SMiRT-12 / K. Kussmaul (Editor)

SD105/5

HIGH TEMPERATURE THERMOMECHANICAL CHARACTERIZATION BY THERMAL SHOCK TESTS ON C/C COMPOSITES FOR NUCLEAR APPLICATIONS

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ABSTRACT

A new experimental method has been developed to investigate thermomechanics of candidate C/C composites(CFCs). The test apparatus enables to measure transients of the temperature profile and diametral displacement of a round disk specimen which is subjected to moderate and severe thermal loads by induction heating. The observed thermal behavior of three CFCs and isotropic graphite has been used to determine their thermal expansion as a function of temperature. The 50mm dia. disks made of two CFCs for fusion application have endured repeated severe thermal shocks, during which the thermal loads have reached the max. diametral temperature difference of 1320K with the maximum temperature of 2750K. The results are useful for examining quantitative thermal and fracture characteristics of anisotropic composite materials together with a nonlinear thermal/elastic analysis.

1 INTRODUCTION

Carbon fiber-reinforced carbon composites(referred to as C/C composites or CFCs hereafter) are being developed for such advanced nuclear components as hot gas ducts in a gas-cooled reactor(Mittenbuehler et al. 1990; Roedig et al. 1991) and plasma facing components in fusion facilities(Akiba et al. 1990). Features of individual grades of C/C composites are dependent strongly on their macroscopic structures, which are devised to meet specific performance requirements at high temperatures. As a result, they possess anisotropy and nonlinearity in some of thermal and mechanical properties as polygranular graphite materials exhibit. This aspect requires a nonlinear thermomechanical method to be developed for the design and assessment of C/C composite structures.

The present paper concerns a new approach to the thermomechanical investigation which involves a thermal shock testing by means of induction heating and a nonlinear thermoelastic analysis. The round disks made of three different grades of C/C composites for nuclear components have been subjected to moderate and severe thermal loads in order to measure thermal and fracture characteristics, respectively. The thermomechanical behavior observed under various heating and cooling conditions is compared with that of an isotropic graphite as reference carbon-based material.

2 EXPERIMENTAL

2.1 Materials and test specimens

Three grades of CFCs and one grade of isotropic graphite have been used.

Grade CC1501G of SIGRI GmbH is a 2D woven textile plate product. The material was applied to fabricate and test the large-sized hot gas duct (Mittenbuehler et al. 1990). Grade Aeroler 05(A05) of Le Carbone Lorraine is a PAN-based fiber, 2D-felt CFC densified by CVD processing. It is a candidate for plasma facing materials and components(Akiba et al. 1991). Grade PCC-2S of Hitachi Chem. Co. Ltd. is a pitch-based fiber, 2D-felt CFC which was developed for the divertor armor tiles of the large tokamak facility JT-60U(Ando et al. 1992). Isotropic IG-11 graphite of Toyo Tanso Co. Ltd., as a reference, is a petroleum coke-based, fine-grained isostatically pressed product. Its purified grade, IG-110, was used as a structural material for core components of the HTTR(Arai et al. 1991).

Typical properties of these four carbon-based materials are shown in Table 1 (SIGRI 1988; Zolti, 1990; Thiele 1990; Ando et al., 1992; Arai et al., 1991). It is noted that they differ each other with respect to the degree of anisotropy in thermal and mechanical properties. The authors have taken care of this aspect in conducting the present tests.

All test specimens have been prepared in consideration of their installation inside a workcoil having 53mm in inner diameter and 5mm in height. The dimensions of round disk specimens are 5mm thick, and 5mm/50mm and 5mm/48.6mm in inner/outer diameters for PCC-2S, IG-11 disks and A05, CC1501G disks, respectively. Orientation axes of the specimen and the material have been selected so that the radial and tangential directions coincide with the isotropic layered plane direction(//) and the thickness direction is perpendicular to the layered plane(⊥). A few specimens of each grade, which are to be used exclusively in temperature profile measurements, provide four holes drilled for thermocouple insertion.

