Available online at www.sciencedirect.com
ScienceDirect
Journal of Nuclear Materials 377 (2008) 28–33
journal of nuclear materials
www.elsevier.com/locate/jnucmat

The present status of R&D for the muon target at J-PARC: The development of silver-brazing method for graphite

Shunsuke Makimura [a,*], Hidetsugu Ozaki [b], Hisanori Okamura [b], Masatoshi Futakawa [c], Takashi Naoe [c], Yasuhiro Miyake [a], Naritoshi Kawamura [a], Kusuo Nishiyama [a], Masayoshi Kawai [a]

[a] *Institute of Materials Structural Science, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba-shi, Ibaraki-ken 305-0801, Japan*
[b] *Kinzoku Giken Co., LTD., 276-21, Motoishikawa, Mito-shi, Ibaraki-ken 310-0843, Japan*
[c] *Japan Atomic Energy Agency, Tokai-mura, Ibaraki-ken 319-1195, Japan*

Abstract

At the J-PARC muon science facility, the muon target was made of an isotropic graphite (IG-43). The energy deposited by the proton beam is estimated to be 3.3 kW on graphite and 600 W on the copper frame. To alleviate the thermal stress, a titanium stress absorber is inserted between the graphite and the copper. Although graphite is known to be difficult to be brazed, the titanium is attached to the graphite through silver-brazing. In this report, we will describe the development of a silver-brazing method for graphite in the fabrication of the J-PARC muon target. A capillary test between the graphite and the titanium was performed to determine the optimal brazing conditions. The test involved bonding graphite and titanium plates while varying the gap between them in order to determine the brazing material and the optimal surface treatment of graphite. Subsequently, a trial muon-production target was fabricated using this optimized brazing method. Specimens were cut from the trial target, and bending test experiments were performed to determine the tensile and shear strength of the interface. As a result, it was confirmed that graphite could be bonded adequately through the silver-brazing.
© 2008 Elsevier B.V. All rights reserved.

1. Introduction

At the J-PARC muon science facility, the most intense pulsed muon beam in the world will be produced by a 3 GeV/1 MW/25 Hz proton beam on a target made of 20-mm thick, disc-shaped, isotropic graphite (IG-43). The target frame will be constructed using copper with a stainless steel tube embedded for water cooling. The energy deposited by the proton beam is estimated to be 3.3 kW on the graphite target and 600 W on the copper frame by PHITS [1]. Using the results obtained by PHITS, both the static and the dynamic characteristics of the target such as temperature distributions, thermal stresses, shockwaves, and transient responses were evaluated thorough a finite element method (FEM) simulation. It was found that most of the thermal stress is located at the boundary edge between the graphite and the copper frame because of the difference in thermal coefficients between graphite and copper. To alleviate the thermal stress, a titanium stress absorber is inserted between graphite and copper [2]. Fig. 1 shows the schematic drawing and the picture of the muon target.

Considering that the beta-transition temperature in titanium is 885 °C, the bonding of the muon target must be performed under this temperature. Since the temperature of the interface between graphite and titanium will reach more than 200 °C during the full beam proton operation through the evaluation of an FEM simulation, the brazing material must have a much higher melting point simultaneously. Therefore, the silver-brazing method was selected to bond the two interfaces, which were graphite–titanium and titanium–copper. In general, graphite is known to be difficult to be brazed because the low wetting of graphite

* Corresponding author.
E-mail address: shunsuke.makimura@kek.jp (S. Makimura).

