk/branch Si-SiC matrix is distributed over the base material C/C composite. The same structure is also found in the Cu matrix C/C composite (Figure 5 [B1] and [B2]) in which three-dimensional structural trunk/branch matrix Cu is distributed in the base material C/C composite.

From this point, it is considered that structure of the three-dimensional structural trunk/branch matrix itself is not a direct factor in reducing the C/C composite properties.

Furthermore, comparing Figure 4 [A2] with Figure 5 [B2], both trunk matrix/branch matrix of [A2] in which a part of carbon constituent is used for matrix synthesis grow more thickly than [B2] in which carbon constituent is not consumed at the time of matrix synthesis, as a result, [A2] has smaller pores after removing carbon fiber yarns. This indicates the relationship between [A1] and [B1], the percentage of carbon constituent in [A1] is 12 Vol.% less than [B1] (ratio of constituents of the Si-SiC matrix C/C composite is "carbon constituent vs. Si-SiC = 74vol% vs. 26vol%" from the publication **(**Hanzawa, 2012**)**. The ratio of constituents of the Cu matrix C/C composite is "carbon constituent vs. Cu =86vol% vs. 14vol%" from bulk density data in Table 1 and Cu's theoretical density 8.9 g/cc). However, this does not lead to an explanation of large divergence from a ratio (-54% to -77%) that bending/tensile strength of the Si-SiC matrix C/C composite decreased compared to the base material C/C composite. From this point, it is also considered that the structure of three-dimensional structural trunk/branch matrix itself is not a direct factor in reducing bending/tensile strength properties of the base material C/C composite.

4.2 Discussion (Mechanical Properties Evaluation with the Use of Complex Rules)

When the Si-SiC matrix is synthesized in the base material C/C composite, bending/tensile strength is decreased largely (-54% to -77%) as against reduction of carbon constituent (-12%). On the contrary, when the Cu matrix is synthesized in the base material C/C composite, there is no change of carbon constituent (-0%) and reduction of bending/tensile strength is not recognized. A relation of this value of strength is examined from a standpoint of complex rules that considers dispersion and orientation of fibers in the composite.

Formulas 1, 2 and 3 are enumerated for complex rules for calculating characteristic values of composite comprising a dual-element simple system base material and a matrix **(**Kagawa *et al.*, 1990**)**.

$$P_c = P_m V_m + (1\text{-}V_m) P_f \tag{1}$$

$$\ln P_c = V_m \ln P_m + (1\text{-}V_m) \ln P_f \tag{2}$$

$$1/P_c = V_m / P_m + (1\text{-}V_m) / P_f \tag{3}$$

Here in, P_c= Characteristic values of composite, P_f= Characteristic values of base materials,

P_m= Characteristic values of matrix, V_m= Volume fraction of matrix.

Formula 1 is a complex rule of elastic modulus, Poisson's ratio, strength, thermal conductivity and electric conductivity in the direction of fiber axis when the base material is unidirectional fiber reinforced material. Formula 2 is a complex rule of estimation of elastic modulus and dielectric constant when the base material is spherical particle dispersion, elastic modulus when base material is irregular structure, and elastic modulus and thermal conductivity when base material is three-dimensional random oriented material. Formula 3 is a complex rule of elastic modulus, dielectric constant, thermal conductivity and electric conductivity in the direction perpendicular to the fiber axis when the base material is unidirectional fiber reinforced material **(**Kagawa, *et al.*, 1990**)**. Here, a characteristic value common to these three formulas is elastic modulus.

Accordingly, a relationship was established among bending elastic modulus (35±6 GPa, Table 1)of the base material C/C composite, and bending elastic modulus obtained from complex rules using bending elastic modulus of the Si-SiC matrix in consideration of "the use of NEWSIC's value (352 GPa±30) for bending elastic modulus of the Si-SiC matrix. Herein, volume ratio of Si and SiC in the Si-SiC matrix C/C composite is Si:SiC=17:83 Vol.% from the publication **(**Hanzawa, 2012**)** and close to volume ratio of Si and SiC (Si:SiC=18:82 Vol.%) of commercially available Si-SiC composite (NEWSIC made by NGK, Hanzawa *et al.*,1996)". Actual measurement value (42±13 GPa, Table 1) of bending elastic modulus of the Si-SiC matrix C/C composite was compared.

The result is shown in Figure 7. In addition, calculations were made with volume ratio of the Si-SiC matrix portion of the Si-SiC matrix C/C composite considered as 26 Vol.% (refer to 4.1).

Similarly, relation among tensile elastic modulus (54.1±10 GPa, Table 1) of the base material C/C composite, tensile elastic modulus of calculated according to complex rules using the published value (129.8 GPa, **(**Wang, *et al.*, 2008**)**) of tensile elastic modulus of the Cu matrix, and actual measurement value (62.5±14 GPa, Table 1) of tensile elastic modulus of the Cu matrix C/C composite was compared. The result is shown in Figure 8. In addition, calculations were made with volume amount of the Cu matrix portion of the Cu matrix C/C composite considered as 14 Vol.% (refer to 4.1).

