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EVALUATION OF NEW CARBON-CARBON COMPOSITE MATERIAL FOR A 20 CM ION ENGINE

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Abstract

New carbon-carbon composite (C/C) materials for a 20 cm ion engine grid system have been evaluated. Basic physical properties of two materials, named CC2000 and CC3000, have been evaluated. The measurement items and results are 1.9 g/cc of bulk density, 120 ~ 130 MPa of flexural strength, 35 ~ 45 MPa of flexural elastic modulus, 91 MPa of tensile strength, 80 GPa of tensile elastic modulus or Young's modulus, no detrimental remaining strain by ten cycle tension-compression test, 0.3 of Poisson's ratio, the order of -1x 10^{-6}/K of thermal expansion coefficient, the order of 1x10^{-5} m^2/s thermal diffusivity at room temperature, 0.5 ~ 0.6 of thermal emissivity, □□ x10^{-3} Ωm of electrical resistivity for CC2000, and 5 x10^{-3} Ωm for CC3000 at room temperature. A drill machining has been attempted to the new materials. It can be said by visual inspection that the result is excellent for both materials. Consequently, using CC2000 material, actual 20 cm diameter grid system has been designed and fabricated.

1. Introduction

The Institute of Space and Astronautical Science (ISAS) adopts a carbon-carbon composite material of the Ion Engine grids for the asteroid sample return mission (MUSES-C) [Ref. 1)]. The Ion Engine System (IES) takes three grids system that consists with a screen grid, an accelerator grid and a decelerator grid. Each grid has 105 mm of effective diameter, and 0.98 ~ 1 mm in thickness with ion exhausting 855 orifice holes. Each grid is kept at 0.38 ~ 0.5 mm spacing. The carbon-carbon composite material grids are characterized by low sputtering rate against Xenon ion impingement and low thermal expansion coefficient. Especially, it shows three times of durability than that of conventional Molybdenum grids [Ref. 2)]. Generally, following properties are required as the grid material, i.e., light weight, high fracture toughness, high tensile toughness, good electric conductivity, good machinability, high resistance against ion sputtering erosion, and so on.

In order to develop a large engine of 200 mm in effective diameter or more, new C/C materials are produced. The expected character to the new materials is higher Young's modulus than that of IES grid material. The IES grid material has been supplied by Toyo Tanso Co., Ltd. Characteristics of the IES grids are, 1.7 g/cc of bulk density, 130 MPa of flexural strength, 22 GPa of flexural modulus, 91 MPa of tensile strength, 25 GPa of tensile elastic modulus, 10 GPa of elastic modulus in shear, 0.22 of Poisson's ratio, 1.9 x10^{-6} /K of thermal expansion coefficient, 6 watt /mK of thermal conductivity and 0.67 of thermal emissivity and 29 x 10^{-6} Ωm of electrical resistivity.

2. New Materials

In this study, two types of new carbon-carbon composite (C/C) materials have been produced by Nippon Carbon Co., Ltd. The difference between the IES grid material and the new C/C materials is manufacturing method of the fiber sheets. The IES grid material consists of felt type sheets. On the other hand, the new C/C materials consist of thin fiber sheets.

Both two types of new C/C materials are based on a material that supplied by Mitsubishi Chemical Corporation. This material is made of piled thin sheets. Each sheet contains short pitch based carbon fibers to obtain a quasi-isotropic carbon-carbon reinforced in a direction parallel to the surface. New C/C materials are treated with high temperature in an inert gas atmosphere. The first new material is processed in 2000 degree in centigrade heat treatment. It is called "CC2000" hereafter. The second material is highly graphytized. It is processed in heat treatment at 3000 degree in centigrade. It is called “CC3000” hereafter.

As a quick result of the supplying company, characteristics of the original material are, 1.85 g/cc of bulk density, 180 MPa of flexural strength, 110 MPa of tensile strength, 70 GPa of flexural elasticity modulus, 20 MPa of shear strength in layers of fiber sheet, respectively.

3. Basic Physical Property Measurements and Results

3.1 Bulk Density Measurement

The bulk density was simply calculated from its weight and dimensions. The weight was measured by the Model R300S electronic balance of Sartorius Co., Ltd., in Germany. The weight sensibility of the electronic balance is 100 x 10^{-6} grams in 300 grams of maximum weighing. The dimensions were measured by a linear micrometer and a slide calipers. The accuracy of the dimensions is 50 x 10^{-6} meters.