0022-3115/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2008.02.025

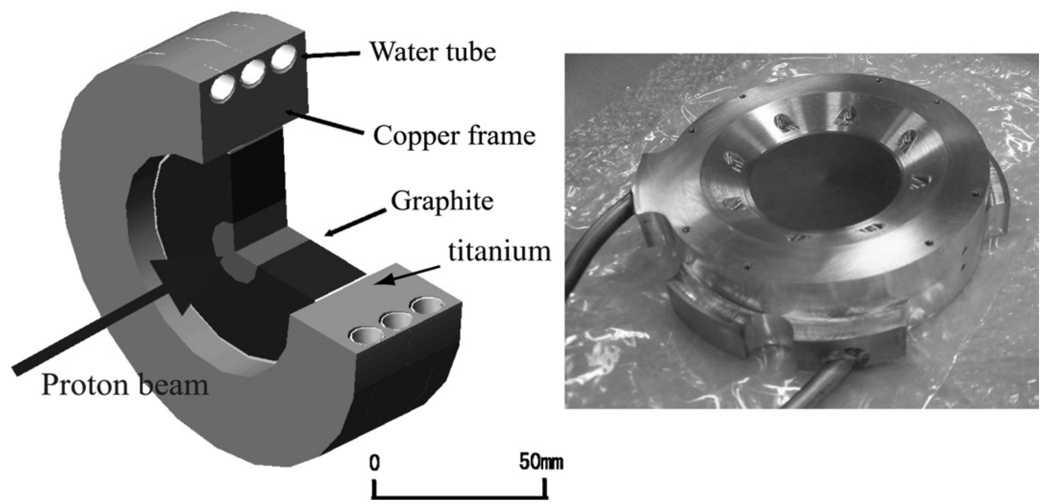

Fig. 1. The schematic drawing and the picture of the muon target. The target itself is made of 20-mm thick, disc-shaped, isotropic graphite (IG-43). The target frame is constructed using copper with a stainless steel tube embedded for water cooling. A titanium stress absorber is inserted between graphite and copper.

disturbs the capillarity, and the brazing material has difficulties to permeate the gap. At first, the commercial silver-brazing Incusil-Aba (59Ag/27.25Cu/12.5In/1.25Ti) was applied to the muon target, since graphite and titanium can be combined to make titanium carbide. But the graphite could not be bonded to the titanium adequately because the silver-brazing did not permeate the whole interface. Later we used a *special* silver-brazing material (76Ag/22Cu/2Ti), which was used to bond C/C composite and the oxygen-free copper in the development of the nuclear diverter [3]. We also considered that the surface treatment might affect the capillarity. Therefore, we performed a capillary test, in which graphite and titanium plates were bonded while varying the gap between them in order to determine the brazing material and the optimal surface treatment of graphite. The capillary test is described in Section 2.

Graphite is known to shrink due to radiation damage [4]. To reduce the tensile stress by the shrinkage, we could expect that the compressive stress, which results as the residual stress from the fabrication process, would compensate the tensile stress. Therefore, the graphite, shaped as a tapered cylinder, and the titanium, shaped as a tapered ring, are inserted into the copper frame at high temperature [5]. Fig. 2 shows the schematic drawing of this configuration used in the silver-brazing method. At room temperature, the copper frame and the titanium layer would shrink more than the graphite target. Then this compressive stress would act on the graphite like a shrink fit. Because the muon target is fabricated by this special configuration, it can be predicted that the properties of the interface are different from that in the capillary test. Subsequently, a trial muon target was fabricated using the optimized brazing method. In Section 3, the interface, which was obtained from the fabricated trial muon target, was observed by using a scanning electron microscope (SEM).

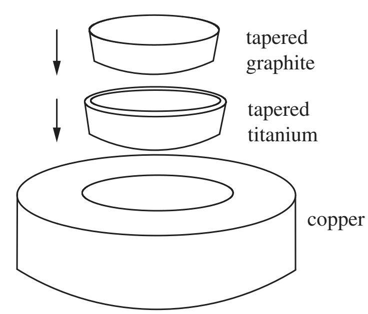

Fig. 2. The schematic drawing of the silver-brazing process for the fabrication of the muon target.

Through an evaluation by FEM, it was found that the compressive stress would take place at almost whole the interface of the graphite and the titanium during the proton beam operation, while the tensile and shear stress would occur simultaneously at the edge of the interface. Hence, specimens were cut from the trial target, and a bending test was performed to measure the tensile and shear strength of the interface. The stress analysis and the bending test experiment are described in Section 4.