It is found from Figure 7 that the actual measurement value (including distribution) of bending elastic modulus of the Si-SiC matrix C/C composite coincides with calculation values according to Formula 3 of complex rules and partly coincides with calculations according to Formula 2. Furthermore, it is found from Figure 8 that the actual measurement value (including distribution) of tensile elastic modulus of the Cu matrix C/C composite coincides with any of the calculations according to Formulas 1/2/3 of complex rules. From this, it can be said that elastic modulus of the Si-SiC matrix C/C composite and the Cu matrix C/C composite indicates the property that coincides with complex rules.

Next, examination by means of complex rules was performed for strength of the C/C composite of the Si-SiC matrix and the Cu matrix. Here, although complex rules to be applied to strength is Formula 1, calculations according to Formulas 2 and 3 were also performed for comparison.

Figure 9 shows the result of comparing a relation among bending strength (240±16 MPa, Table 1) of the base material C/C composite, bending strength calculated according to complex rules using bending strength of the Si-SiC matrix (in consideration of the use of bending strength (240 MPa±21) of NEWSIC made by NGK according to way of thinking of bending elastic modulus), and actual measurement value (111±16 MPa, Table 1) of bending strength of the Si-SiC matrix C/C composite.

Figure 10 shows the result of comparing a relation among tensile strength (238.7±19 MPa, Table 1) of the base material C/C composite, tensile strength calculated according to complex rules using the published value (216 MPa, **(**Wang, *et al.*, 2008**)**) of tensile strength of the Cu matrix, and actual measurement value (279.4±15 GPa, Table 1) of tensile strength of the Cu matrix C/C composite.

In Figure 9, with regards to actual measurement value (including distribution) of bending strength of the Si-SiC matrix C/C composite, percentage of coincidence with calculations according to Formulas 1/2/3 is 58% or less (divergence minimum portion=137 MPa (actual measurement value)/235 MPa (complex rules)=58%), it can be said that this is a material difficult to explain according to complex rules. On the contrary, as shown in Figure 10, with regard to actual measurement value (including distribution) of tensile strength of the Cu matrix C/C composite, percentage of coincidence with calculations according to any of the Formulas 1/2/3 is 85% or more (divergence maximum portion=224 MPa (complex rules)/264.4 MPa (actual measurement value)), and therefore it is considered that this material has the property in conformity to complex rules.

Here, measured strength of the Si-SiC matrix C/C composite as shown in Figure 9 diverges from calculated

strength by complex rules, and therefore cause of behavior greatly degraded against strength performance of the base material C/C composite is examined at the same time. Figure 11 shows microstructure near the boundary of the Si-SiC matrix portion and the carbon fiber yarn of the base material C/C composite and gradient of concentration of Si and C constituents at this portion. It is found from Figure 11 that the surface of the carbon fiber in a range where Si and C coexist is intensely uneven and smooth surface of the carbon fiber is broken. At the same time, there also exist cracks from the Si-SiC matrix region extending to the inside of the carbon fiber yarn. This phenomenon suggests that the carbon constituent which reacts with Si and is converted to SiC remains at 12 Vol.% and that the carbon fiber yarn of volume of 12 Vol.% or more is damaged.

Figure 12 shows the result of examining an amount of the damaged carbon fiber yarn using complex rules. In addition, although for estimated calculation of strength, applying Formula 1 of complex rules is in conformity to the way of thinking of the formula, there is a tendency that calculation values with Formulas 1/2/3 for estimated calculation (Figure 10) of tensile strength of the Cu matrix C/C composite coincide with actual measurement values, and therefore examination is performed using three formulas. In Figure 12, with volume of carbon constituent of the Si-SiC matrix C/C composite, the carbon constituent of which is reduced (12 Vol.%) due to Si-SiC matrix synthesizing, taken as 100%, on the assumption that volume of carbon constituent contributing to development of strength is reduced to a range from 11% (Formula 1) to 47% (Formula 3), it is possible to calculate that strength property of the Si-SiC matrix C/C composite coincides with complex rules.

Consequently, reduction of bending/tensile strength (111 MPa/55 MPa, Table 1) of the Si-SiC matrix C/C composite against bending/tensile strength (240 MPa/239 MPa, Table 1) of the base material C/C composite is an unavoidable phenomenon at the time of synthesizing the Si-SiC matrix, and therefore wisdom and ingenuity are required to design structural components, which maintain and improve the properties of the base material C/C composite, using the Si-SiC matrix C/C composite, as bending/tensile strength (248 MPa/279 MPa, Table 1) of the Cu matrix C/C composite.