The bulk density of the CC2000 is 1.87 g/cc. The density of the CC3000 is also 1.87 g/cc. The accuracy of the value is ±1.5 %. In a word, the density of the new C/C materials is 1.9 g/cc.

3.2 Flexural Strength and Flexural Elastic Modulus Measurement

Flexural strength was measured by the four-point loading method. The specimen is the same board shape with the bulk density measurement. The flexural strength measurement was conducted using a screw driven tensile-compression test machine of the Shimadzu Corporation, Model AG-5000G. For the measurement, a 500 kgf sensitivity load-cell was attached to the AG-5000G machine. All tests were conducted at room temperature. The strains were measured by KFG type strain gauges of Kyowa Electronics Instruments Co., Ltd. The strain gauge was bonded on the center of a specimen parallel with the longitudinal direction of the specimen. Figures 1 and 2 show the flexural strength for CC2000 and CC3000 as in the Strain versus Stress graphs. As a result, the flexural strength of the CC2000 is 130 MPa. The flexural strength of the CC3000 is 122 MPa, respectively. The flexural elastic modulus is also read from the Fig. 1 and Fig. 2. The flexure elastic modulus of the CC2000 is 45 GPa. The flexure elastic modulus of the CC3000 is 35 GPa, respectively.

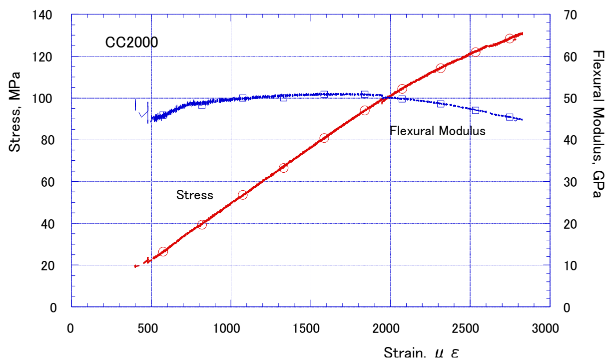


Fig. 1 Flexural test result in strain versus stress graph for the CC2000.

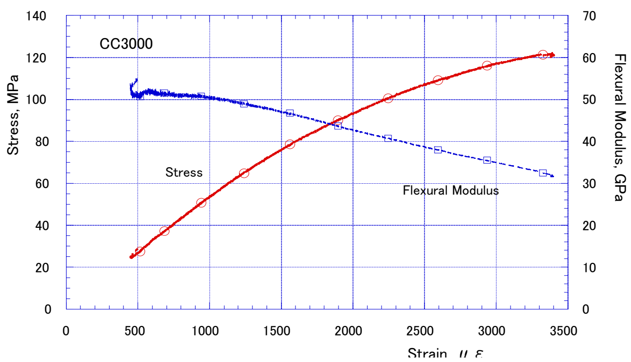


Fig. 2 Flexural test result in strain versus stress graph for the CC3000.

3.3 Tensile Strength and Tensile Elastic Modulus Measurement

For the tensile strength measurement, dumbbell shaped specimen with aluminum tabs affixed to the grip portions were adopted. The tensile tests were also conducted using the AG-5000G with a 5000 kgf load-cell. The strains were also measured by KFG type strain gauges. The strain gauge was bonded on the center of a specimen aligned with the loading direction. Tensile strength is read from the Strain versus Stress graphs as shown in Fig. 3 and Fig. 4. As a result, the values of tensile strength for CC2000 and CC3000 materials are both 91 MPa.

The tensile elastic modulus or Young’s modulus is read out from the right hand vertical axis in Fig. 3 and Fig. 4. The tensile elastic modulus of CC2000 is 78 GPa and the modulus of CC3000 is 89 GPa, respectively. These values show about 3 times toughness than that of IES material. Figure 5 shows tensile elastic modulus of CC2000 comparing with the modulus of the IES material.

Additionally, remaining strain in the C/C material by ten cycles tension-compression test was measured. The tests were tried by 10 MPa, 20 MPa, 30 MPa, 50 MPa and 70 MPa maximum tensional force of 10 cycles. In a cycle, a tensional force was slowly added to the specimen until reaching to the maximum tensional force, after reaching to the maximum value it was slowly released to zero. Figure 6 shows the test result of the test case of 50 MPa in a strain versus stress chart. The strain (shows in horizontal axis) grows up with stress (shows in vertical axis) increases. The permanent or remaining strain was yielded by the first tensional force. The remaining strain did not extend in next 9 cycles. This value of 50 με is about half of the IES material.

