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RELATIONSHIP BETWEEN POROSITY INSIDE CFRP SPECIMEN AND RESOLUTION OF MICRO X-RAY CT

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Abstract

CFRP (Carbon Fiber Reinforced Plastics) laminated structure has been widely applied to aerospace structures. And many non-destructive testing techniques using ultrasonic, X-ray, and so on, have been developed to find internal damages due to impacts or heat shock. However, it is not clear whether the resolution of such testing devices is enough or not, since few devices have submicron resolution. In this paper, we introduce a micro X-ray computer tomography scanner attached to a scanning electron microscope with submicron resolution. And we present the relationship between the resolution of the scanner and porosity which directly express internal defects inside the CFRP specimen.

1 Introduction

CFRP has recently been used as main parts in the aerospace field [1], because of its high specific tensile strength and rigidity, fatigue endurance, and lightweight mass compared with metals. It gets a lot of attention in the auto industrial field because it reduces fuel consumption by reducing the weight of the body. However, there are various problems in using CFRP. For example, its laminated structure contains anisotropic and heterogeneous mechanical properties. And internal damages due to impacts or heat shocks seriously reduce its mechanical strength and stiffness. We need non-destructive tests in order to distinguish internal damages and mechanical properties, but it is difficult to find the internal damages. Therefore, various inspection equipment, including ultrasonic flaw detectors and X-ray computed tomography (CT) scanners, have been developed for non–destructive material tests [2]. Especially a commercial X-ray CT is widely used in the industrial field. However, the system is so expensive and generally has the capacity to scan from 1 to 5 um/pixel resolution. It is not clear whether the resolution is sufficient for CFRP inspection.

In this paper, we used a micro X-ray computer tomography scanner which is introduced to research three dimensional tiny structures of marine plankton skeletons [3]. The highest resolution of the scanner is 0.3um/pixel. We will show transmission and reconstructed sectional images inside the CFRP specimen. From reconstructed sectional images at five different resolutions, we calculated porosity which directly expresses internal defects including delamination, cracks, voids, and so on. We will discuss the relationship between the resolution and porosity.

2 Micro CT system and CFRP specimen

2.1 Micro-CT Systems

Our scanner system consists of several modules attached to a scanning electron microscope, JSM-6510. Fig.1 illustrates the principle of the system. This system uses an X-ray generated from a metal target irradiated by an electron beam of the microscope. A specimen is glued on a metal holder which is fit on a rotation stage. Fig.2 shows a metal holder with CFRP specimen and setting in the microscope tube. We use aluminum foil to avoid charging nonconductive CFRP specimen. Every time the stage rotates, a transmission image is captured by an attached CCD camera, which size is 1024 x 1024 pixels. In this study, 410 transmission images were obtained in half-scan (180-degree rotation) mode with 0.45 degree angular step. Image resolution varies with distance between the metal target and specimen. We can reconstruct sectional images from these 410 transmission images by software.