4.3 Discussion (Application Example to Practical Use)

Advantage of the properties of the Si-SiC matrix C/C composite to the properties of the base material C/C composite is an increase of compressive strength, and drawback is a decrease of bending/tensile strength (refer to Table 1). Furthermore, sections 4.1 and 4.2 consider that this drawback (decrease of bending/tensile strength) is an unavoidable phenomenon when the Si-SiC matrix accompanied by SiC synthesizing reaction is used for the matrix inside of the C/C composite. In view of these backgrounds, the author considers it necessary to innovate "structural component design by configuring with the Si-SiC matrix converted C/C composite for the portions receiving compressive stress and configuring with the C/C composite for the portions receiving bending/tensile stress" when designing structural components which use the Si-SiC matrix C/C composite for alternative material of the C/C composite. Accordingly, a fracture experimental method (refer to Figure 13) for applying loads at crosshead speed of 0.5 mm/min in the direction (Y-axis) of tearing a notch of 32x11 mm (R4) provided centering the X-axis short portion of the material with outside size of 40/80/10 mm of X-/Y-/Z-axis is used to examine effectiveness of author's way of thinking. The results of fracture experiment are indicated in Figure 14 (where, C0 indicates a state of the base material C/C composite **(**Chang, Nakagawa & Okura, 1991**)** after experiment, C1X is an X-ray photo of the C/C composite **(**Hanzawa, 2012**)** by synthesizing the Si-SiC matrix all over the C/C composite before experiment (densified portion by Si impregnation is shown white), C1 indicates a state after experiment, C2X is an X-ray photo of partial Si-SiC matrix C/C composite **(**Hanzawa & Hashimoto, 2010**)** by synthesizing the Si-SiC matrix partially on the C/C composite before experiment (densified portion by Si impregnation is shown white), C2 indicates a state after experiment). Here, the C2 specimen has three holes of 0.5 mm in diameter indicated in the C2X and is prepared from these holes through the use of a method **(**Hanzawa & Hashimoto, 2010**)** of performing the Si impregnation, portions around three holes and periphery of the specimen are densified by Si impregnation and recognized in white in the X-ray photo. Table 2 shows the breaking loads of these specimens and the result of processing specimens of X:Y:Z = 10:10:10 mm from four corner ends and measuring compressive strength with regard to partial Si-SiC matrix C/C composite.

When comparing fracture morphology of thee kinds of materials indicated in Figure 14, there exists interlaminar /shear fracture at portions getting contact with a jig for C0 and no fracture at portions of contact for C1 and C2. Although it is considered that such interlaminar/shear fracture is attributable to compressive stress at portions having contact with the jig, with regards to compressive strength, which is also the result of effectively utilizing the properties (Table 1) of the Si-SiC matrix C/C composite superior to the C/C composite. Furthermore, when comparing fracture sections of C1 and C2, C2 has long traces extracting carbon fibers of about 10 mm, and C1 has short traces extracting carbon fibers of about 2 mm. It is considered that this difference in length links to difference in breaking load of these three kinds of materials: "as against breaking load (100%) of the base

material C/C composite, breaking load of the Si-SiC matrix C/C composite is reduced to 65%, but breaking load of partial Si-SiC matrix C/C composite remains 93% (Table 2)". In other words, it can be said that partial Si-SiC matrix C/C composite is effective material design technique against maintenance of advantage and improvement of drawback of the base material C/C composite.

5. Conclusions

1). The cause of greatly decreasing bending/tensile strength of the Si-SiC matrix C/C composite as against the C/C composite is not subjected to trunk/branch three-dimensional matrix structure stemming from densified composite, but is attributable to the fact that 50% or more of the carbon fiber yarn structure is broken when 12 Vol.% of carbon constituent in the base material C/C composite is converted to SiC, and therefore is an unavoidable phenomenon during the synthesizing process of dense Si-SiC matrix C/C composite.

2). To maintain the advantage of strength of the base material C/C composite and simultaneously to improve the drawback of strength, the following structural component design using the Si-SiC matrix C/C composite is effective. This is a partial Si-SiC matrix C/C composite that produces the Si-SiC matrix structure for portions where compressive stress occurs and that does not produce the Si-SiC matrix structure for portions where bending/tensile stress occurs, rather than the structure of synthesizing the Si-SiC matrix all over the C/C composite.

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Table 1. Mechanical property of C/C composite, Si-SiC matrix C/C composite and Cu matrix C/C composite

	C/C composite (Base material)	Si-SiC matrix C/C composite	Cu matrix C/C composite	N.B. Test method
Bulk density	1.65 g/cc	2.05 g/cc	2.50 g/cc	Archimedes method
Porosity	16.1 Vol.%	3.5 Vol.%	2.5 Vol.%	Ibid
Compressive strength Average value	129±31 MPa	265±45 MPa	243±19 MPa	Test is based on JIS R1673(2007)
Bending strength Average value	240±16 MPa	111±26 MPa	248±21 MPa	Test is based on JIS R 1663(2004)
Bending elastic modulus Average value	35±6 GPa	42±13 GPa	105±16 GPa	Test is based on JIS R 1644(2002)
Tensile strength Average value	238.7±19 MPa	55.4±7 MPa	279.4±15 MPa	Data's taken from Wang *et al.* (2008)
Tensile elastic modulus Average value	54.1±10 GPa	57.8±10 GPa	62.5±14 GPa	Data's taken from Wang *et al.* (2008)

Table 2. Breaking load of C/C composite, Si-SiC matrix C/C composite and partial Si-SiC matrix C/C composite

	C/C composite (Base material)	Si-SiC matrix C/C composite	Partially Si-SiC matrix C/C composite	N.B. Test method
Breaking load Average value [kgf]	217±21 kgf	142±15 kgf	202±28 kgf	Written in Figure 13
Breaking load ratio [%]	100 %	65 %	93 %	---
Compressive strength Average value [MPa]	129±27 MPa (From Table 1)	265±24 MPa (From Table 1)	218±30 MPa (Samples cut from edge portion)	Test is based on JIS R1673(2007)

