A New Lightweight Structure System for a Nano Deep Space Probe

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Abstract

A nano deep space probe, which was named the SHINEN-2, is currently being developed at the Kyushu Institute of Technology; it will be launched with the new asteroid explorer Hayabusa-2, which has been in development by the Japan Aerospace Exploration Agency (JAXA). The SHINEN-2 is in the shape of an associate sphere of approximately 50 cm in diameter and its mass is approximately 16kg. The SHINEN-2 is very small and light, and is designed with an integral structure for weight reduction, using hardly any bolts. Using Carbon Fiber Reinforced Thermo Plastics (CFRTPs), it is possible to construct the material of the probe. This paper shows a new structure that can be created to decrease the number of metal fittings and the total mass by CFRTP use.

1. Introduction

An asteroid probe named the Hayabusa-2 and three nano probes will be launched with an H-IIA rocket in December 2014. One of these probes is our deep space probe, named the SHINEN-2; this probe, currently under development in the Kyushu Institute of Technology (KIT), is shown in Figure 1. This probe’s main missions are to demonstrate a deep space communication method at a far distance from the moon and with a CFRTP-structured system. CFRTP is a material made of thermoplastic resin, such as polyether ether ketone (PEEK) resin. In the aerospace industry, a thermosetting resin, such as the epoxy resin, has been used to create a CFRP until recently, and has been applied to the structural material of many aircrafts and spacecrafts. This is because a thermosetting resin is thermally stabilized at a high temperature of 100 degrees Celsius or more, which is the temperature a satellite encounters in space. On the other hand, at approximately 145 degrees Celsius [1], which is the glass transition temperature of the PEEK resin, there is a high thermal resistance in the thermoplastic resin, and consequently a possibility that the mechanical properties are significantly lowered at this temperature. However, the melting point of the PEEK resin is approximately 345 degrees Celsius, and this material becomes softened at this temperature. The formability at a high temperature and improvement of the workability, which are not provided in thermosetting resin, are provided from this characteristic. Therefore, it is likely that this material can be applied to a structural element.

This paper shows the manufacturing of the SHINEN-2 that applied CFRTPs as structure materials. A matrix of CFRTP is the PEEK resin, which is called PEEK/CFRP in this paper.

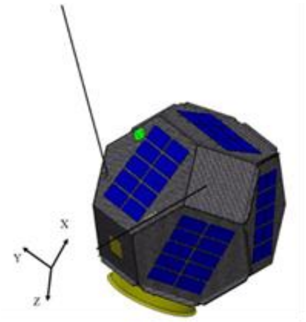

Figure 1. SHINEN-2 model

2. Carbon fiber reinforced thermoplastic resin

CFRTP is softened at a high temperature and stiffened by a cooling material temperature and returned to the strength of the original material by the property of thermo-plasticity. In addition, because this property can be repeatedly duplicated, CFRTP has a good formability of materials and a high flexibility of shape. On the other hand, carbon fiber reinforced thermosetting resin (CFRP) causes a chemical reaction in a high temperature environment and stiffens. In addition, once this material stiffens, it cannot soften again. In this way, the CFRTP has many advantages compared to the CFRP which continued being used conventionally. The advantages of the CFRTP are shown below [2].

- ✓ High toughness
- ✓ Reduction of molding time and cost by high temperature molding
- ✓ Second processing is simple
- ✓ Welding with CFRTPs is possible
- ✓ Improvement of the recyclability

In applying CFRTP to the space probe structure, it is necessary to consider whether the CFRTP can be applied in space. The space probe is launched by a rocket, such as an H-IIA, but tough environment resistances are required from an agency to launch the rocket. Therefore, it is necessary to confirm the satisfaction of the required performance capabilities by testing the material to be applied to the space probe. Various space environment characteristics of the CFRTP are shown below.

2.1. Outgassing characteristics

Because space is a high-vacuum environment, organic materials will radiate outgas. There is a possibility that the performance of devices is worsened by gasses adhering to the space probe's onboard equipment. Allowable outgassing values are determined from the rocket-launching side. Therefore, materials to be applied to the space probe must satisfy the required outgassing characteristics. In Japan, JAXA measures the outgassing characteristics of organic materials for space, and releases its data on the JAXA website. Table 1 shows an example of PEEK/CFRP outgassing characteristics made by the authors.