A conclusion is given in Section 5.

2. Determination of the silver-brazing method

To determine the optimal silver-brazing method, a capillary test was performed under the following four conditions. (1) The commercial silver-brazing 'Incusil-Aba' was applied without any surface treatment to provide a basis of comparison. (2) The *special* silver-brazing material (76Ag/22Cu/2Ti) was applied without any surface treatment to compare with the example of the nuclear diverter. (3) A commercial silver-brazing material BAg-8 was applied after the graphite surface was painted and baked with the special silver-brazing material (76Ag/22Cu/2Ti).

Under this condition, we can expect that the surface of the graphite was wrapped by the metal which is easy to wet, and that the graphite and the titanium in the *special* silver-brazing will combine to make titanium carbide during the baking process. However, the thickness of the wrapped brazing cannot be uniform if the treated surface is vertical against gravity, such as the muon target, where the whole surface of the cylinder cannot stay horizontal at all-time. In fact, the redundant brazing material was removed by machining after baking. (4) The commercial silver-brazing material BAg-8 was applied after the graphite was surface treated using a titanium arc ion plating (AIP) method. We considered that a high ion acceleration voltage is required for the titanium ion to be implanted in the graphite. But too high an acceleration voltage (more than 100 V) will lead to the brittleness of the implanted surface through sputter-etching effect. Therefore, it was decided that the titanium ion should be accelerated to 50 eV in the AIP process. The implantation thickness of the titanium layer was 5 μm.

For each of those four conditions, the graphite and the titanium plates were bonded while varying the gap between them. The gap distance was 0.1 mm, 0.05 mm, and 0.01 mm, since the precision of the machining is better than 0.1 mm for the parts of the muon target. Fig. 3 shows a picture of the capillary test under the second condition with a gap of 0.05 mm. To observe the permeation of the silver-brazing, an ultra-sonic method was utilized. The ultra-sounds were incident to the graphite plate. If there is a gap between the graphite and the titanium, the ultra-sound is reflected on the gap and the echo is detected on the graphite surface faster than if the echo is reflected on the surface of the titanium. Through the capillary test, the following results were obtained. (1) Incusil-Aba could not permeate the gap for each gap distance. (2) The *special* silver-brazing material (76Ag/22Cu/2Ti) could permeate only a gap of 0.1 mm, but could not permeate narrower gaps. The wetting of the brazing material is improved compared with Incusil-Aba. (3) BAg-8 could permeate the gap between the titanium and the graphite with a surface treatment using the *special* silver-brazing material for each gap distance. (4) When using AIP of titanium on graphite, the result was similar to the second case. Thus, we could determine that the graphite and titanium could be bonded by BAg-8 with a surface treatment using the *special* silver-brazing material (76Ag/22Cu/2Ti).

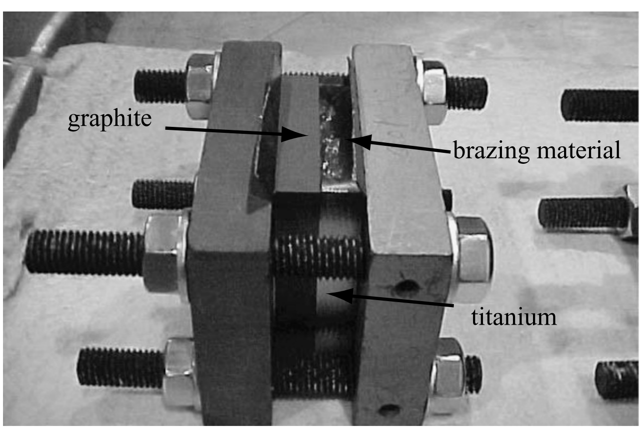

Fig. 3. The picture of the capillary test under the second condition, where the *special* silver-brazing material (76Ag/22Cu/2Ti) was applied without any surface treatment, with a gap of 0.05 mm.