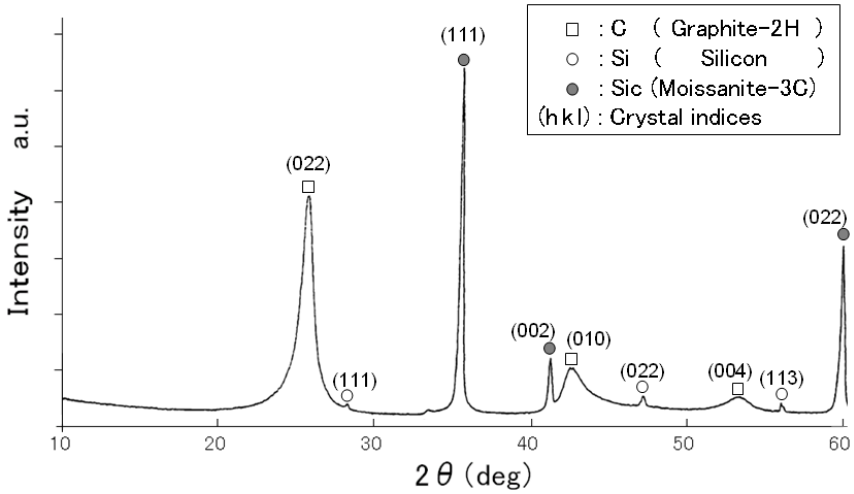

Figure 1. Result of X-ray diffraction of Si-SiC matrix C/C composite

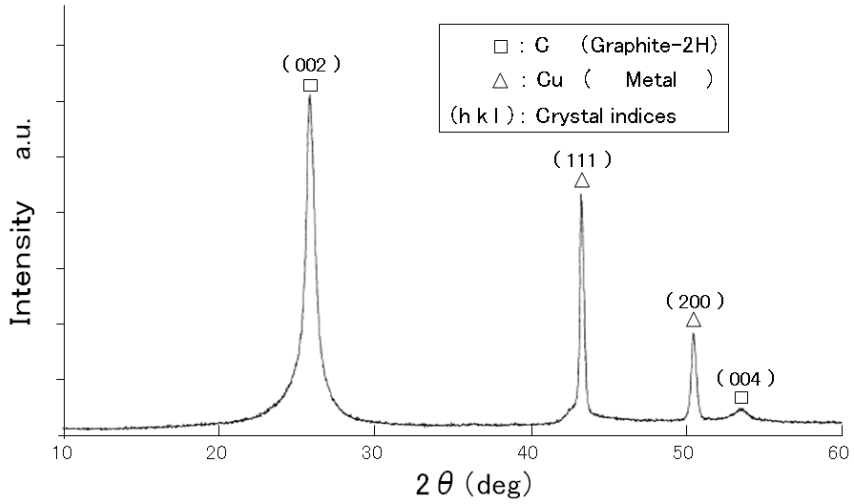

Figure 2. Result of X-ray diffraction of Cu matrix C/C composite

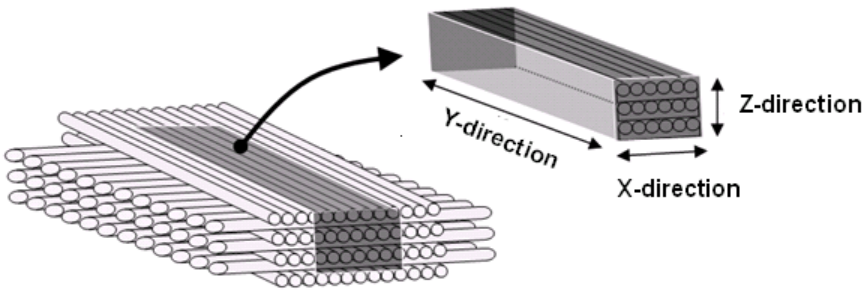

Figure 3. Direction of processing of test specimen from composite containing carbon fiber yarn and sheet