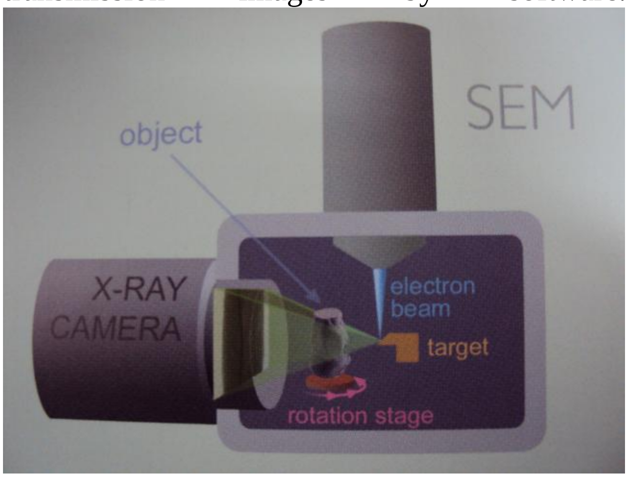


Fig.1 Mechanism of Micro X-ray CT in SEM

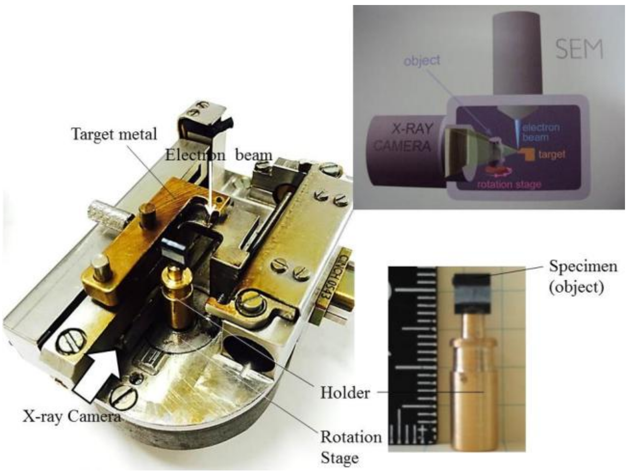


Fig.2 Specimen on a metal holer

2.2 Specimens

In this study, we prepare three types of samples, named CF1, CF2 and CF3. Each three samples size is 200mm×15mm×1.2mm. They are cut out from CFRP board with 200mm×200mm×1.2mm in size and its laminates constitution is [0/0/90/90]s. After cutting out from the board, CF2 and CF3 are loaded with a tensile tester, INSTRON. We investigate unloaded and loaded samples, CF1, CF2, and CF3, using a general X-ray CT (TOSHIBA, TOSCANER-32250 μhd) with lower resolution in order to check rather large defects inside them. Finally we cut out smaller specimens with about 5mm×5mm×1.2mm in size for examination under the micro X-ray CT in SEM. As shown in Fig.1 each cutting area is marked and each cutout specimen is called upper, center, and bottom. We will describe details of tensile test and results obtained by using TOSHIBA s follows.

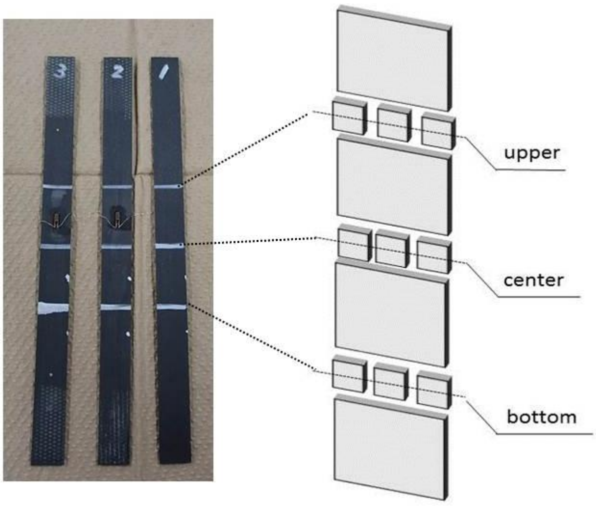


Fig. 3 Three samples and specimens

2.2.1 Tensile test on CF2 and CF3 samples

As described above, CF2 and CF3 samples are loaded with a tensile tester. Figure 4 show the tensile tester, INSTRON5582. We applied tensile stress on CF2 up to its strain of a 0.5 %, and CF3 up to its strain of a 1.0 %, respectively. For reference, breaking strain of this CFRP board is ca 1.5 %. Figure 5 shows a profile of tensile testing process on CF3. When an indicated value of strain gauge attached to the specimen exceeds a setup level, we immediately unloaded the tensile stress.