3. Observation of the interfaces on the trial muon target

In the silver-brazing process, the two interfaces, graphite–titanium and titanium–copper, were bonded. Therefore, we must consider the validity of both interfaces. The interfaces, which were obtained from the fabricated trial muon target, were observed by using a scanning electron microscope (SEM). Fig. 4 shows a picture of the interfaces by SEM between the graphite and the titanium on the right-hand side, and between the titanium and the copper on the left-hand side. We could not find any gaps on the whole interfaces through SEM.

4. Stress analysis and bending test experiment

4.1. First stress analysis and FEM simulation

During the proton beam operation, it was found through FEM that 8 MPa of the tensile stress and 6 MPa

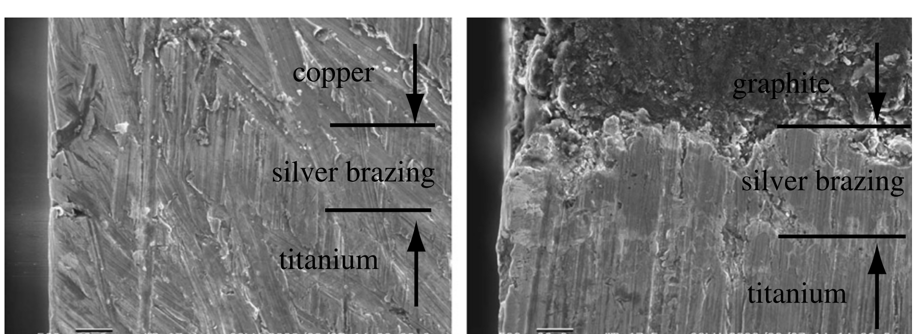

Fig. 4. The picture of the interfaces by SEM between the graphite and the titanium on the right-hand side, and between the titanium and the copper on the left-hand side.

of the shear stress will take place on the interface between the graphite and the titanium [2]. In general, the testing of tensile strength and shear strength is performed by stretching and giving a torque to a specimen, which is chucked at both ends by the testing apparatuses. However in our case, the specimen must be cut from the trial muon target, which is not large enough. Moreover, it is not easy to chuck graphite, since it easily brittles. Therefore, we decided to adopt the bending test of a simple bar, which was cut from the trial muon target with a shape of a parallelepiped. In that way, both the tensile stress and the shear stress on the interface could be evaluated through FEM. If both stresses in the bending test are beyond the design stress values, it can be confirmed that the bonded interface will withstand the proton beam operation. Although the stress-distribution was calculated in detail through FEM, we previously introduced a simple stress analysis to predict the effect of the configuration such as the dimensions of the specimen, the location of the interface, the location of the loading point, and so on. In this analysis, it was assumed that the specimen was made of an uniform material. As shown in Fig. 5, the bar has a distance l of the two support points, a width w, a height h, and a load F, which is loaded at the center between the two support points. Then the tensile stress occurs at the lower part of the bar. The maximum tensile stress T at a location x apart from the loading point is expressed as

$$T = \frac{M}{Z} = \frac{F}{2} \cdot \left(\frac{l}{2} - x\right) \cdot \frac{6}{wh^2} = \frac{3F}{wh^2}\left(\frac{l}{2} - x\right), \tag{1}$$

where M is the bending moment and Z is the section modulus [6].