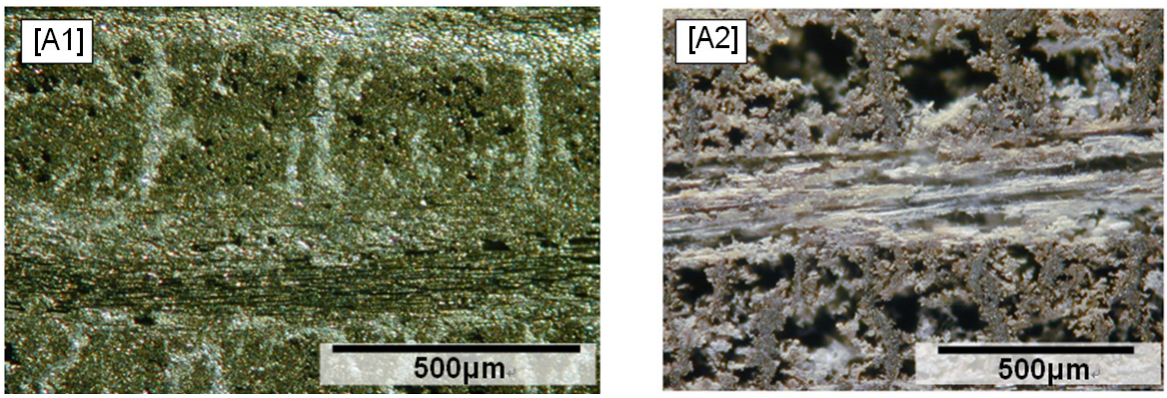

Figure 4. Optical micrograph of Si-SiC matrix C/C composite

[A1] shows the surface of a material polished by #800 grinding stone

[A2] shows the surface of A1 after retaining in the air at 880°C for 1 hour

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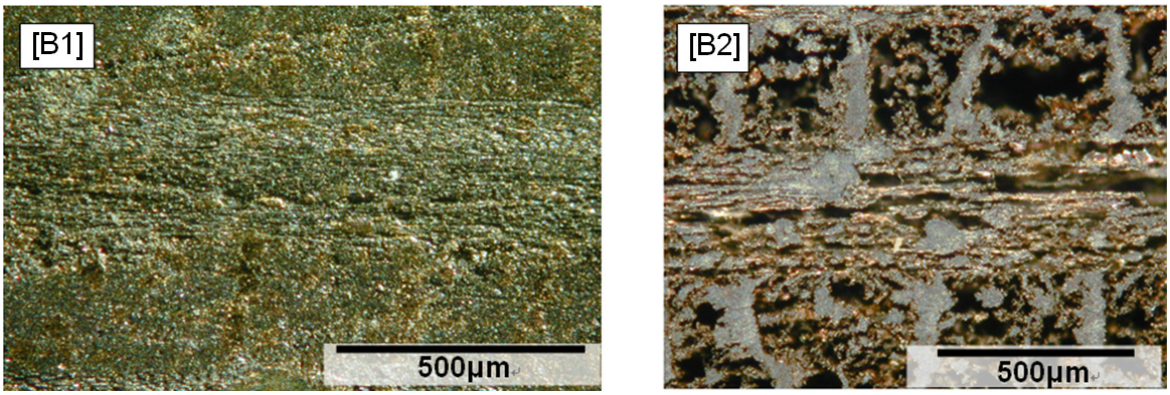

Figure 5. Optical micrograph of Cu matrix C/C composite

［B1］shows the surface of a material polished by #800 grinding stone

［B2］shows the surface of B1 after retaining in the air at 880°C for 1 hour

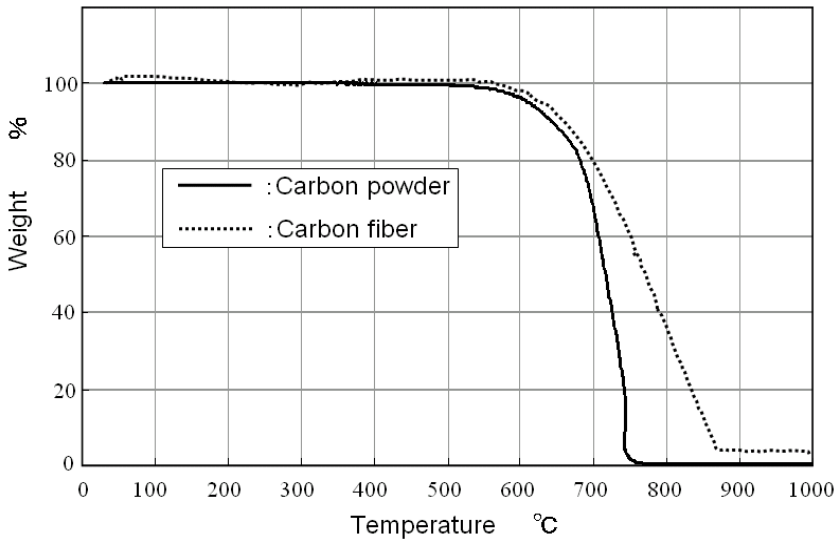

Figure 6. Thermo-gravity of carbon powder and carbon fiber used for C/C composite (AC200)

Measurement conditions：in the air, temperature rising speed 10°C/min

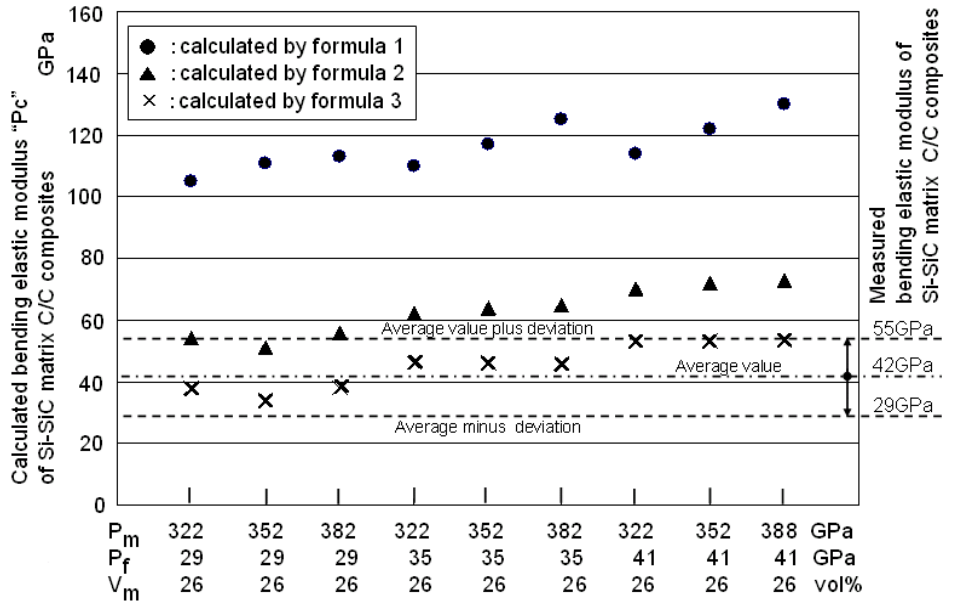

Figure 7. Relation between bending elastic modulus P_c of the Si-SiC matrix C/C composite and actual measurement value using complex rules

Herein, P_f= Characteristic values (35±6 GPa) of base material C/C composite

P_m = Characteristic values (352±30 GPa) of Si-SiC matrix

V_m = Volume ratio (26 Vol.%) of Si-SiC matrix.