Fig.4 Tensile test on CF3 sample

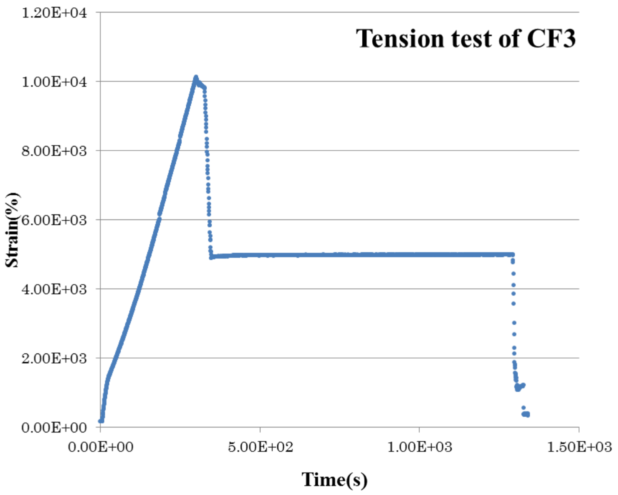


Fig.5 Profile of tensile testing process on CF3 sample

2.2.2 Results obtained by micro CT system with lower resolution

Before we cut out small specimens from three samples, we investigated inside the samples in order to check rather large defects using another micro CT system, TOSHIBA, with 30um/pixel in resolution. Fig. 6 shows a transmission image of CF3 sample and we can see many horizontal cracks. Fig. 6 shows a reconstructed sectional image of the same sample. White area in this figure represents some defects including cracks, delamination, voids, and so on. But we cannot know details of the defects with this lower resolution.

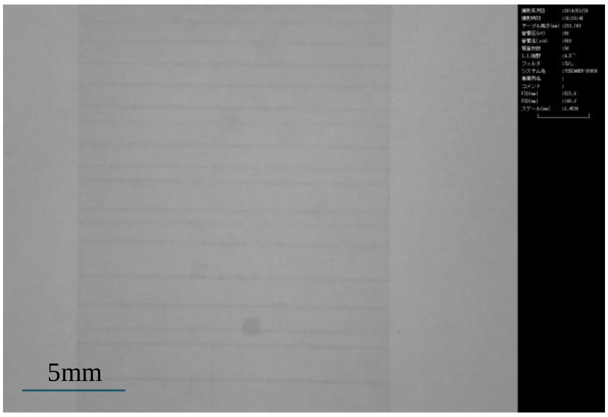


Fig.6 Transmission image of CF3 sample (TOSHIBA)

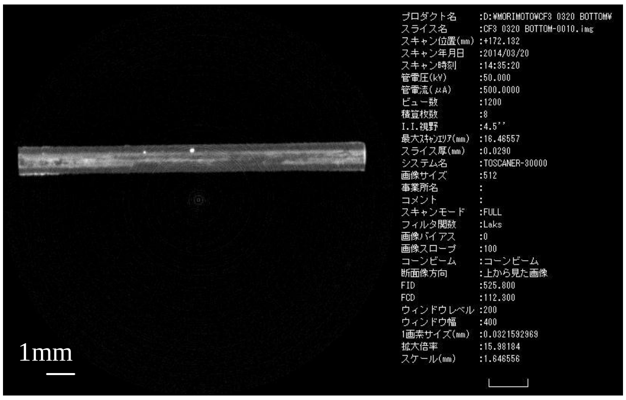


Fig.7 Reconstructed sectional image of CF3 sample (TOSHIBA)

3 Analysis Method

3.1 Area of analysis on reconstructed images

In this paper, we treat "porosity" which directly expresses internal defects including cracks, delamination, voids, and so on. Porosity is calculated from two dimensional sectional images reconstructed from transmission images obtained by the micro CT scanner. At first, we scanned in each specimen at five different resolutions; 0.5, 0.8, 1.0, 1.5, and 2.0 um/pixel. Fig. 8 shows transmission images of the CF3 upper specimen at different resolutions except 0.8um/pixel. Also Fig.9 shows reconstructed sectional images of the same specimen at different resolution in the same way.

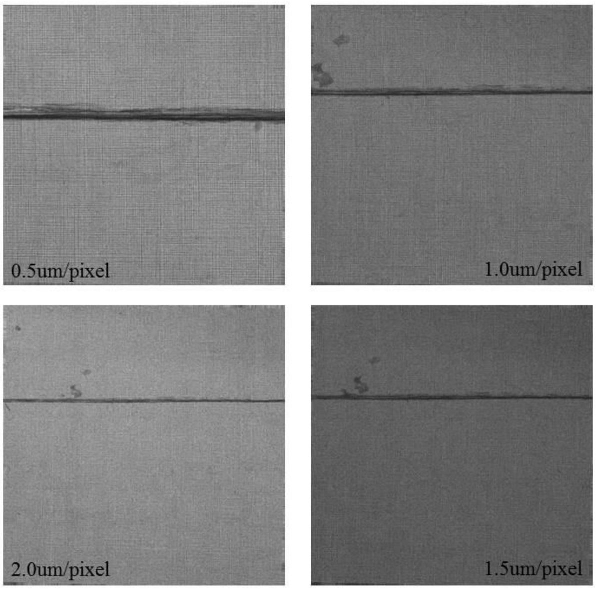


Fig.8 Transmission image (CF3)