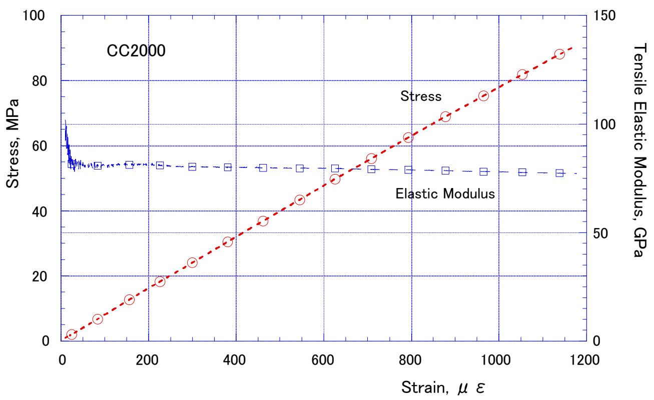


Fig. 3 Tensile elastic modulus versus strain graph for CC2000.

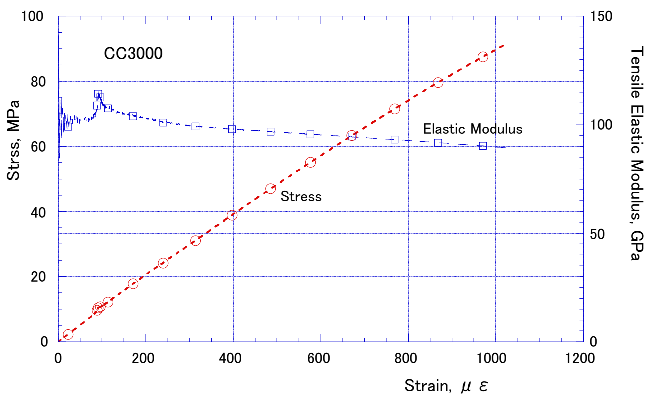


Fig. 4 Tensile elastic modulus versus strain graph for CC3000.

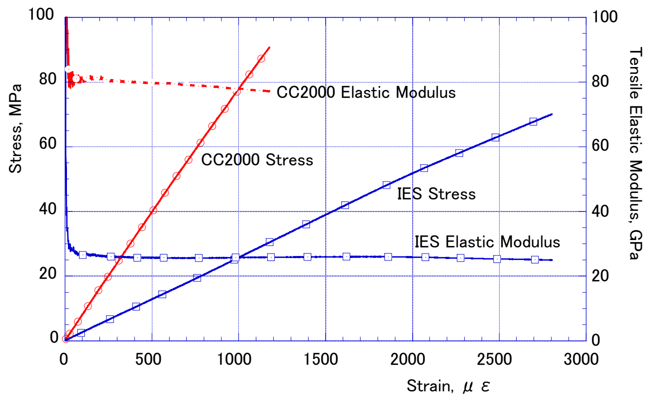


Fig. 5 Tensile elastic modulus of CC2000 comparing with IES material.

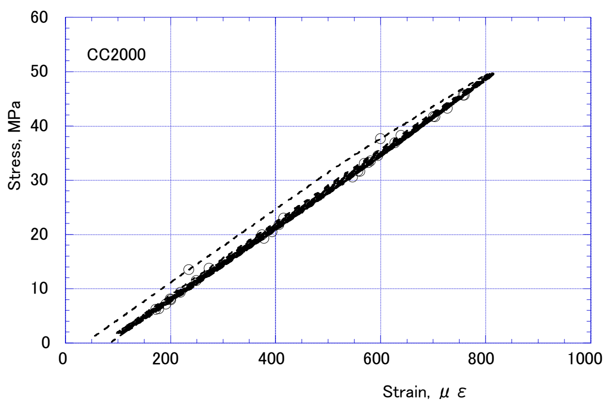
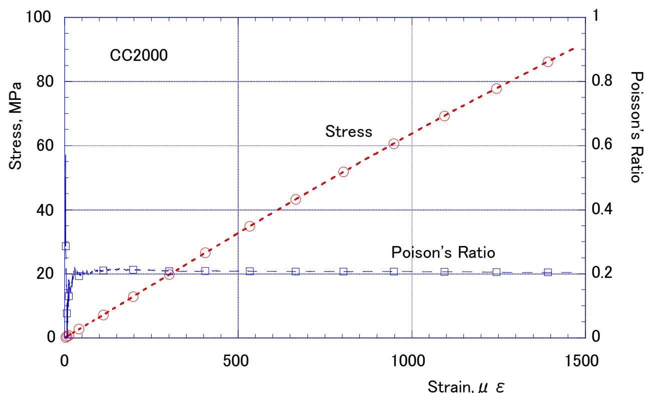


Fig. 6 Remaining strain in strain versus stress graph for CC2000.