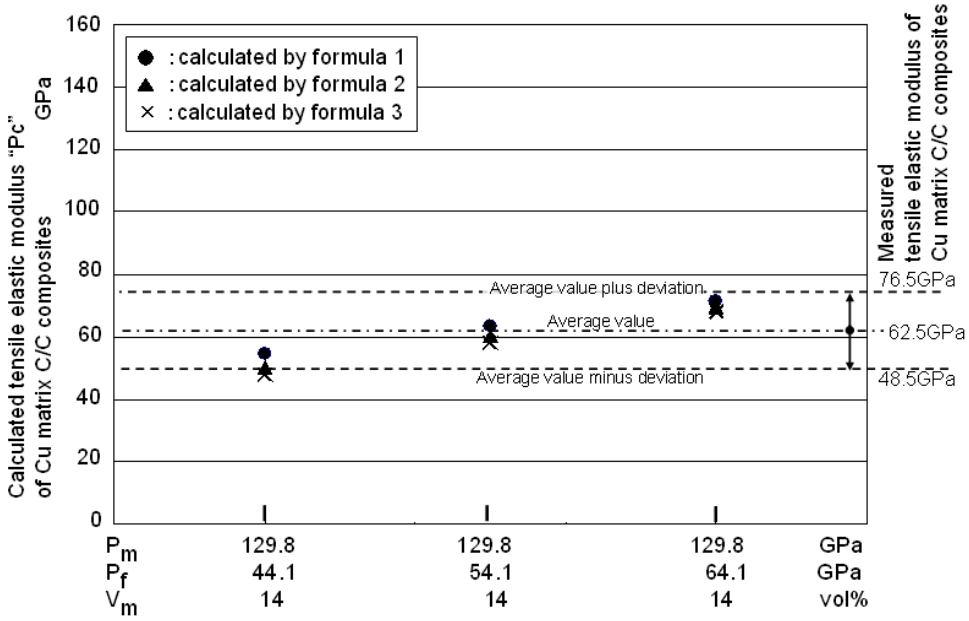

Figure 8. Relation between tensile elastic modulus P_c of the Cu matrix C/C composite and actual measurement value using complex rules

Herein, P_f= Characteristic values (54.1±10 GPa) of base material C/C composite

P_m = Characteristic values (129.8 GPa) of Cu matrix

V_f = Volume ratio (14 Vol.%) of Cu matrix.

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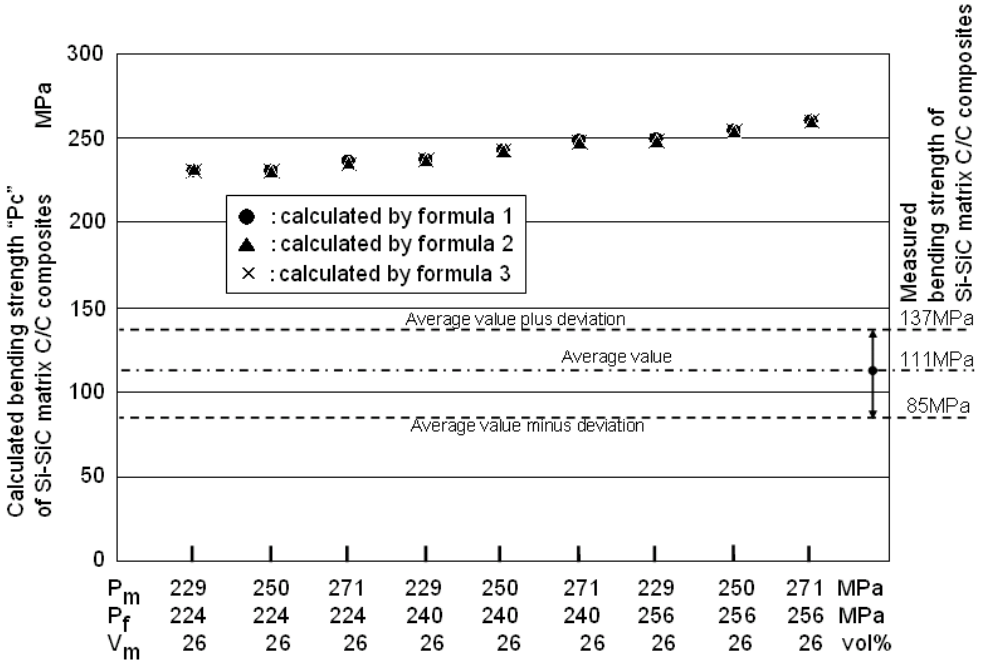