The shear stress on the vertical plane against the bar axis is expressed as

$$S = \frac{F}{2wh}. \tag{2}$$

When the bending test was actually performed, the existing testing apparatus gave some limitations on the available load and the size of the specimen as well. In our case, the available load was from 1 N to 1000 N, and the specimen dimensions were decided as $l = 30$ mm, $w = 4$ mm, and $h = 6$ mm (variable). When x becomes too large, the properties of the support point and the setting precision of the specimen against the support point cannot be ignored. Therefore, we also applied $x = 5$ mm. In this section, it is assumed that the interface is parallel to the vertical plane against the bar axis. The simple bar model with a tilted interface is discussed in the following section. Although 8 MPa of the tensile stress and 6 MPa of the shear stress on the interface were the criteria, it would be favorable if the interface could be stronger than the graphite itself. Because graphite is known to break under the tensile stress, it is difficult to know the precise shear strength of graphite. Hence, 40 MPa of the tensile strength, that is the tensile strength of graphite, and 6 MPa of the shear strength on the interface were applied as criteria. To let the shear stress S beyond 8 MPa (safety factor of 1.3), F must be beyond 380 N. Then we can obtain $T = 80$ MPa. This means that the graphite will break before the shear stress reaches the criteria of 8 MPa. In the analysis, T was proportional to h^{-2}, and S is to h^{-1}. Hence, if $h = 12$ mm and $F = 760$ N are used, we would obtain $T = 40$ MPa and $S = 8$ MPa. Then the evaluation through a FEM was performed again under these different conditions. Consequently, $T_{\mathrm{fem}} = 57$ MPa and $S_{\mathrm{fem}} = 7$ MPa were obtained. The tensile stress was still larger than that in the stress analysis. We could consider that h was large enough so that the specimen could not be considered as a simple bar anymore. Therefore, it was concluded that the graphite will break under tensile stress before the shear stress can reach the design value, if the interface is on the vertical plane against the bar axis.

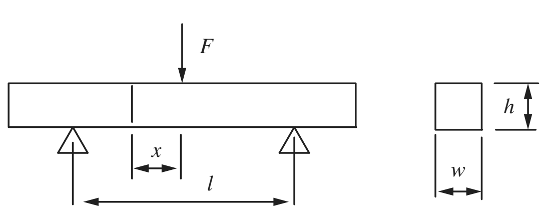

Fig. 5. The schematic drawing of the simple bar for the stress analysis. The bar has a distance l of the two support points, a width w, a height h, and a load F, which is loaded at the center between the two support points.

4.2. Second stress analysis and FEM simulation

Before a discussion of the specimen with the tilted interface, the shear stress on the stretched bar will be described. In general, when the tensile load is introduced to the bar, the shear stress occurs on the tilted plane against the load axis. Furthermore, the shear stress is maximized when the tilted angle is 45°. Then the shear stress becomes half of the tensile stress. The bending test in this section was based on this consideration. A tilted angle of 45° against the bar axis was applied to the specimen. Then it was assumed that $l = 30$ mm, $w = 4$ mm, $h = 6$ mm, and $F = 150$ N, which was loaded on the interface between the titanium and the copper. Here the shear stress was defined against the plane, which was parallel to the interface. Fig. 6 shows the shear stress-distribution calculated through FEM, when the bending test was performed. Fig. 7 shows the distribution of the shear stress, the maximum principal stress, and the minimum principal stress, along the interface between the graphite and titanium, where the horizontal axis was defined as the distance from the lower surface to the upper surface. As a result, the maximum stress $T_{\mathrm{fem}} = 41$ MPa and $S_{\mathrm{fem}} = 21$ MPa were obtained on the lower surface. As predicted, the shear stress was approximately half of the tensile stress and it was enough large compared with the criteria of 8 MPa. Finally, we determined that this configuration would be used in the actual bending test. Here, the specimen with the vertical interface was also evaluated through a FEM simulation to confirm that the shear stress

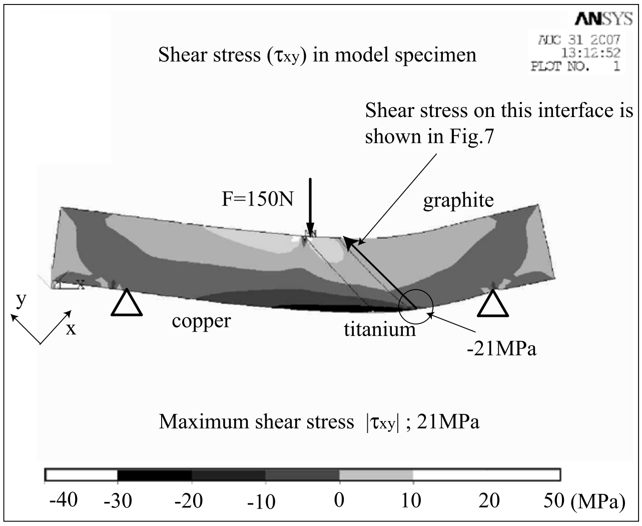

Fig. 6. The shear stress-distribution calculated through FEM, when the bending test with the tilted interface was performed.