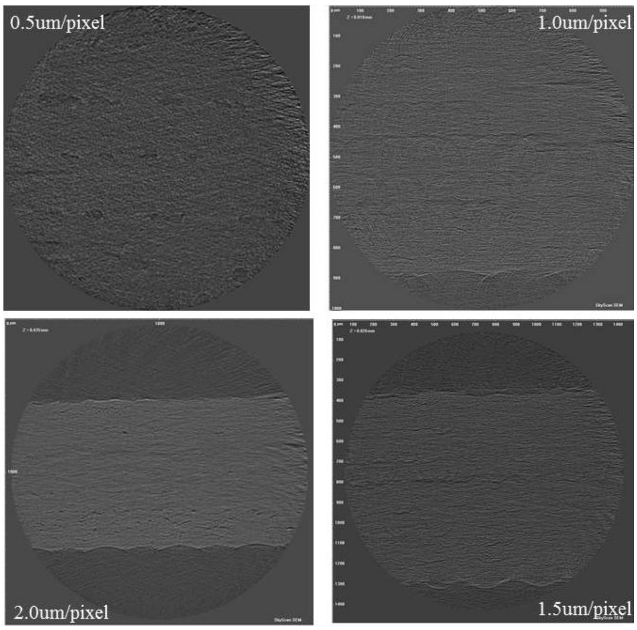


Fig.9 Reconstructed images

Since a resolution is directly proportional to a field of view, the field of views becomes narrower as the resolution gets higher. To clarify the relationship between resolution and porosity, we need to analysis the same part of specimen at different resolutions. Then we extracted analysis area from original acquisition area shown in Fig.10. Specifically porosity was calculated only inside white circles such as Fig.11 for a certain section, and we compute the average and deviation of porosities for selected sections. Table 1 indicates number of selected sections for analysis. At the 0.5um/pixel resolution, all sectional images were used. But at the other resolutions, there is some variability because a value of resolution really includes fraction error.