Figure 9. Bending strength P_c of Si-SiC matrix C/C composite

Herein, P_f= Characteristic values (240±16 MPa) of base material C/C composite

P_m = Characteristic values (250±21 MPa) of Si-SiC matrix

V_f = Volume ratio (26 Vol.%) of Si-SiC matrix

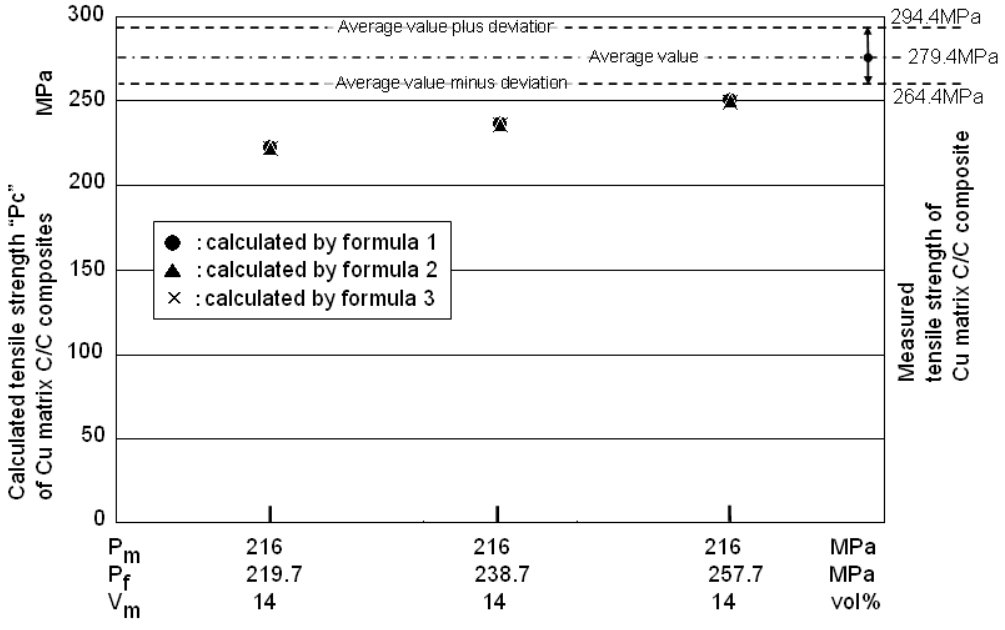

Figure 10. Tensile strength P_c of Cu matrix C/C composite

Herein, P_f= Characteristic values (238.7±19 MPa) of base material C/C composite

P_m = Characteristic values (216 MPa) of Cu matrix

V_f = Volume ratio (14 Vol.%) of Cu matrix

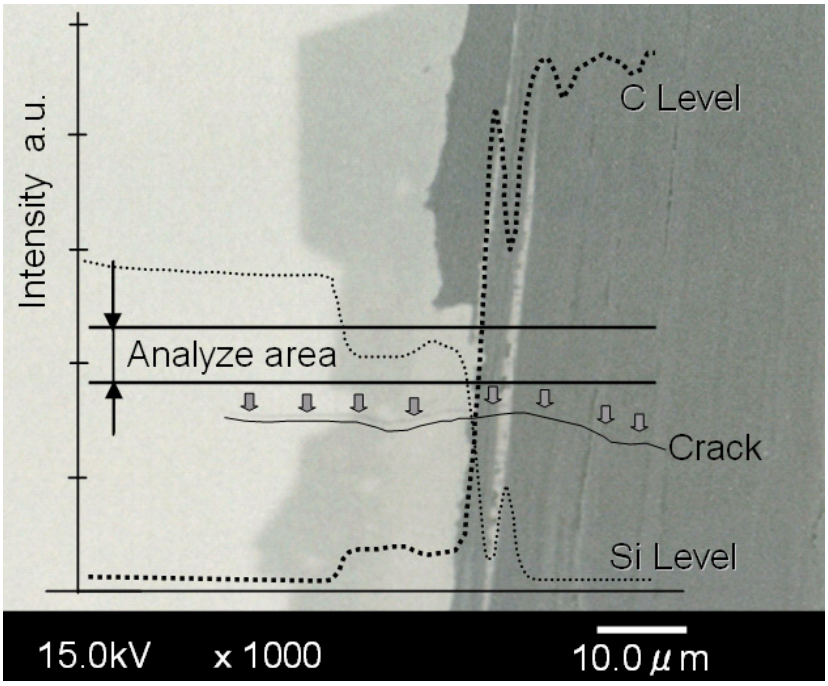

Figure 11. Microstructure (SEM) of Si-SiC matrix C/C composite and gradient of concentration of Si and C