DATA No.	TML[%]	CVCM[%]	WVR[%]
1370	0.161	0.002	0.068
1371	0.182	0.002	0.061
1372	0.181	0.001	0.065

Table 1. PEEK/CFRP outgassing characteristics [3]

TML stands for the Total Mass Loss, the CVCM is the Collected Volatile Condensable Material, and the WVR is the Water Vapor Regained. Generally, characteristics required for space equipment materials are a TML of less than 1% and the CVCM equal to 0.1% or less, which PEEK/CFRP satisfies [4].

2.2. Thermo-mechanical properties

The mechanical properties of a material in a high-temperature environment are of concern when applying a CFRTP to a space probe. The SHINEN-2 will be released into orbit around the sun with a perihelion of approximately 0.9AU and an aphelion of approximately 1.1AU. Although the SHINEN-2 doesn’t contain a 3-axis attitude control system, this space probe revolves at a speed of one rotation every eight minutes. The maximum and the minimum surface temperatures are approximately 50 degrees Celsius at 0.9AU and approximately -50 degrees Celsius at 1.1AU, respectively. This sets the design temperature range from -100 degrees Celsius to +100 degrees Celsius by adding ±50 degrees Celsius to this predictive temperature as a design margin. When this space probe is within this temperature range, it is important to grasp a thermo mechanical characteristic of the PEEK/CFRP at +100 degrees Celsius from room temperature. Therefore, a mechanical characteristic change of the PEEK/CFRP was confirmed with temperature rises from room temperature to +200 degrees Celsius.

A tensile strength test was performed in the temperature range mentioned above and the temperature-dependent properties of the strength and elastic modulus of the PEEK/CFRP were obtained. The testing equipment used was AG-100kNX, made by the Shimadzu Corporation. The dumbbell-shaped test pieces are shown in Figure 2, having a length, width and thickness of 100 mm, 20 mm and 0.4 mm respectively. The carbon fiber of this material is HTS-40 [5], made by TOHO TENAX Co., Ltd., weaved in a plain weave with a laminated constitution of [＋/×/×/＋] (+ direction: 0 degrees and 90 degrees, ×direction: 45degrees and -45degrees). The PEEK resin was manufactured by Victrex Inc. This test was conducted in a thermal environment between room temperature and 200 degrees Celsius. Figure 3 shows the temperature dependence of tensile strength, and the elastic modulus is shown in Figure 4. From this test result, a decrease of material strength was not shown at 20 to 100 degrees Celsius but was shown at 150 to 200 degrees Celsius. However, the strength of this material at 200 degrees Celsius is approximately 250MPa, which is almost the same value as the strength of A5052, the materials used for space. Therefore, it is thought that there are no serious problems with this material, such as causing structure destruction in strength. A decrease in the elastic modulus of this material was not shown at the temperature range from 20 to 200 degrees Celsius.

Depending on the orbit altitude, the highest temperature that the space probe will encounter in space is approximately 100 degrees Celsius in general. For this reason and from the test result, it is thought that the use of PEEK/CFRP in space does not pose any problems.