3.4 Poisson's Ratio Measurement

In order to measure the Poisson's ratio, the KFG type double strain gauge was used. The shape of the specimen for the Poisson's ratio measurement is the same of the tensile tests.

The Poisson's ratio is read from the right hand vertical axis in the Strain versus Stress graphs as shown in Fig. 7 and Fig. 8. As a result, the Poisson's ratio of the CC2000 and of the CC3000 are 0.32 and 0.35, respectively.



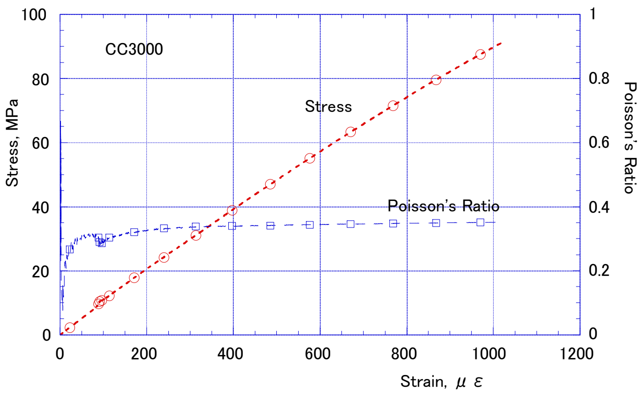


Fig. 7 Poisson's ratio versus strain graph for CC2000.
Fig. 8 Poisson's ratio versus strain graph for CC3000.

3.5 Thermal Expansion Coefficient Measurement

The thermal expansion coefficient is measured by LIX-1 of Shinku-Riko Co. Ltd. This apparatus employs laser interferometer technique. The thermal expansion coefficient was measured under vacuum pressure and at –50 to +130 degree in centigrade temperature range.

The measurement results are shown in Fig. 9 and Fig. 10. Both values of thermal expansion coefficient of CC2000 and CC3000 materials are almost the same and are order of -1×10^{-6} at all temperature range. In other words, it has negative rate, or no change is appeared with temperature increase.

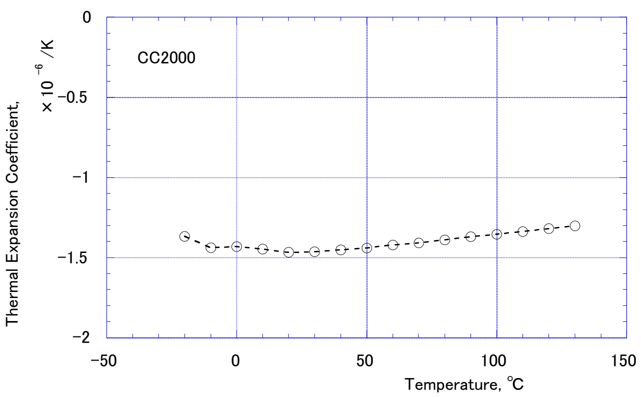


Fig. 9 Thermal expansion coefficient versus temperature graph for CC2000.

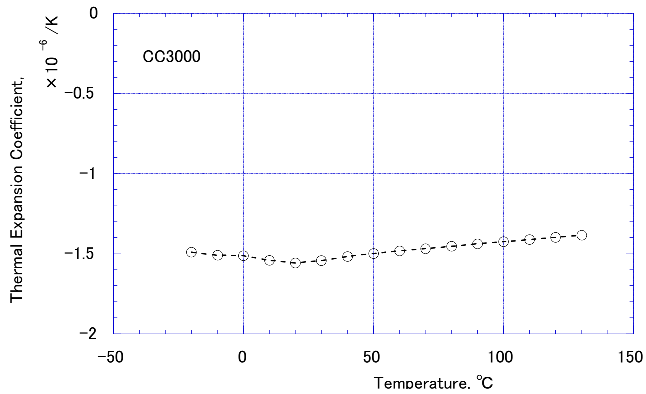


Fig. 10 Thermal expansion coefficient versus temperature graph for CC3000.