2.2 Thermal shock test apparatus

A schematic diagram of the thermal shock test apparatus with radio-frequency induction heating is shown in Fig. 1. A hollow round disk is fixed by six insulating ceramic rods and positioned axisymmetrically inside the water cooled copper coil. The radio-frequency power source of 50 kW rating at 170kHz is able to supply a maximum current of approximately 3400A in the workcoil. The power supply is regulated by a power setting device to be operated manually. A magnitude of power output is here given by a relative power level of 0～1000, which corresponds to 0～100% of the rated power, respectively. The magnitude of distributed eddy current is different from one material to another at the same power level.

However, measurements of temperature and displacement devised for the

Table 1 Typical properties of carbon-based materials for the present study.

Carbon grade		CC1501G	A05	PCC-2S	IG-11
Bulk density (g/cm³)		1.3～1.4	1.8	1.81	1.77
Electrical resistivity (μΩm)	//	25～30	4	3.3	11
	⊥		11	–	11
Thermal conductivity (W/mK)	//	20/500℃	230	310	79/500℃
	⊥	2/500℃	80	190	78/500℃
Coeff. thermal expansion (10^{-6}/K)	//	0.5/RT-500℃	1.1/RT	1.0	4.0/RT-500℃
	⊥	5.5/RT-500℃	8/RT	5.8	4.2/RT-500℃
Young's modulus (GPa)	//	50-60	20	14	9.7
	⊥	–	–	–	9.3
Tensile strength (MPa)	//	160-200	54	27	26
	⊥	–	9	–	26
Bending strength (MPa)	//	130-150	–	31	34
	⊥	–	–	–	34

// : parallele to layer plane (horizontal)

⊥ : perpendicular to layer plane (vertical)

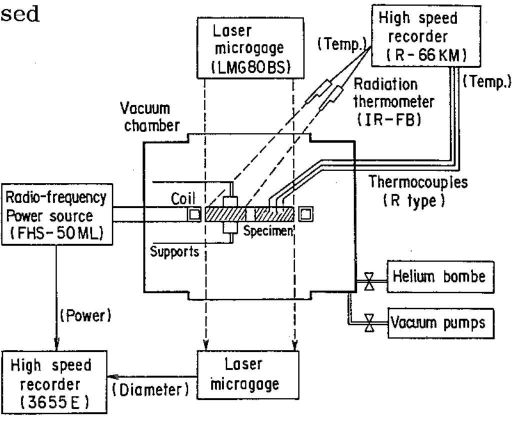

Fig. 1 Schematic diagram of thermal shock test apparatus.

present tests have made it possible to examine quantitative thermomechanical behavior, as explained in the following. During each heating and cooling transient the radial temperature profile has been measured by four R type (Pt-13Rh/Pt) thermocouples (T/Cs) below 1600℃ and/or two radiation thermometers (R/Ts), one above 800℃ and the other above 1100℃. Considering that the heat generation in the specimen is localized in the outermost volume due to the skin effect of eddy current(Davies et al. 1979), the ϕ 0.5mm T/Cs have been inserted into ϕ 1.0xh3mm holes arranged at radial positions of 5, 10. 12.5 and 20mm in the specimen. R/Ts have been set up to measure two temperatures in the ϕ 2mm surface areas around the inner and outer peripheries. Changes of outer and inner diameters have been measured by a specially designed laser displacement meter(Tokyo Kogyo Microgage Model LMG80BS). The equipment has operated within an overall accuracy of $\pm 10\mu$m up to a maximum specimen temperature of 1900 ℃. Those transient data have been recorded autographically on two high speed recorders.

A series of thermal shock tests for each specimen have consisted of moderate heatups followed by severe heatups; both under vacuum of a pressure of $1\text{x}10^{-2}$ Pa or less, or in helium at atmospheric pressure to avoid excessive carbon sublimation. The former tests have been made to observe thermal behavior in the course of heatup, steady state and cooldown. The latter have been repeated with increasing power supply until thermal shock fracture has occurred.