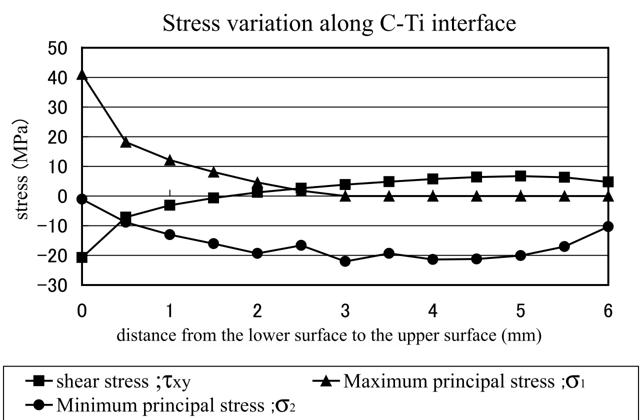

Fig. 7. The distribution of the shear stress, the maximum principal stress, and the minimum principal stress, along the interface between the graphite and titanium, where the horizontal axis was defined as the distance from the lower surface to the upper surface.

increases by tilting the interface. In this model, h, w, and l were the same as for the specimen with the tilted interface. The load was 140 N, and was added on the interface between the titanium and the copper. The difference between the two models is shown in Table 1.

4.3. Experiment

For the bending test, three kinds of the specimens (five samples each) were prepared. First, specimens made of only graphite were tested to make sure the validity of the testing method and the data scatter of the material strength. The specimen would break when the load reaches 130 N. Second, the specimens with the interface vertical to the beam axis were prepared. Although the number of samples was not enough to evaluate the data scatter, it was difficult to obtain more specimens from our trial target. The purpose to test these specimens was to confirm that the interface was stronger than graphite in terms of the tensile stress. Those specimens would break through a FEM simulation when the load reaches 140 N, which is on the interface between the titanium and the copper. Finally, the specimens discussed in the former section were prepared to confirm that the interface could withstand the design shear stress. Those last specimens would break when the load reaches 150 N. Fig. 8 shows a picture of the bending test, in which a specimen with the tilted interface was tested. From the bending test, the following results were obtained: (1) the specimens composed of only graphite were broken when the load reached 160 N, 170 N, 167 N, 160 N, and 160 N, respectively; (2) the specimens with the vertical interface were broken when the load reached a value of 160 N, 180 N, 174 N, 160 N, and 180 N, respectively; and (3) the specimens with the tilted interface were broken when the load reached 170 N, 165 N, 186 N, 192 N, and 164 N, respectively. The calculated loads in the FEM simulation, the measured average loads and their standard deviation are shown in Table 2. The breaking loads in the bending test were beyond the calculated loads in all the specimens. Moreover, it seems that the difference of the standard deviation is caused by the precision of setting the specimens. As shown in Fig. 6, the load was applied on the interface between the titanium and the copper. The brazed interface looked thicker than the actual one, because the brazing material diffused into the titanium and the copper. Considering that the specimens were set by hand, the specimens were positioned with a precision of about 0.7 mm. Since the tensile stress is proportional to $l/2 - x$, and also that the location of breaking is almost

Table 1
The calculated tensile and shear stress by FEM, for the tilted interface model and the vertical interface model

Interface	Load (N)	Tensile stress (MPa)	Shear stress (MPa)
45°-tilted	150	41	21
Vertical	140	44	3.6

Fig. 8. The picture of the bending test, in which a specimen with the tilted interface was tested.