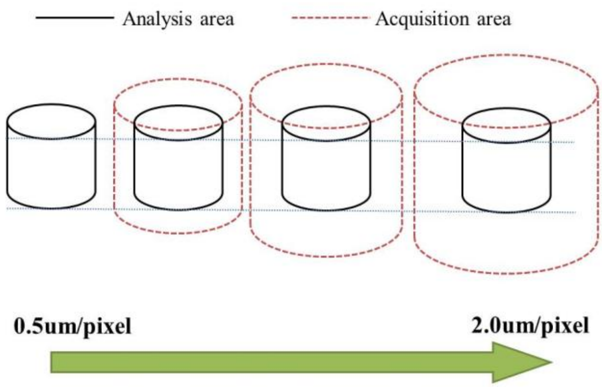


Fig.10 Extracting same analysis area

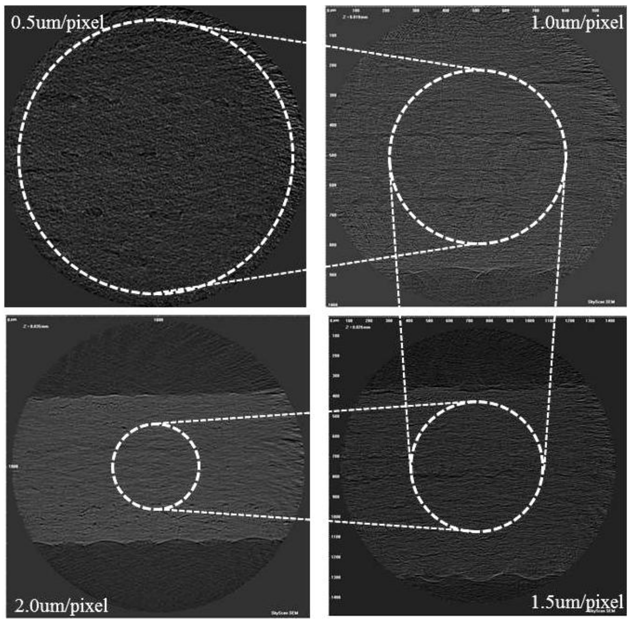


Fig11. Analysis area at different resolutions

Table1 Number of analyzed sections

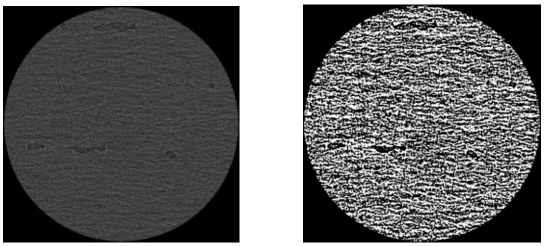
		Resolution				
		0.5um/pixel	0.8um/pixel	1.0um/pixel	1.5um/pixel	2.0um/pixel
CF1	upper		684	514	347	259
	center		693	548	363	265
	bottom		646	526	347	257
CF2	upper	987	646	514	353	257
	center		646	514	337	260
	bottom		628	514	342	257
CF3	upper		647	526	348	261
	center		618	491	332	248
	bottom		655	539	352	271

3.2 Porosity calculation from reconstructed sectional images

The porosity is directly affected by defects inside both fibers and resins of a specimen. In this paper, we calculated porosity using two dimensional reconstructed sectional images for simplicity. As previously mentioned, analysis area is property extracted for the same area of a specimen.

How to calculate porosity is as follows. At first, we binarize reconstructed sectional images using discriminant analysis method (Otsu) [4] on software of Image-J. Fig.11 shows a reconstructed image and its binarized image of a certain cross section of CF3_upper specimen at resolution of 1.0um/pixel. Then, the number of all pixels and black pixels are counted on software and porosity is calculated according to the following equation.

$$\text{Porosity } (\%) = \frac{\textit{Number of black pixels}}{\textit{Number of all pixels}} \times 100 \quad (1)$$



(a)reconstructed (b)binalized

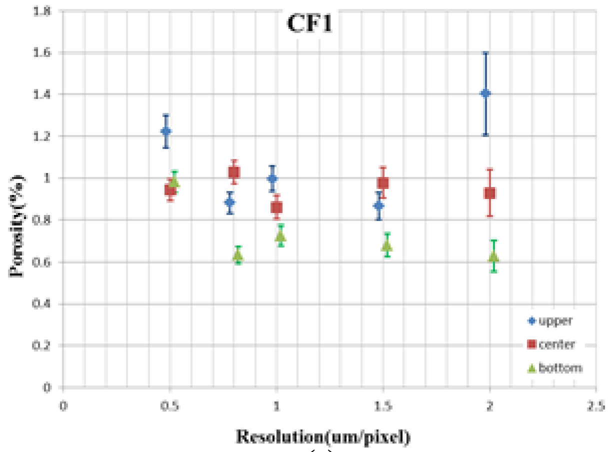
Fig.11 Reconstructed and binalized sectional images (CF3_upper, 1.0um/pixel)

4 Results and discussion

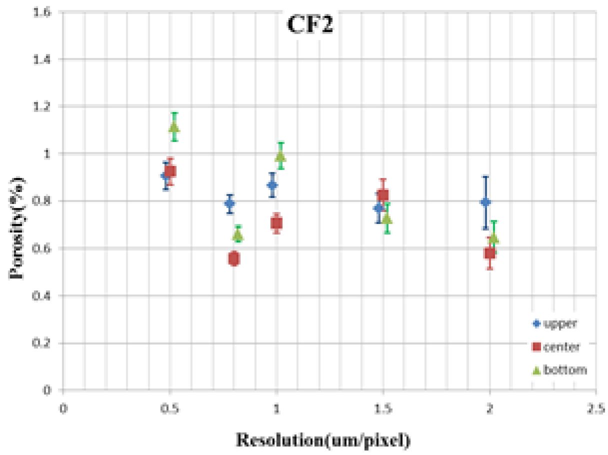
Table 2 shows calculated average values of porosities for nine specimens at five different resolutions. We show the relationship between resolutions and porosities graphically in Fig.12. Horizontal axis indicates resolution of scanner, and vertical axis indicates calculated porosity denoted on percentage.