3 RESULTS AND DISCUSSION

3.1 Testing capabilities

The test apparatus involves the new heating method as well as the new instrumentation. The induction heating capability in the present experimental setup is explained in the following, while observed transients are shown in the succeeding subsections.

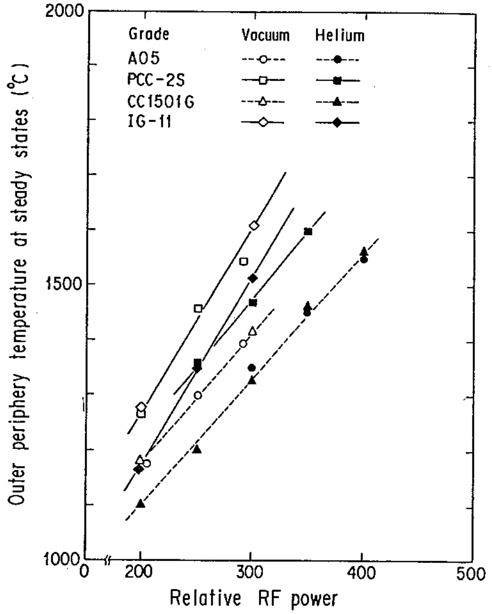

Fig. 2 Maximum surface temperature at steady states as a function of relative RF power.

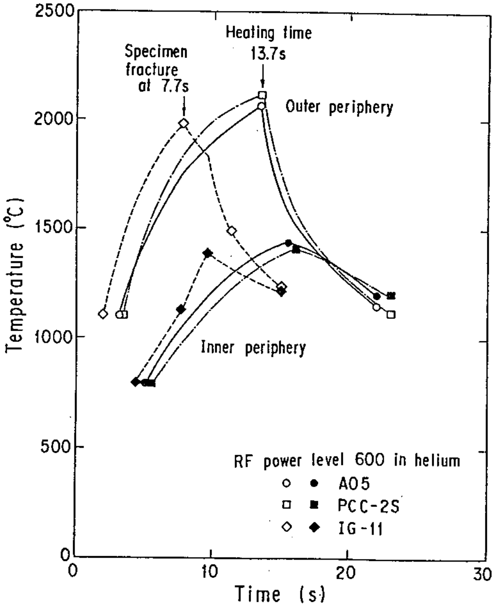

Fig. 3 Typical temperature transients of three disks at 60% of full power.

Figure 2 shows the maximum surface(outer periphery) temperatures at various steady states in four types of disk specimens heated at different RF power levels. It is found that the present setup can achieve the thermal equilibria in a temperature range of 1000 - 1600℃ at moderate heating rates. They are dependent not only heat on transfer conditions inside and outside the disks but also on heat generation rates which are different for the materials having different electrical resistivity.

Another purpose of the tests is to examine thermal shock resistance, i.e. fracture conditions or endurance. Fig. 3 shows the temperature transients of three kinds of disks heated in helium at a power level of 600 (60% of full power). This severe heating has been endured by both A05 and PCC-2S disks but caused fracture of IG-11 disk. The critical thermal conditions of the IG-11 disk defined by a set of outer and inner periphery temperatures at fracture initiation can be determined by the thermometer records. The CFC disks have endured up to the ultimate thermal shocks by the apparatus, details of which are given in 3.3. The critical thermal conditions of IG-11 disks have been analyzed to determine thermally induced fracture stresses on the basis of a nonlinear thermoelastic theory(Arai et al. 1993).

3.2 Thermal behavior

Figure 4 shows typical thermal behavior of the A05 disk in one of moderate heatup cycles in helium where the steady state temperature profile has been achieved in 90 seconds. These temperature transients will be used to determine thermal conductivity of the material by a nonlinear heat transfer analysis which is combined with an electromagnetic analysis(Arai et al. 1990).