Table 2
The calculated loads in FEM compared with the measured average loads and their standard deviation

Specimens	Calculation (N)	Average (N)	Standard deviation (N)
Graphite	130	163	4.3
Vertical interface	140	171	9.1
Tilted interface	150	175	11.4

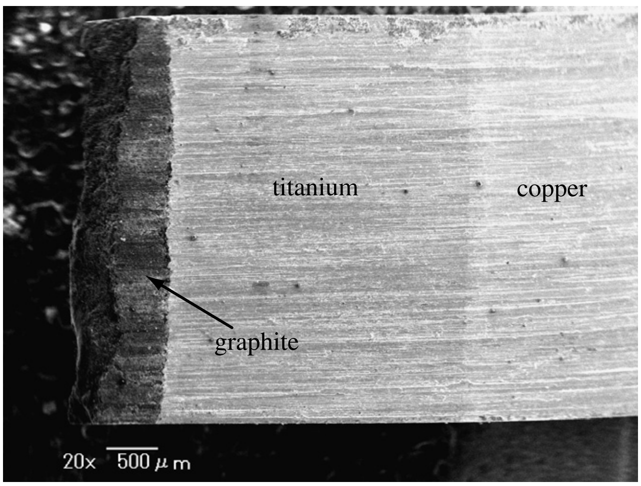

Fig. 9. The picture of a typical broken surface in the bending test observed through SEM.

on the interface ($l/2x = 9$ in the tilted interface), an error of 0.7 mm on x would correspond to an error on the tensile stress in the tilted interface of 14 MPa. Even in the vertical interface, we can obtain an error on the tensile stress of 9 MPa. This seems consistent with the measured values. As a result, it was concluded that the interface could withstand a tensile stress of 41 MPa and a shear stress of 21 MPa.

Additionally, it should be noted that all the specimens broke at the graphite. Fig. 9 shows a picture of a typical broken surface in the bending test observed through SEM. From this experiment, it was concluded that the interface between the graphite and the titanium was bonded adequately during the fabrication process of the muon target.

5. Summary

The silver-brazing method for graphite in fabrication of the muon target has improved. The capillary test was performed to obtain the optimal conditions by observing the interface through an ultra-sonic method. As a result, we could determine that the graphite and the titanium would be bonded by BAg-8 with a surface treatment by the *special* silver-brazing material (76Ag/22Cu/2Ti). Then this method was used to fabricate the trial muon target, and specimens for the bending test were cut. The bending test was performed to confirm that the tensile strength of the interface between the graphite and the titanium was beyond that of graphite (40 MPa), and that the shear strength was beyond the shear stress (8 MPa), which would take place during the proton beam operation. The interface was tilted with an angle of 45° against the bar axis to confirm the shear strength. To extract these strengths from the measurements, a FEM simulation was used. Consequently, it was proved that the tensile strength of the interface was beyond 41 MPa and the shear strength was beyond 21 MPa. Finally, we could determine the optimum silver-brazing method for graphite in the fabrication of the muon target.

References

[1] Hiroshi Iwase, Koji Niita, Takashi Nakamura, J. Nucl. Sci. Technol. 39 (2002) 1142.
[2] Shunsuke Makimura, Yasuhiro Miyake, Kusuo Nishiyama, Kanetada Nagamine, in: Proceedings of the 14th Symposium on Accelerator Science and Technology, Tsukuba, Japan, 2003, p. 22.
[3] Hisanori Okamura, Shouji Kajiura, Masato Akiba, Quart. J. Jpn. Weld. Soc. (1996) 39.
[4] H. Matsuo, Graphite1991 [No. 150], 290.
[5] Shunsuke Makimura, Naritoshi Kawamura, Kusuo Nishiyama, Yasuhiro Miyake, Takashi Anzai, Tomoya Suzuki, Takahiro Sawahata, in: Proceedings of the Second Annual Meeting of Particle Accelerator Society of Japan and the 30th Linear Accelerator Meeting in Japan, Tosu Japan, 2005, p. 173.
[6] S. Timoshenko, D.H. Young, Elements of Strength of Materials, fifth Ed.