3.6 Thermal Diffusivity Measurement

Instead of a thermal conductivity measurement, a thermal diffusivity measurement was conducted. The thermal diffusivity was measured by using the laser flash technique at the National Institute of advanced Industrial Science and Technology (AIST), Tsukuba. The apparatus for the measurement is Model LFN-502N, manufactured by Kyoto Electronics Manufacturing Co., Ltd. A pulse Nd-YAG laser, Model DY-5J-KEN, 3J/300ms of energy, was set in the apparatus. The specimen for the thermal diffusivity measurement has a size of 10 mm in diameter. Four types of thickness, i.e., 1.0 mm, 1.41 mm, 2.0 mm and 2.82 mm, were provided to the measurements. There were no dispersion from laser power, individuality and the thickness. The measurement was conducted under the same laser power condition and used 2.82 mm thickness specimen. The thermal diffusivity was measured under vacuum condition and at room temperature to about 300 degree in centigrade temperature range.

The results of the thermal diffusivity measurement are shown in a semi-logarithmic Fig. 11. The measured value for the CC2000 and CC3000 are 1.25×10^{-5} m^2/s and 3.96×10^{-5} m^2/s at room temperature, respectively. The thermal diffusivity decreases with temperature increase, as shown in the figure. This behavior is observed generally in carbon-based materials.

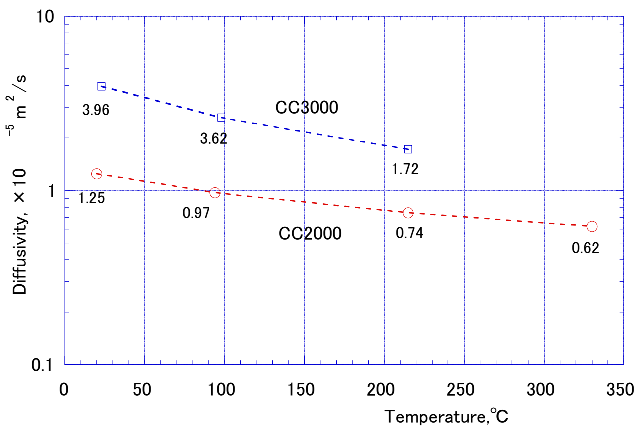


Fig. 11 Thermal diffusivity versus temperature graph.

3.7 Thermal Emissivity Measurement

The principle of thermal emissivity measurement is based on the steady-state calorimetric method. Total hemispherical emissivity is calculated by electrical heat input power to the specimen and radiation heat loss mainly from material surface. The specimen was suspended by heater lead wires and thermocouple wires in a test chamber. The test chamber was cooled down by LN_2. The specimen consists of a 0.5 mm thickness test material, a sheet heater, an insulation film, and a 0.5 mm thickness aluminum plate that coated by known quantity aluminum vaporized film. The thermal emissivity versus ambient temperature is shown in Fig. 12. In a word, the thermal emissivity of CC2000 is 0.6 and 0.5 for CC3000, respectively. Both values are slightly increased with increasing temperature.

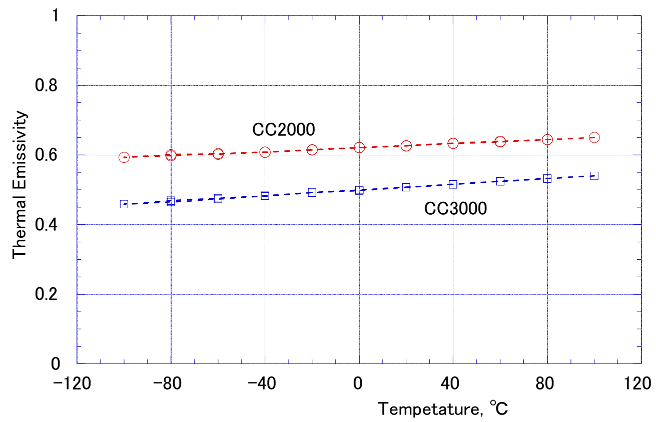


Fig. 12 Thermal emissivity versus temperature graph.