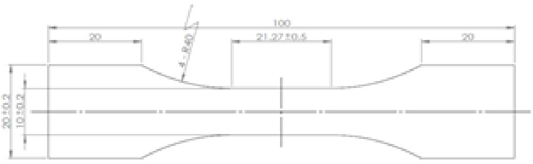

Figure 2. Tensile test piece

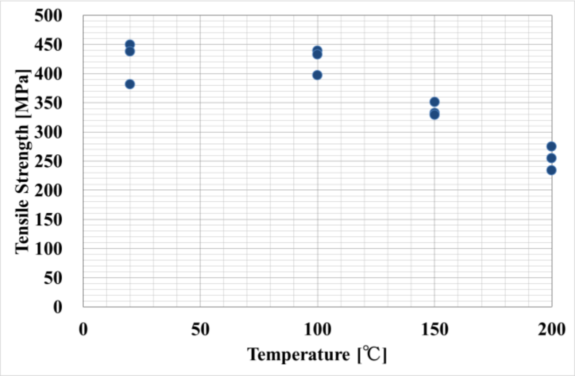

Figure 3. Temperature dependence of the tensile strength

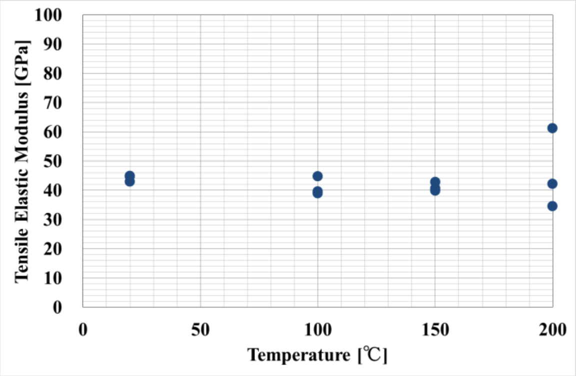

Figure 4. Temperature dependence of the elastic modulus

2.3. Radiation resistance

The structure material of a space probe in space may possibly be deteriorated by space radiation such as ultraviolet and atomic oxygen. Therefore, it is necessary to understand the material characteristics by performing a space radiation test. In particular, the effects on the mechanical properties of the material by radiation have been considered, and the space environment exposure test has been performed for a PEEK film [6]. The operation period of the space probe will be at least several months at most or several years, during which time the space probe will be exposed to a radiation environment, causing concerns about the deterioration of the material over the years. Therefore, it is necessary to evaluate the changes in the mechanical properties of the PEEK/CFRP in radiation environments. Ito et al. measured the change in the tensile modulus and the tensile strength of a PEEK/CFRP by γ-ray irradiation; there were not many changes in the mechanical properties due to the irradiation of 10 to 2000 kGy with γ-ray according to it [7]. From this result, because the effects of radiation on the PEEK/CFRP are small, this material can be applied to the space probe.

3. The overview of SHINEN-2

The deep space probe SHINEN-2 will be launched using the surplus space of an H-IIA rocket launching with the Hayabusa-2. The size and the mass of the sub-payload to ride with the Hayabusa-2 are limited. The design requirements for the SHINEN-2 are shown in Table 2. The external structure of the SHINEN-2 is a truncated octahedron in order to stabilize the temperature of the probe in the thermal environment of deep space.

The body structure of the SHINEN-2 is shaped by autoclaving a CFRTP using a polyhedron-shaped molding tool and molding half of the tops and half of the bottoms. The molding tool is shown in Figure 5 and the molding outline figure is shown in Figure 6. The part that the molding tool has bent outward serves as the flange, and it becomes one structure by welding the top and bottom parts together. The carbon fiber fabric is spread all over the inside of this tool for the molding, and the PEEK film is laid on this fabric. Both the fabric and PEEK film are laminated to the target thickness. As for the top surface and undersurface, the inside is dug out along with two lateral hexagon parts. The boards of different hexagonal CFRTPs are attached to these surfaces by bolt inclusion, causing the access characteristics on the inside to improve. The X, Y and Z sizes of the polyhedron shape of the CFRTP produced by the above method are 470 mm, 495 mm and 495 mm respectively. In addition, the total mass of the SHINEN-2 is approximately 16kg including the internal structure.

Requirement	Verification Requirement		Requirement	Remarks
Mass Requirement	Mass [kg]		≦16.8	
Size Requirement	Size [mm]	X axis	≦450	Except for Satellite flame
		Y axis	≦500	
		Z axis	≦500	
Rigidity Requirement	Natural Frequency [Hz]	X axis	100≦	
		Y axis	50≦	
		Z axis	50≦	
Strength Requirement	Margin of safety	Quasi-static Accelerations (Yield condition)	Positive value	The margin of safety is the minimum value of analysis
		Quasi-static Accelerations (Ultimate condition)	Positive value	The margin of safety is the minimum value of analysis
		Random Vibration	Positive value	The margin of safety is the minimum value of analysis

Table 2. Design Requirements [8]