Referring to Fig. 4, it is noted that the temperature gradients within the specimen are far less than 50K during the cooldown period. This observation leads to a calculation of the coefficient of thermal expansion in the radial direction. The measured data on diametral displacement of the A05 disk are shown in Fig. 5 in comparison with those of other materials. Fig. 5 indicates large differences in thermal expansion behavior between the materials. The repeated measurements during different cooldowns have resulted in the relation between outer diameter displacement and specimen temperature with a good accuracy, as shown in Fig. 6. The linear thermal expansion depends strongly on specimen temperature. The results are converted into the mean coefficient of thermal expansion(mean CTE) as a function of temperature up to

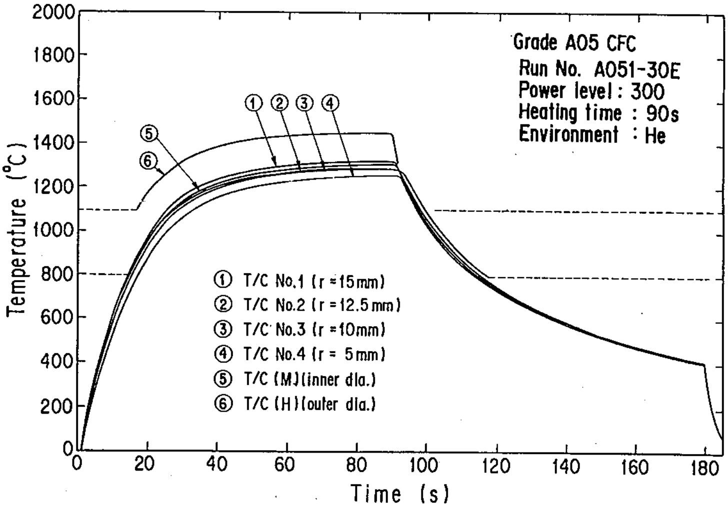

Fig.4 Typical temperature transients of A0 disk heated up to steady state and cooled down in helium.

1400℃, which is depicted in Fig. 7. The mean CTE of IG-11 graphite thus determined is in good agreement with that measured by conventional methods, as referred to in Table 1.

3.3 Thermal shock endurance

Figure 8 shows transients of the outer periphery temperature and the diametral temperature difference of the A05 disk which have been subjected to repeated severe heatups. In these thermal cycles we notice the evolution of the diametral temperature difference during short heating period. It increases rapidly in the beginning and then decreases slowly after reaching the maximum value. The ultimate heating at 90% of full power has resulted in the highest thermal shock endurance of the A05 disks at 4.5s, whose thermal parameters are 2480℃, 1150℃ and 1320K for the outer, inner periphery temperatures and the diametral temperature difference, respectively. These test results of severe heatup cycles are summarized in Fig. 9. Both A05 and PCC-2S CFC disks have endured all severe thermal loads generated by the present setup, while all IG-11 disks have fractured at a diametral temperature difference of 1000 - 1300K in vacuum or 750 - 1100K in helium.

The critical tensile stress, i.e. maximum tangential stress at the inner diameter of the IG-11 disk, was calculated to be approximately 1.6 times the average tensile strength at room temperature. Referring to Fig. 9, The maximum endured temperature differences of A05 and PCC-2S disks are larger at least by 40% and 50%, respectively, than that of IG-11 disk. Of course, this does not mean a difference between inherent stress limits of two CFC materials because they possess different thermomechanical properties. Estimation of the maximum tensile stresses developed in CFC disks will require a nonlinear thermoelastic analysis for a transversely isotropic material. It may be based on a plane-stress approximation or on a two dimensional modeling, depending on the observed temperature profiles.