3.8 Machinability Trial

In order to confirm the machinability of new materials, a drilling test has been attempted. In the case of 20 cm of effective diameter grid, over 2850 orifice holes are necessary. Then, It was required to drill seven 3.05 mm diameter holes by a mechanical drilling machine. It was also required to drill with equal intervals in 0.02 mm accuracy of inter-center length between the holes. The drilled specimen is shown in Fig. 13. It seems no whiskers, no flaws, no irregularity, or no unqualified in visual inspection. It can be said very excellent.

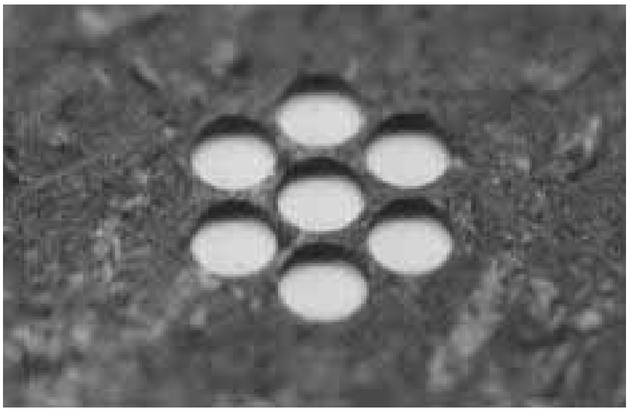


Fig. 13 Photograph of the drilled specimen.

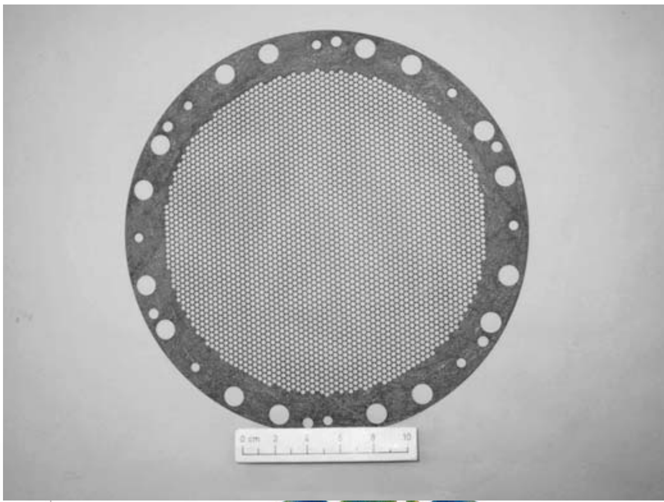
3.9 Electrical Resistivity Measurement

The electrical resistivity of the C/C materials were measured by a digital LCR meter, Model 2330A, the NF Electronic Instrument Co., Ltd. made. The measurement was used the two points method. The specimen for the bending test was selected to the resistivity measurement by reason of its simple shape. The results are 15.8 $\times 10^{-3}$ Ωm for CC2000 and 4.57 $\times 10^{-3}$ Ωm for CC3000 at room temperature. The measurement accuracy of the value is 0.2 %.

4. Analysis, Designs and Manufacturing of 20 cm Grids

4.1 Analysis

Before design and manufacturing the grid system, structural analysis has been made. The MSC/NASTRAN program has been used for the analysis. Analyzed items were characteristic frequency



analysis, static analysis and thermal stress analysis. About 33000 number of nodes and about 46500 number of elements have been provided to the analysis model. Changeable parameters were number of fastener points, fastening diameter, Young Modulus and grid thickness.

The value of 250 G acceleration force was added to three grid axes in the static analysis. The value of 100 degree of temperature change was added to the grids to generate thermal stress in the analysis.

As the analysis results, the lowest characteristic frequency is 150 Hz in z-axis of the acceleration grid. This value is safe enough because it is much higher than the dangerous resonance frequency by rocket launching. Figure 14 shows the analytical result of the characteristic frequency and an emphatic displacement by 250 G to the acceleration grid. In the static analysis, about 0.7 MPa of the maximum stress was found in the z-axis of the acceleration grid. The margin of safety ratio (MS) of this maximum case is still positive. As a typical result of thermal stress analysis, the thermal stress is appeared just only around fastener holes by 100 degree of temperature change as shown in Fig. 15. The highest stress value is about 30 MPa. This value is not critical to the new material.