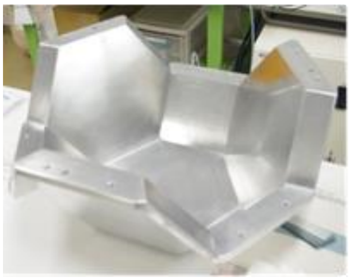

Figure 4. Molding Tool

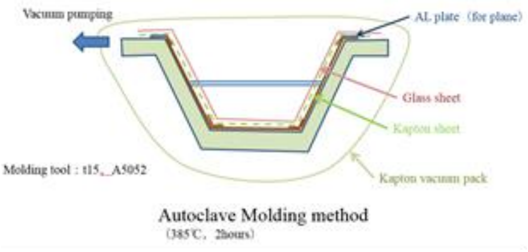

Figure 5. Molding Model

4. Structure Analysis of the Shinen-2

During the initial H-IIA rocket launch, the combustion of the engine produces a strong vibration inside the sub-payload. Therefore, the sub-payload must be designed to endure this vibration. In addition, the natural frequency of the sub-payload is higher than the rocket, to prevent the resonance of the rocket and the sub-payload. Therefore, its structure must be designed at a higher than natural frequency decided by the rocket launching side. The stress occurring to a structure material must be lower than the yield stress and the strength of this material, so this must be considered in the structure design. The definition formulas for the margin of safety (MS) are shown in (1) and (2) [9].

$$MS_y = \frac{Yield\ \ Stress}{The\ stress\ at\ which\ \ yield\ \ load\ occures} - 1 \tag{1}$$

$$MS_u = \frac{Tensile\ Strength\ (Material)}{The\ stress\ at\ which\ ultimate\ load\ occures} - 1 \tag{2}$$

A structure analysis was carried out, and the validity of the structure was evaluated. The yield load condition that multiplied 1.25times (the yield safety factor) by a quasi-static acceleration condition of the H-IIA is shown in Table 3, the ultimate load condition that multiplied 1.5times (the ultimate safety factor) by a quasi-static acceleration condition is shown in Table 4, the random vibration acceleration condition is shown in Table 5, and the analysis model is shown in Figure 6. SolidWorks was used for the analysis. In this analysis, bolt inclusion sections of a payload attach fitting (PAF) was restricted and assumed a rigid connection. The internal structure is composed of a prop with A6061-T6 materials. It is equipped with a battery inside and with communication equipment. The communication control unit (CCU), the power control unit (PCU) and the SHINEN-2 control unit (SCU) are placed on the inside. They are designed with a redundant, such as the A and B system. In addition, main and sub systems are established with each system, and each device except the SCU are comprised in the sub system. In this way, the sub system can act as a supplement if one system breaks down, and the failure of the communication mission is prevented by the problem.

Axis	**Case 1**	**Case 2**	**Case 3**	**Case 4**
X	-6.0×1.25 G	-6.0×1.25 G	-6.0×1.25 G	-6.0×1.25 G
Y	5.75×1.25 G	-5.75×1.25 G	0	0
Z	0	0	5.0×1.25 G	-5.0×1.25 G

Table 3. Quasi-static and Dynamic Accelerations (Yield)

Axis	**Case 5**	**Case 6**	**Case 7**	**Case 8**
X	-6.0×1.50 G	-6.0×1.50 G	-6.0×1.50 G	-6.0×1.50 G
Y	5.75×1.50 G	-5.75×1.50 G	0	0
Z	0	0	5.0×1.50 G	-5.0×1.50 G

Table 4. Quasi-static and Dynamic Accelerations (Ultimate)

Axis	**Case 9**	**Case 10**	**Case 11**
X	11.0×3G	-	-
Y	-	11.0×3G	-
Z	-	-	11.0×3G

Table 5. Random Vibration

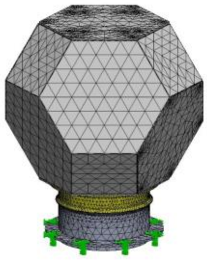

Figure 6. Analysis Model

4.1. Quasi-Static Acceleration Analysis

The load combining static acceleration and vibration acceleration are loaded into the center of gravity of the space probe when a rocket is launched. The results of the analysis under the conditions of Table 3 are shown in Table 6. The yield strength of the material used for this analysis is 443MPa for the CFRTP, 390MPa for the PAF (A7075-T7351), and 275MPa for the internal prop (A6061-T6). When the Quasi-Static load was applied under conditions of cases 1 to 8, the maximum stress that occurred to this space probe was 48.5MPa. This value is small enough to endure the quasi-static acceleration expected during the initial rocket launch.