Table2 Porosity of each Specimen

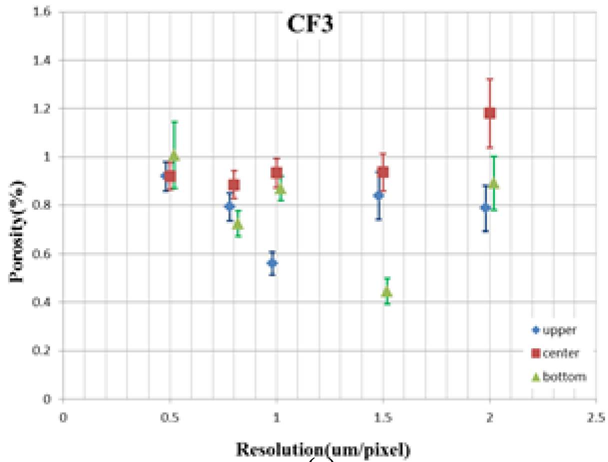
	Porosity(%)	0.5um/pixel	0.8um/pixel	1.0um/pixel	1.5um/pixel	2.0um/pixel
CF1	upper	1.223	0.881	0.997	0.866	1.403
	center	0.945	1.027	0.861	0.977	0.928
	bottom	0.981	0.634	0.726	0.680	0.629
CF2	upper	0.906	0.787	0.866	0.768	0.794
	center	0.925	0.559	0.706	0.825	0.581
	bottom	1.114	0.662	0.991	0.728	0.648
CF3	upper	0.920	0.793	0.560	0.839	0.787
	center	0.921	0.884	0.934	0.936	1.180
	bottom	1.007	0.725	0.886	0.446	0.892



(a)



(b)



(c)

Fig.12 Relationship between Porosity and Resolution
(a) CF1 (b) CF2 (c) CF3

The bars of each value is an error bar.
We were able to know the following from the graph of Fig.12.

- High resolution provides high porosity before 1.0um/pixel.
- It is not constant with the relationship between the porosity and the resolution after 1.0um/pixel.
- Dispersion of porosity is wide when the resolutions become low.

As described in 3.1, we specified for analyzing the same position like Fig.13. Low resolutions decrease the number of pixels for analyzing. Finally, we become less able to cognize the voids, cracks and the boundary of voids and cracks unlike high resolution. Therefore, great variation and wide dispersion of the porosity was provided at low resolution.
We can cognize tiny voids and cracks at high resolution. Therefore, high resolution provides high porosity.

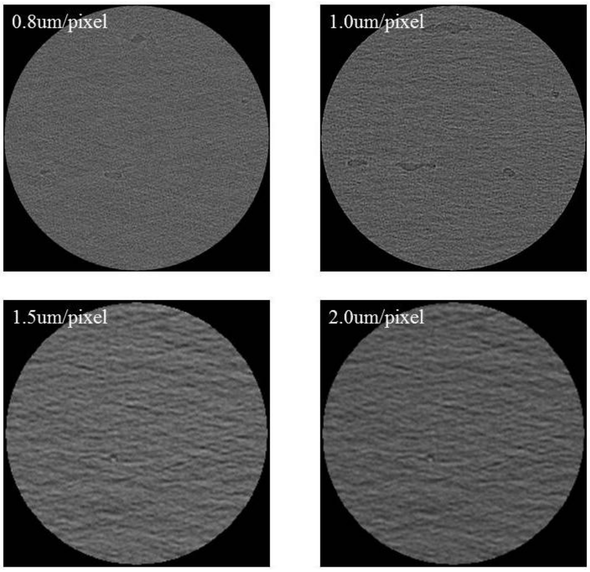


Fig.13 Difference in vision by Resolution

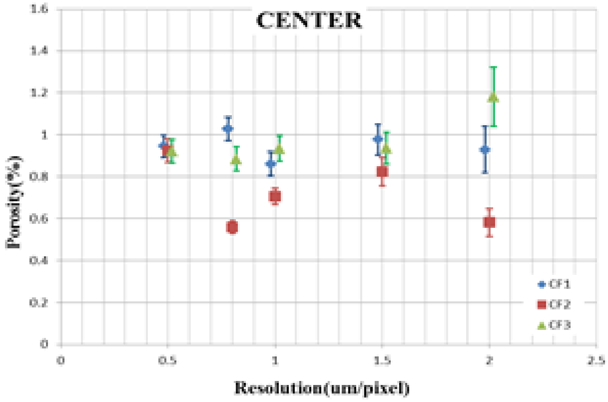


Fig.14 Porosity of three types samples (Center)