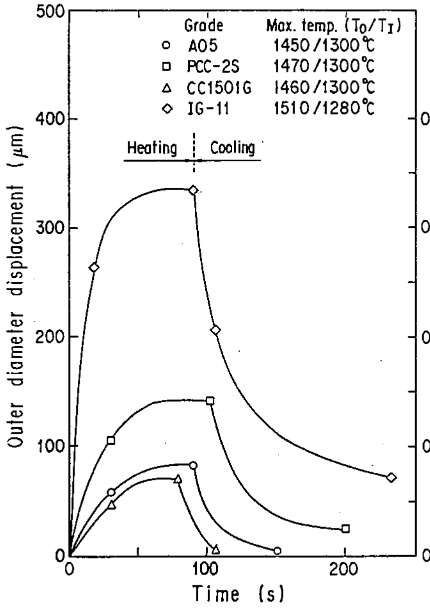

Fig. 5 Typical displacement transients of four disks during heating to 1500℃ and cooldown.

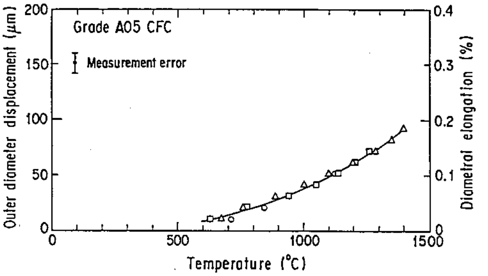

Fig. 6 Outer diameter displacement of A05 disk as a function of temperature.

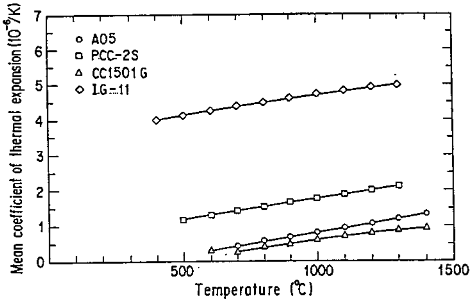

Fig. 7 Mean coefficient of thermal expansion of materials tested as a function of temperature.

ACKNOWLEDGMENT

The authors would express their thanks to Drs. N. Wakayama, M. Eto and Y. Muto of JAERI, and Prof. Dr. H. Nickel for encouragement and support in the study.

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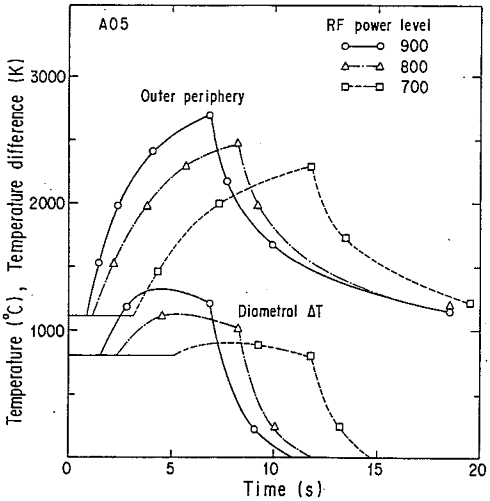

Fig. 8 Temperature transients during severe heatups of A05 disk.

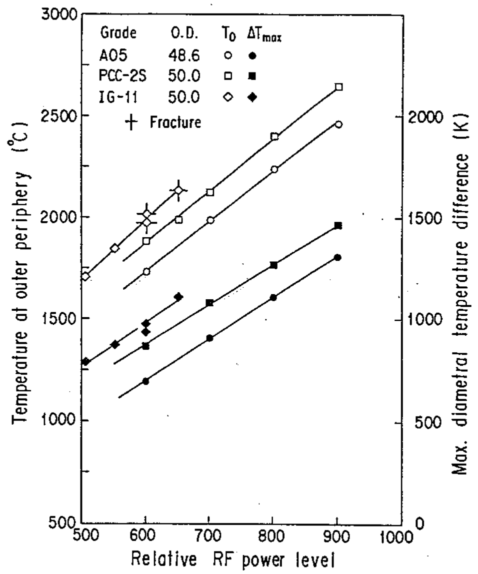

Fig. 9 Relation of maximum diametral temperature difference with its concurrent outer periphery temperature.