		Yield condition				Ultimate condition			
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
CFRP	Strength [MPa]	443				443			
	Maximum Stress [MPa]	23.8	23.3	21.6	22.0	30.5	28.1	25.9	26.3
	MS	17.6	18.0	19.5	19.1	13.5	14.8	16.1	15.8
PAF （A7075-T7351）	Strength [MPa]	390				475			
	Maximum Stress [MPa]	22.9	25.7	21.4	19.9	27.5	30.9	25.7	23.9
	MS	16.0	14.2	17.2	18.6	16.3	14.4	17.5	18.9
Internal structure (A6061-T6)	Strength [MPa]	275				310			
	Maximum Stress [MPa]	38.7	38.5	40.4	39.7	46.5	46.1	48.5	47.6
	MS	6.1	6.1	5.8	5.9	5.7	5.7	5.4	5.5

Table 6. The results of Quasi-Static Acceleration Analysis

4.2. Random Vibration Analysis

The space probe received a structure vibration from the spacecraft system such as a vibration caused by the engine combustion during the rocket launch [10]. The rocket launching organization defines the random vibration load, and the sub-payload must be designed to endure this load. The results of the analysis under the conditions of Table 4 are shown in Table 7. The MS are smaller than the quasi-static acceleration condition, but the minimum MS was a positive, so this structure can endure the random vibration during the rocket launch.

		Case 9	Case 10	Case 11
CFRP	Yield Strength [MPa]		443	
	Maximum Stress [MPa]	57.2	60.2	57.4
	MS	6.7	6.4	6.7
PAF (A7075-T7351)	Yield Strength [MPa]		390	
	Maximum Stress [MPa]	36.2	94.9	74.2
	MS	9.8	3.1	4.3
Internal structure (A6061-T6)	Yield Strength [MPa]		275	
	Maximum Stress [MPa]	99.7	74.0	131.3
	MS	1.8	2.7	1.1

Table 7. The results of Random Vibration Analysis

4.3. Natural Frequency Analysis

Because the space probe received a vibration load during the rocket launch, it might be damaged by resonance if it and the natural frequency of the rocket are close. The vibration demands to a nano sub-payload riding inside an H-IIA are more than 100 Hz in an axis direction (X-axis) and 50 Hz in an orthogonal axis direction (Y and Z axis) [8]. The first natural frequency of the space probe must satisfy this condition. The results of the structure analysis under the conditions of Table 5 are shown in Table 8. Each natural axial frequency satisfies a demand level from the eigenvalue analysis results.

	Axis	**Analysis Model**	**Requirement**
Natural Frequency [Hz]	X	168.9	100≦
	Y	101.8	50≦
	Z	100.7	50≦

Table 8. The results of Natural Frequency Analysis

5. Conclusions

The matter involved in the space utilization of CFRTP, which was a structural material of deep space probe “SHINEN-2” under development, was investigated. Mechanical properties of CFRTP at high temperatures were of concern due to the thermoplastic characteristics, but a remarkable decrease was not shown. In addition, no influence caused by space radiation was shown. In other words, it may be said that there is no problem in space utilization.

A structure design for SHINEN-2 was described in this paper, so that the structure of this space probe could satisfy the design requirements from this analysis. An engineering model (EM) will be manufactured in the future, and the validity of the analysis results will be evaluated by the vibration test. The structure of this space probe hardly used metal fasteners, and was assembled by welding. Therefore, the strength of the weld was evaluated, and it is necessary for the most suitable welding method to be established. A vibration test will be conducted, and it will be shifted to Flight Model (FM) if no damage is shown.

Acknowledgments

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