Next, we were able to know the following from the graph of Fig.14.

- CF3 has a big crack, but does not have a great difference in porosity compared to CF1 and CF2.

The porosity means cracks and voids. Why does the porosity of CF3 not have as great a difference?

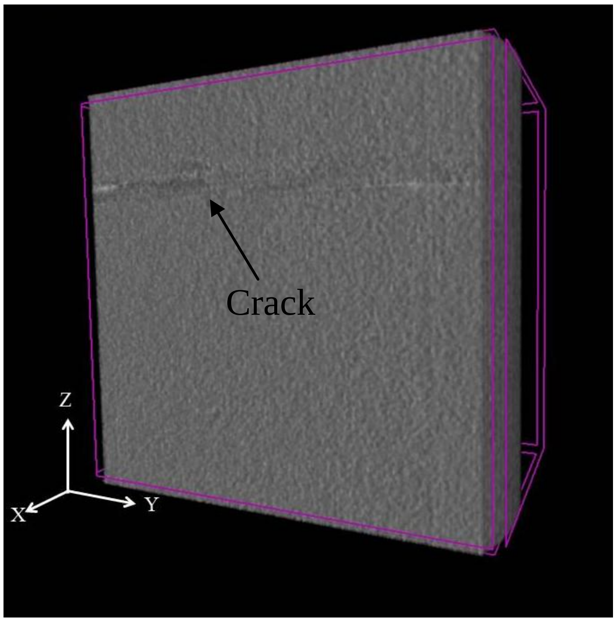


Fig. 15 Three dimensional reconstructed image

Fig.15 shows a three dimensional reconstructed image. Line of x-y plane is crack.
In this study, we used cross-sectional reconstructed images. Analysis direction is Z in Fig15. Now, we checked cross-sectional reconstructed image of using analysis which has a crack. That shows Fig.16. It is difficult for us to cognize from Z direction a cracks of x-y

plane. Therefore, CF3 has not great difference of porosity.

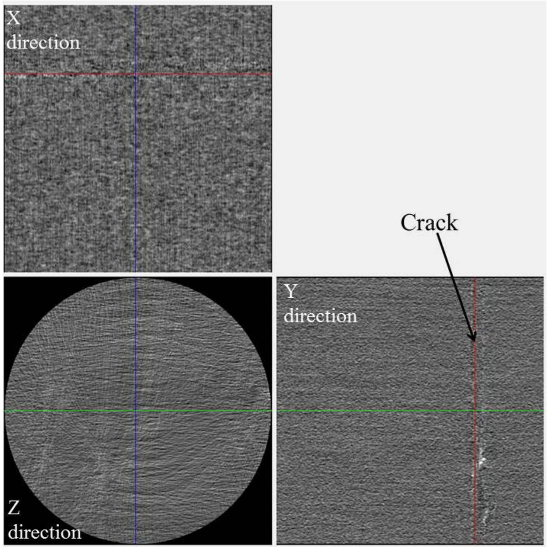


Fig.16 Reconstructed image of three direction

So first, we sliced the three dimensional image which direction is X for easy cognition. Second, we extracted an image of X direction and calculated the porosity. The porosity of Z direction is 0.92%, however, the porosity of X direction is 1.64%. Suitably, difference of cognition is difference of porosity.
In the future, we should analyze the porosity of three directions which are X, Y and Z.

4 Conclusions

We succeeded in knowing of relationship between the porosity inside CFRP specimen and the resolution of Micro X-ray CT.
High resolution provides high porosity until 1.0um/pixel. If we want to know the real porosity, we should use high resolution CT and calculate the porosity at all directions.

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