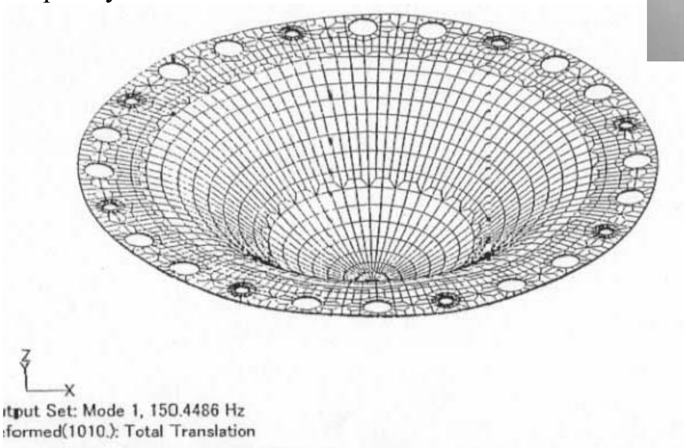


Fig. 14 Analytical result of grid characteristics and emphatic displacement.

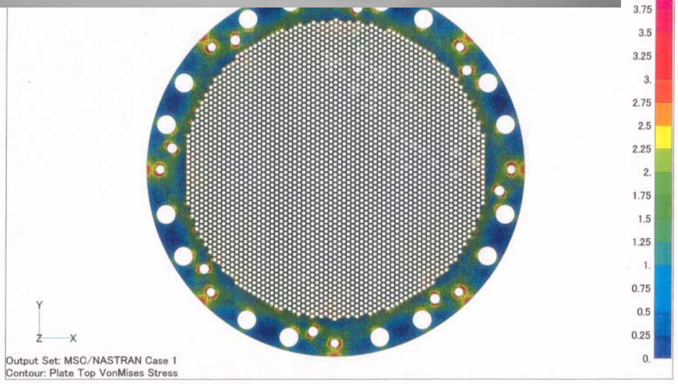


Fig. 15 Analytical result of thermal stress.

4.2 Designs and Manufacturing

Based on the above results, the CC2000 material is selected for the new 20 cm ion thruster grid system. The grid system is consisting of three grids, i.e. a screen grid, an acceleration grid and a deceleration grid. In order to set the effective diameter of the thruster exhaust diameter to be 20 cm, the actual diameter of each grid was designed 254 mm. Each grid is fastened to a grid housing body by 8 bolts at its outer edge part. Thickness of each grid is 0.95 mm. All grids have 2859 exhaust orifice holes. From the ion beam optics analysis[Ref.4)], the screen grid has 3.05 mm in diameter orifice holes, the acceleration grid has 1.80 mm orifice holes and the deceleration gird has 2.50 mm holes, respectively.

Three grid was manufactured by Nippon Carbon Co. Ltd. Basic check up items such as weight, dimensions, hole size and position, existence of voids by X-ray and existence detrimental cracks by visual and photo, were inspected. Each grid weight is 41.3 grams for screen grid, 71.6 grams for acceleration grid and 58.5 grams for deceleration grid, respectively. Flatness or undulation was also inspected whether it was kept within 0.05 mm at 5 points in a grid. Figure 16 is a photograph of the screen grid.

Fig. 16 Photograph of the screen grid.

5. Summary and Future Plan

Basic physical properties of two new carbon-carbon composite materials have been obtained. The measurement results are 1.9 g/cc of bulk density, 120 ~ 130 MPa of flexural strength, 35 ~ 45 MPa of flexural elastic modulus, 91 MPa of tensile strength, 80 GPa of tensile elastic modulus or Young's modulus, no detrimental remaining strain by ten cycle tension-compression test, 0.3 of Poison's rate, the order of -1×10^{-6}/K of thermal expansion rate, the order of 1×10^{-5} m^2/s thermal diffusivity, 0.5 ~ 0.6 of thermal emission rate, □□ $\times 10^{-3}$ Ωm of electrical resistivity for CC2000, and 5×10^{-3} Ωm for CC3000, respectively. Then many useful data has been obtained. The new materials have about three times higher Young's modulus than that of IES grid material as shown in Fig. 5. So, CC2000 and CC3000 materials are able to use to the new large ion engine grids. Conclusively, using CC2000 material, actual 20 cm diameter grid system has been designed and manufactured. A many useful information has been taken from the structural analysis.

This new 20 cm grid system will be set on the ion engine case, then, engine performance will be taken.

Acknowledgement

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