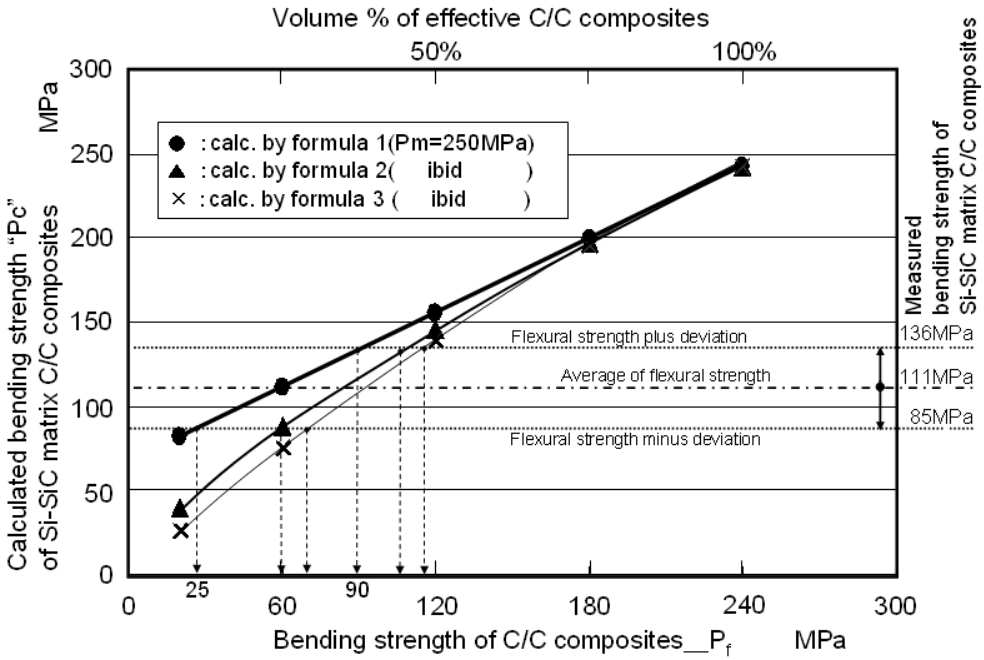

Figure 12. Estimated amount of damage of carbon fiber yarn using complex rules

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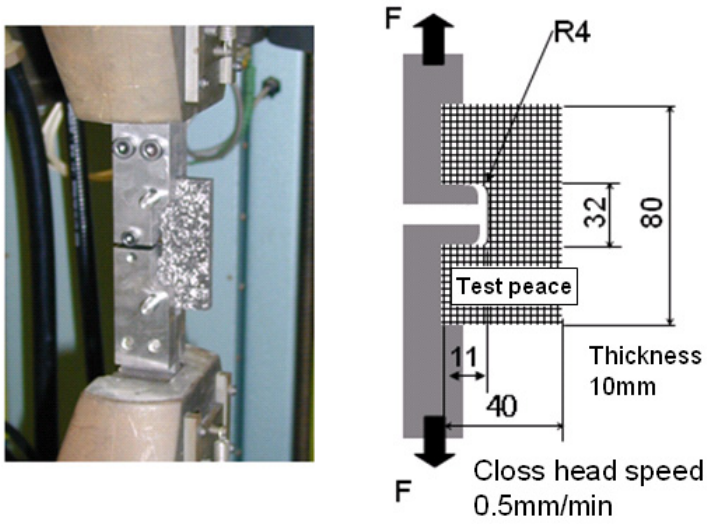

Figure 13. Evaluation experimental method of breaking load using notched specimens

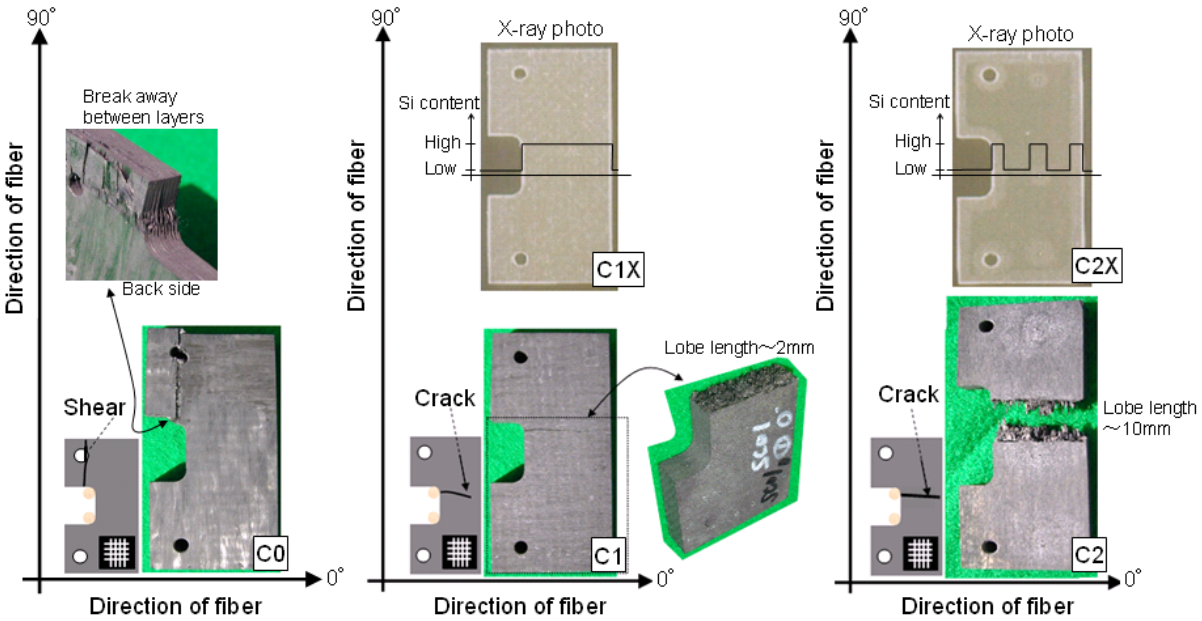

Figure 14. Result of evaluation of breaking load using notched specimens

State after breakage: C/C composite for C0, Si-SiC matrix C/C composite for C1, partial Si-SiC matrix C/C composite for C2

X-ray photo: Si-SiC matrix C/C composite for C1X, partial Si-SiC matrix C/C composite for C2X